Bulletin of Earth Sciences of Thailand

Preliminary Study on Petrography and Geochemistry of Basaltic Rock in Central Phetchabun, Thailand

Maythira Sriwichai[1*], Bunthita Rachanark[1], Prakhin Assavapanuvat[1], Pawat Wattanachareekul[1], Chanida Makakum[1], Thanaz Watcharamai[1], Pimolpat Ardkham[1], Amporn Chaikam[1], Chawisa Phujareanchaiwon[1], Prapawadee Srisunthon[1], Smith Leknettip[1], Sirawit Kaewpaluk[1], Sutthikan Khamsiri[1] and Sakonvan Chawchai[1,2*]

1. *Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand*
2. *Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit (MESA RU)*

*Corresponding author e-mail: maythira.saw@gmail.com and sakonvan.c@chula.ac.th ([1] equally contributed)

Abstract

The basalt of the Loei-Phetchabun Fold Belt is complicated in its distribution because of the association of Cenozoic with Permo-Triassic volcanic rocks. Phetchabun is well-known as tectonically impacted terrane having undergone several magmatic phases. Volcanic rocks in Phetchabun have been classified into two main groups: Wang Pong and Wichian Buri due to tectonics and age of origin. Our study area is located in central Phetchabun between the Nong Phai, Chon Daen, Bueng Sam Phan and Wichian Buri districts. Volcanic rocks in some part of the area have not been well described and classified. In this study, we aim to identify type and composition of basalts in Central Phetchabun by emploring petrological, XRD and XRF analysis. Four volcanic rock samples were chosen to represent the northern and southern part of the study area as they demonstrated different physical properties related to the various mineral composition. The results show that the samples can be classified into three groups by chemical and mineral composition. G2 and G4 from the southern part (in Bueng Sam Phan and Wichian Buri districts) which are basaltic andesite and basalt, show similar chemical characteristics, and represents the transition from Tholeiite to Calc-alkaline Series. By comparing with previous studies, the samples from the southern part can be correlated with basalt from Wichian Buri group, which occurred during a Cenozoic rifting event. The samples G1 and G3 are from the northern part of the study area (in Chon Daen district). G1 has anomalously high alkaline values and shows altered olivine phenocrysts. It was classified as mugearite. G3, an andesitic basalt, has a predominantly porphyritic texture and represents Calc-alkaline Series. Based on mineralogy and chemical composition, samples from the northern part are possible to be classified in the Wang Pong group which occurred during pre-Cenozoic subduction event. Trace and rare earth elements studies are recommended for further study.

Keywords: Volcanic Rock, Basalt, Phetchabun, Geochemistry, Petrography

1. Introduction

In Thailand, volcanic rocks can be divided into two major periods: Pre-Cenozoic and Cenozoic (Figure 1B.), which are related to two major tectonic events (Barr & Macdonald, 1991; Bunopas & Vella, 1978, 1983, 1992; Charusiri et al., 2002; Charusiri, Kosuwan, & Imsamut, 1997; Hada et al., 1999; Metcalfe, 1996, 1997, 2002; Sone & Metcalfe, 2008; Yang, Mo, & Zhu, 1994). During the Permian and Triassic period, the Sukhothai and Loei-Phetchabun Fold Belts were formed by the collision between Shan-Thai and Indochina terranes (Bunopas, 1982; Hahn, Koch, & Wittekindt, 1986; Wielchowsky & Young, 1985) while Charusiri et al. (2002) proposed that two oceanic plates, Lampang-Chiang Rai and Nakhon Thai, were located between two major continental plates and underwent multiple concurrent subductions.

In the Cenozoic era, during the Oligocene and Late Miocene, the collision between the Indian and the Eurasian plate caused the extension of the Gulf of Thailand and the South China Sea (Barr & Macdonald, 1978; Morley, 2002; Morley et al., 2013; Morley, Charusiri, & Watkinson, 2011). This event provoked rifting-related magmatism and eruption. Therefore, the Loei-Phetchabun Fold Belt exhibits two major magmatic processes which occured before and within the Cenozoic era controlled by complex tectonic processes (Charusiri et al., 2002).

The Pre-Cenozoic volcanic rocks of the Loei-Phetchabun Fold Belt range from felsic to mafic, mainly tholeiite and calc-alkaline volcanic rocks, volcaniclastic rocks and volcanogenic-sedimentary rocks of the Late Permian-Triassic period. Intrusive rocks occur during the Middle Triassic (Barr & Charusiri, 2011). In Thailand, Pre-Cenozoic volcanic rocks are widely distributed, especially in the following areas: Loei (Altermann, 1991; Intasopa, 1993; Intasopa & Dunn, 1994; Panjasawatwong et al., 1997, 2006), Wang Pong in Phetchabun (Boonsoong, Panjasawatwong, & Metparsopsan, 2011; Intasopa, 1993; James & Cumming, 2007; Jungyusuk & Khositanont, 1992), Phai Sali in Nakhon Sawan, Saraburi and Sa Kaeo (Jungyusuk & Khositanont, 1992).

The Cenozoic basalts of the Loei-Phetchabun Fold Belt are complicated in its distribution because of its association with Permo-Triassic volcanic rocks. Cenozoic volcanic rocks are also found in the Wichian Buri area in Phetchabun (Barr & Cooper, 2013; Charusiri, 1989; Intasopa, Dunn, & Lambert, 1995; Sutthirat et al, 1995), and the Lam Narai-Chaibadan area in Lop Buri (Barr & Macdonald, 1981; Intasopa, 1993; Intasopa et al., 1995), both locations located in the south of our study area (Figure 1A.). According to Barr & Charusiri (2011), the Cenozoic basalts in Phetchabun are generally classified into two types; high alkalic basanitoid and less alkalic to tholeiitic basalt.

Phetchabun is a province in Central Thailand located on the left edge of the Khorat Plateau (Figure 1A.). Regarding the geological setting of Thailand, Phetchabun is well-known as tectonically impacted terrane which underwent several magmatic phases. The Pre-Cenozoic volcanic rocks in Phetchabun have been found in the Wang Pong area and around Phetchabun-Chondaen Road. Numerous geochemical studies indicated that the volcanic rocks in the area are Triassic basalt and andesite (244-238 Ma), Permo-Triassic andesitic and rhyolitic flows and breccias (250±6 Ma) (Cumming et al., 2008; James & Cumming, 2007; Jungyusuk & Khositanont, 1992; Kamvong, Charusiri, & Intasopa, 2006; Salam et al., 2008). According to Vichit (1992); Vichit et al. (1988) and Intasopa et al. (1995), the main types of Cenozoic volcanic rocks are alkali olivine basalt, hawaiite, nepheline hawaiite and basanite which are found in the Wichian Buri area. While several studies focused on basalts in Wang Pong and Wichian Buri, the basalts in between these two areas, however, are still poorly understood. During our fieldwork in 2018 (Geo59) in the Phetchabun province, we surveyed and mapped various types of volcanic rocks. Additionally, we collected samples to classify their physical properties for rock identification. Through thorough examination of the samples, we found that basalts from the northern and southern part of the study area (Figure 2.) show different mineral compositions that imply the different/variable origins and geneses. Therefore, we aim to identify type and composition of basalts in the northern and southern parts of the study area (Figure 2.) by using petrological and geochemical analysis. In addition, we also compare our results (mineral compositions and geochemical data) with previous works from the Wang Pong and Wichian Buri areas. The results from our study give an insight into the type of basalts and their distribution in Phetchabun province.

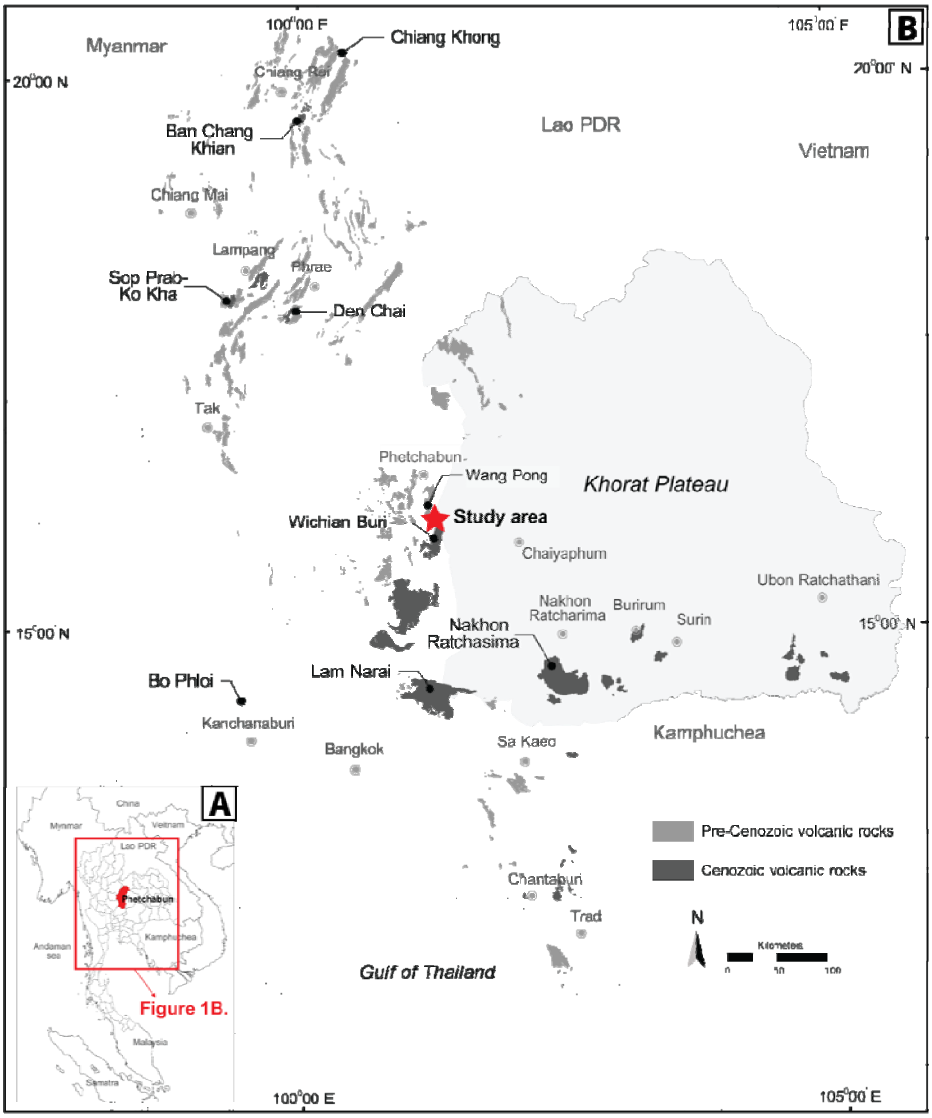

Figure 1. **(A)** Study area (red frame) in the Phetchabun province, central Thailand. **(B)** Distribution of Pre-Cenozoic and Cenozoic volcanic rocks in Thailand (modified from Barr and Charusiri (2011)).

2. Study Site

The fieldwork area is located in Phetchabun (Figure 1A.) including parts of Nong Phai, Chon Daen, Bueng Sam Phan and Wichian Buri districts (Figure 2.). A detailed geological mapping (1:25,000) was created by undergraduate students and staff members from the Department of Geology, Chulalongkorn University (in 2018, GEO59). Outcrops from the study area were classified into; 4 Permian, 1 Triassic and 1 Tertiary stratigraphic formation; coexisting with 4 igneous groups, comprising of dioritic rocks, andesitic rocks and 2 groups of basaltic rocks; and 2 unconsolidated sediments including floodplain sediments and terrace sediments. The least studied units were those 2 basaltic groups which are referred to as “northern group” and “southern group” (Figure 2.)

Several samples were collected during fieldwork. Four basalt samples were used for this study (G1, G2, G3 and G4). The specimens G1 and G3 represent the northern group while G2 and G4 belong to the southern basaltic rocks. The samples G1 and G3 are comprised of a dull dark groundmass, G2 and G4 are characterized by a dark purplish color, a groundmass dominated by plagioclase and olivine phenocrysts. Vesicular texture and columnar joints were also observed at sample locations G2 and G4. Based on visual examination, sample G1 sets itself apart from the other samples by the absence of megacrysts and exhibiting the finest texture.

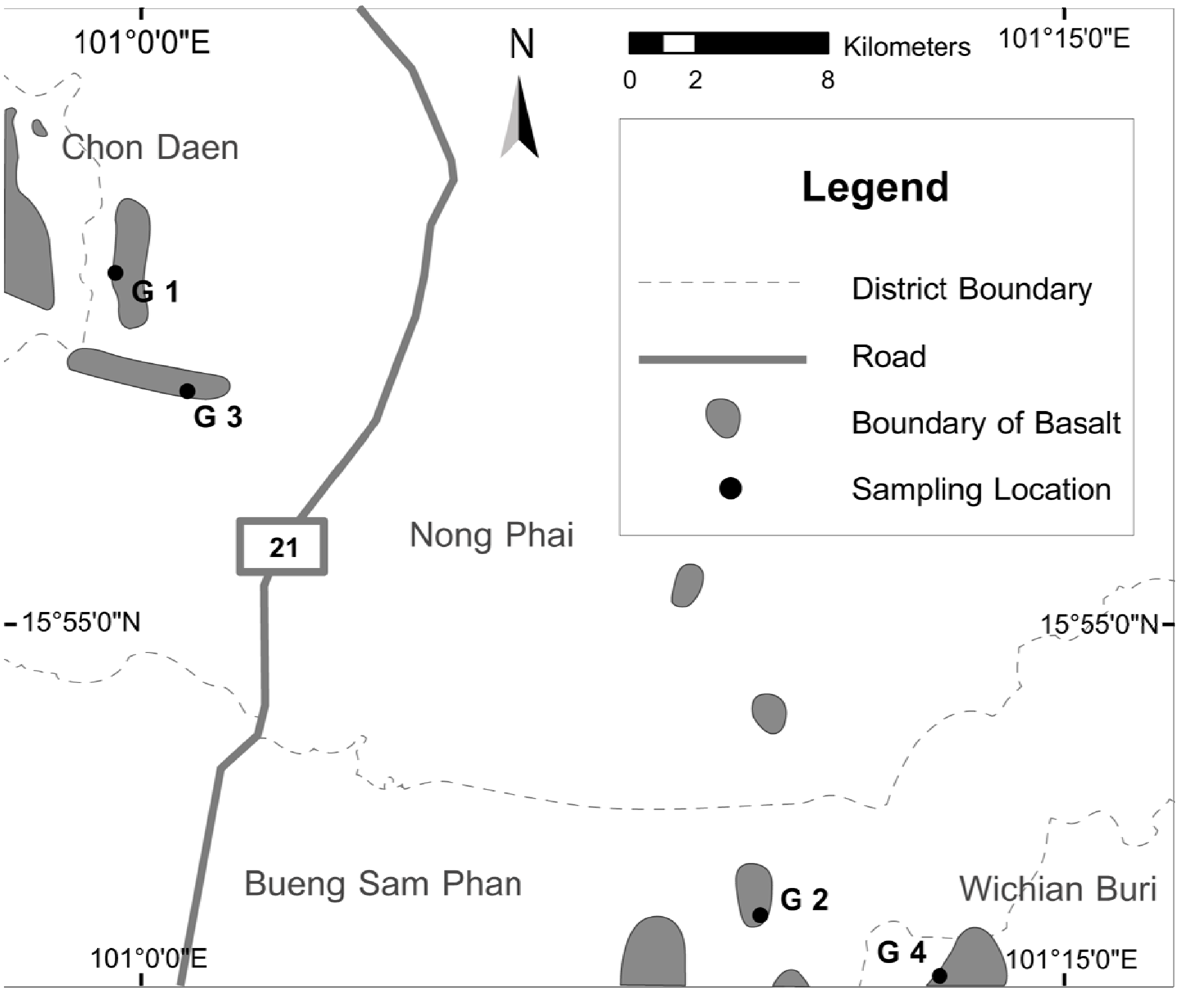

Figure 2. Distribution of basalts in the study area and sampling locations. G1 and G3 represent the basalts from the northern part while G2 and G4 show the basalts from the south part. The map was acquired during fieldwork (2018, Geo59).

3. Methodology

3.1 Sampling and sample preparation

Four samples (about 4x3x1 inches) were collected from different locations in Phetchabun province (Figure 2.). To avoid sampling error, we selected homogeneous basalt rock and removed all superficial weathering crust before dividing the sample into two parts, one for petrological analysis and one for geochemical analysis. The samples for petrological analysis were prepared for thin sections with thickness nearly 30 µm and attached to glass slide and cover slip. For the geochemical analysis, samples were crushed by jaw crusher, subsequently ground into powder (<200 mesh), and finally split into two aliquots for XRD and XRF analysis.

3.2 Petrographic analysis

Four thin sections were studied under a polarized light microscope. The mineral compositions were identified and estimated the percentages of each mineral in the samples. Each sample will represent mineral compositions of basals in each location, especially the results will employ to support results from XRD analysis.

3.3 X-Ray Diffraction Analysis (XRD)

The powdered samples were compressed into a mount. The analysis was operated by XRD (BRUKER model D8 Advance) with X-ray beam diffraction at 2θ angles from 5° to 60° and a step time of 0.01 with scan 1 second/step scan. The results are plotted in 2θ – intensity graphs (Figure 4A-D). Then, peak data from 2θ graph were used to match type of minerals. Finally, the content of minerals was calculated in percentage of whole rock by using EVA and MUAD softwares (http://maud.radiographema.eu/). EVA will help to distinguish the mineral name by comparing with the reference library. Also, we used the MAUD program to identify mineral and indicate weight percentages of each mineral composition.

3.4 X-Ray Fluorescence Analysis (XRF)

Major oxide elements were measured by XRF method. 8 grams of powdered rock sample mixed with 1 g of binder were used to prepare pressed pellets with a sample holder diameter of 34 mm. The analysis was performed by using BRUKER model S4 Pioneer (wavelength dispersive - WDXRF). The XRF machine was set up at a generator voltage of 50 kV at 54 mA. Multiple certified reference standards (USGS SGR-1, BHVO-2, BCR-2 and GSP-2) were run to test the accuracy of the analysis.

4. Results

4.1 Petrology

In this study, basaltic rocks were classified, based on mineral assemblage and textures, into 3 types: 1. Plagioclase-olivine basalt, 2. Olivine-clinopyroxene-orthopyroxene basalt and 3. Porphyritic olivine-clinopyroxene basalt (Figure 3.).

4.1.1 Plagioclase-olivine basalt (G1)

Plagioclase-olivine basalt shows porphyritic texture dominated by olivine phenocrysts (less than 3%; Figure 3A.). The groundmass consists of plagioclase, iddingsite and olivine. Crystal sizes of plagioclase (euhedral) range from 0.05 to 0.15 mm, Olivine (subhedral-anhedral) range from 0.01 to 0.06 mm Olivine core with altered iddingsite rim indicates that iddingsite altered from olivine.

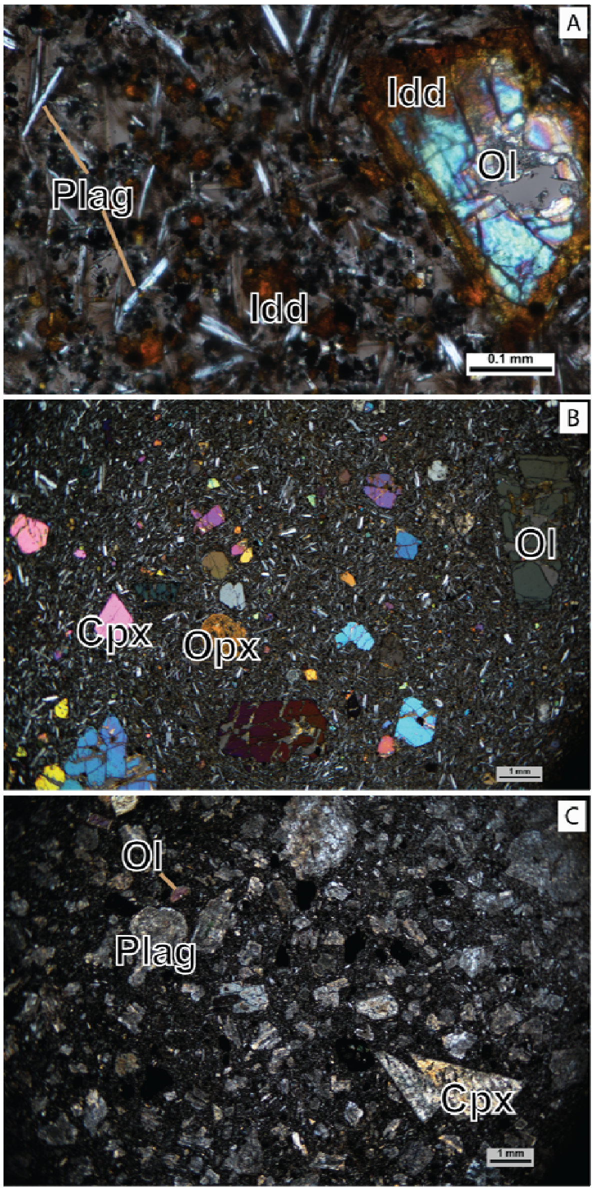

Figure 3. Photomicrographs under cross-polarized light (XPL) showing mineral assemblages and textures: **(A)** Plagioclase-olivine basalt **(B)** Olivine-clinopyroxene-orthopyroxene basalt **(C)** Porphyritic olivine-clinopyroxene basalt. Mineral abbreviations : Plag (plagioclase); Idd (iddingsite; alteration at the rim of olivine); Ol (olivine); Cpx (Clinopyroxene); Opx (Orthopyroxene).

4.1.2 Olivine-clinopyroxene-orthopyroxene basalt (G2 and G4)

Porphyritic texture is presented in this group (Figure 3B.). Phenocrysts (5-10%) of olivine (subhedral-anhedral), clinopyroxene (subhedral) and orthopyroxene (euhedral-anhedral) range from 0.3 to 1.5 mm in size. The groundmass is mainly composed of plagioclase (euhedral) with crystal sizes between 0.03 x 0.10 and 0.25 x 1.10 mm.

4.1.3 Porphyritic olivine-clinopyroxene basalt (G3)

The sample is marked porphyritic texture with abundance of phenocrysts (30%; Figure 3C.). It composes of plagioclase and fewer clinopyroxene and olivine. The plagioclase shows euhedral-subhedral shape with sizes of 0.3 to 2.0 mm. Clinopyroxene (subhedral) and olivine (anhedral) exhibit sizes of 0.25 to 0.5 mm and 0.3 mm, respectively. The groundmass shows intergranular texture and consists of plagioclase (euhedral) with their crystal size of 0.03 x 0.10 mm. Mafic minerals were partially altered to chlorite. Fe oxides occur as additional constituents. Porphyritic texture represents 2 phases of magma cooling.

4.2 X-Ray Diffraction (XRD)

According to the XRD results, the diffraction patterns of samples (Figure 4A-D) were used to identify minerals by corresponding Rietveld fit. The mineralogy of samples is shown in Table 1, which mainly composed of plagioclase ranging from anorthite to andesine, clinopyroxene and minor olivine.

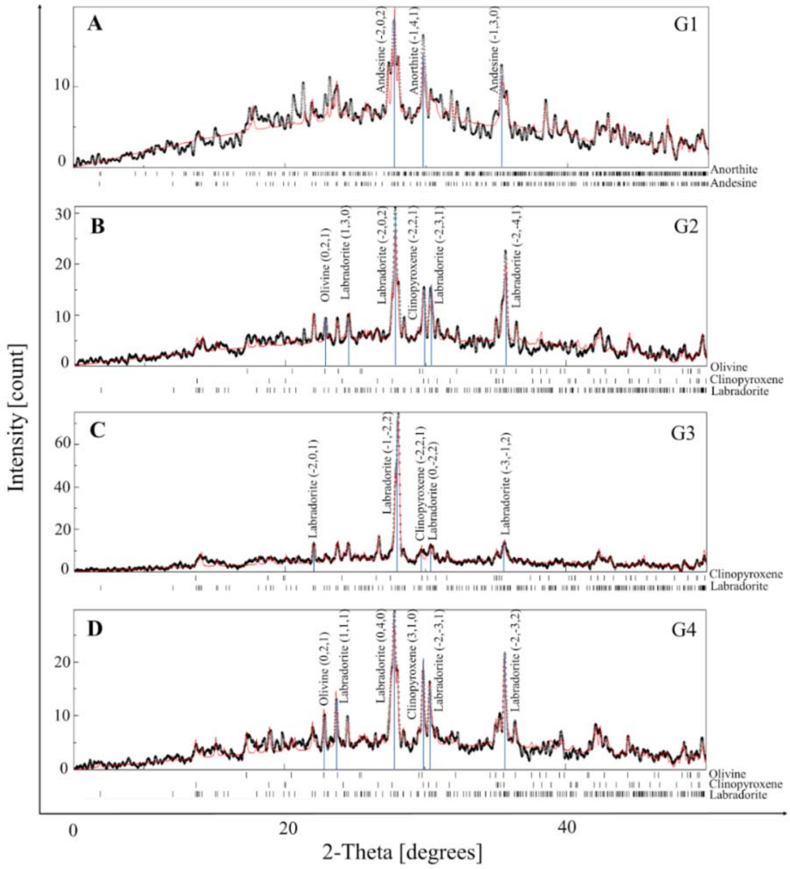

Figure 4. Diffraction pattern of samples. **(A)** Sample G1, **(B)** Sample G2 **(C)** Sample G3 and **(D)** Sample G4. Dots are experimental XRD data and red lines represent the Rietveld fit. Some diffraction peaks are identified (blue lines). The bars below the diffraction pattern are mineral phases and corresponding diffractions.

Table 1. Mineralogy of samples identified by XRD analysis

Sample	Mineralogy by XRD	Thin Section Mineralogy
G1	andesine and anorthite	plagioclase, iddingsite and olivine
G2	labradorite, clinopyroxene and olivine	plagioclase, olivine, clinopyroxene, and orthopyroxene
G3	labradorite and clinopyroxene	plagioclase, clinopyroxene, olivine and chlorite
G4	labradorite, clinopyroxene and olivine	plagioclase, olivine, clinopyroxene and orthopyroxene

The mineralogical differences reveal that G1 is dominated by plagioclase including anorthite and andesine whereas G2 and G4 comprise similar compositions including labradorite, clinopyroxene and olivine. G3 mainly consists of labradorite and clinopyroxene. Clinopyroxene and orthopyroxene indicate magmatic fluid with concentration of Ca, Fe and Mg and plagioclases types represent high concentration of calcium.

4.3 X-Ray Fluorescence (XRF)

Four basaltic rock samples (G1, G2, G3 and G4) from Central Phetchabun were selected to be analyzed regarding their major oxides. The rock samples show the weight percentage of whole rocks (Table 2).

Table 2. Mineralogy of samples identified through XRD analysis

Oxide (wt%)	G1	G2	G3	G4
SiO_2	51.43	48.58	52.88	47.51
TiO_2	1.56	1.88	0.81	1.61
Al_2O_3	17.64	15.86	19.44	14.03
$FeO_{(total)}$	8.86	9.54	9.66	10.43
MnO	0.13	0.16	0.19	0.17
MgO	3.99	8.3	3.91	10.24
CaO	5.57	10.53	7.84	10.75
Na_2O	5	2.29	4.03	3.05
K_2O	3.77	1.64	1.12	1.12
P_2O_5	2.02	1.2	0.1	1.06
Sum	100	99.99	100	100

A plot of total alkalis (Na_2O+K_2O) versus silica (SiO_2) from Cox, Bell, & Pankhurst (1993) (Figure 5A.), is used to classify the rock types. G1, G2 and G4 have basic composition whereas G3 has intermediate composition. Accordingly, G2 and G4 are classified as basalt, G3 as basaltic andesite and G1 as mugearite.

An AFM diagram (Na_2O + K_2O – MgO – FeO_{total}) (Irvine & Baragar, 1971) (Figure 5B) is also used to distinguish between Tholeiitic and Calc-alkaline Series. G1 and G3 are plotted within the Calc-alkaline Series. G2 and G4 are plotted within the transition between Tholeiite and Calc-alkaline Series.

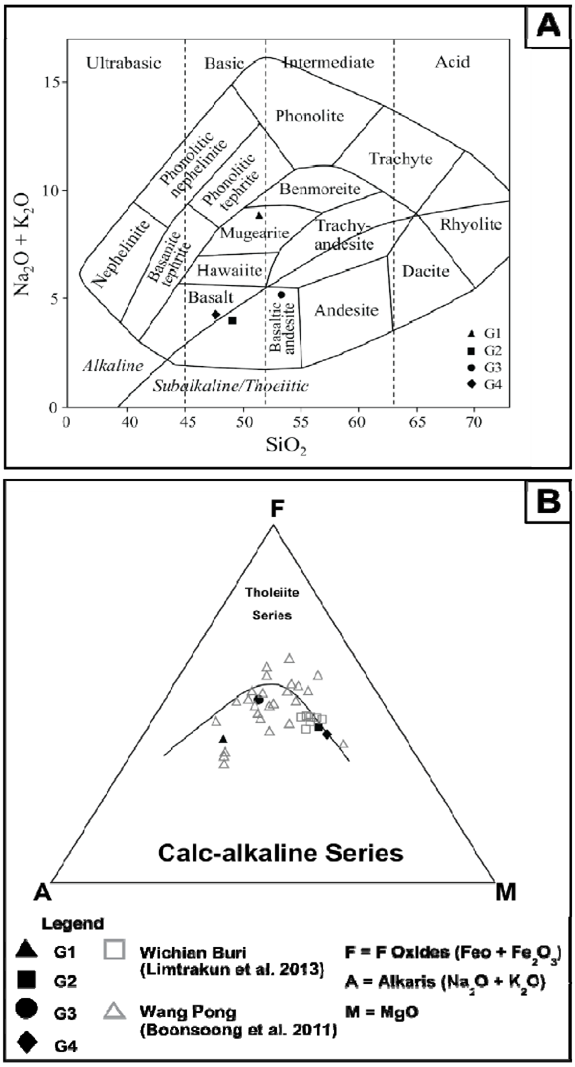

Figure 5. Geochemical plots **(A)** The chemical classification and nomenclature of volcanic rocks using the total alkalis versus silica (TAS) (Cox et al., 1993). The curved solid line subdivides the alkaline from subalkaline rocks. **(B)** The AFM diagram shows the boundary between the calc-

alkaline field and the tholeiitic field (Irvine & Baragar, 1971).

5. Discussion

According to the results, the volcanic rocks in the study area can be classified into three groups. The samples from the southern part in Bueng Sam Phan and Wichian Buri districts (G2 and G4) are basaltic andesite and basalt showing similar mineral compositions with aphanitic textures. This suggests that both were originated from the same magma series, which are predominating in Magnesium Oxide and have transitional composition between Tholeiite and Calc-alkaline Series. While basalt from the northern part (in Chon Daen district) were classified as difference; G1 is mugearite with outstandingly highest Calc-alkali. Their aphanitic texture implies the rapid cooling of magma. G3 is classified as basaltic andesite in Calc-alkaline Series. G3 shows porphyritic texture with fine groundmass which suggests two stages of magma cooling. In the first stage, the magma is cooled slowly deep in the crust, creating the large crystal grains, with a diameter of 2 mm or more. In the final stage, the magma is cooled rapidly at relatively shallow depth or as it erupts from a volcano, creating small grains that are usually invisible to the unaided eye typically referred to as the ground mass. Based on petrology and XRD analysis, types of feldspars (ranging from anorthite to andesine) suggest high concentration of calcium. This supports chemical composition of the Calc-alkaline series.

From plotting, the major oxide of samples from this study and previous studies of Wang Pong volcanic rocks and Wichian Buri volcanic rocks (Figure 5B.), we found that G2 and G4 representing southern part of study area tend to have similar geochemical composition to Wichian Buri basalt. G1 and G3 can be correlated to Wang Pong volcanic rocks as it shows wide range of geochemical composition.

Fitton and Upton (1987) have classified the origin of alkaline rock into 3 types, continental rifting magmatism, oceanic and continental intraplate magmatism and the last one, subduction magmatism. Continental rifting magmatism is the most dominated cause of alkalic and tholeiitic rock enriching in Na and K by crustal assimilation. Continental intraplate magmatism, triggered by the upwelling of mantle plume, is rarely founded in interior continent due to the thick continental pathway that hinders the penetration. In contrast, subduction-related alkaline magma occurs when the system become dehydrated prohibiting the crystallization of calc-alkalic minerals. This process occurs in the deepest part of descending slabs associated with genesis of shoshonitic rock.

From these possible processes and the previous studies, we conclude that the rocks in the study area might associate with two tectonic events, subduction related magmatism and continental rifting magmatism. G1 and G3 which are Calc-alkaline Series are related to subduction magmatism. G2 and G4 which have transitional composition between Tholeiite and Calc-alkaline Series are possible related to continental rifting magmatism. However, in this study we analyzed only major elements which give us limited discussion on tectonic setting of volcanic rocks. For further study, we suggest that the analysis on trace elements and rare earth elements need to be done to confirm there tectonic setting and magma series.

6. Conclusions

The investigation on mineral and chemical compositions of basaltic rock in Central Phetchabun, Thailand using petrographic analysis, X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) gives us a wider perspective on variability of origin and genesis of volcanic rocks in this area. Volcanic rocks from northern part of the study area in Chon Daen District (G1 and G3) consist of mugerlite and basaltic andesite defined as Calc-alkaline Series. The geochemical data reveal that the rock in northern part (Chon Daen district) tend to have similar composition to Wang Pong area, which occurred in subduction process (Boonsoong et al., 2001). On the other hand, the southern part (G2 and G4; in Bueng Sam Phan and Wichian Buri districts) comprises of basaltic andesite and basalt having transitional composition between Tholeiite and Calc-alkaline Series. This show the similar characteristic composition with Wichian Buri basalt, which previously report occurred in continental rifting process (Limtrakul et al., 2013).

Acknowledgement

We would like to thank Geo59 for the field work data. As well as, we would like to thank staffs at Department of Geology, Faculty of Science, Chulalongkorn University for the great support. We also thank Dr. Raphael Bissen for the great input on discussion and for improving English.

References

Altermann, W. (1991). New Permo-Carboniferous geochemical data from central Thailand: implication for a volcanic arc model. *Palaeogeography, Palaeoclimatology, Palaeoecology, 87*(1-4), 191-210.

Barr, S. M., & Charusiri, P. (2011). Volcanic Rocks. In M. F. Ridd, A. J. Barber, & M. J. Crow (Eds.), *The Geology of Thailand* (pp. 415-439). London: The Geological Society.

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

Barr, S. M., & Macdonald, A. S. (1978). Geochemistry and petrogenesis of Late Cenozoic alkaline basalts of Thailand. *Geological Society of Malaysia, 10*, 25-52.

Barr, S. M., & Macdonald, A. S. (1981). Geochemistry and geochronology of Late Cenozoic basalts of Southeast Asia. *Geological Society of American Bulletin, 92*(508-512), 1069-1142.

Barr, S. M., & Macdonald, A. S. (1991). Toward a Late Paleozoic-Early Mesozoic tectonic model for Thailand. *Thailand Journal of Geoscience, 1*, 11-22.

Boonsoong, A., Panjasawatwong, Y., & Metparsopsan, K. (2011). Petrochemistry and tectonic setting of mafic volcanic rocks in the Chon Daen-Wang Pong area, Phetchabun, Thailand. *Island Arc, 20*(1), 107-124Bunopas, S. (1982). *Paleogeographic history of Western Thailand and adjacent parts of Southeast Asia – a plate tectonics interpretation.* Retrieved from Bangkok:

Bunopas, S., & Vella, P. (1978). *Late Palaeozoic and Mesozoic structural evolution of Northern Thailand. Bangkok.* Paper presented at the Third Regional Conference on Geology and Mineral Resources of Southeast Asia, Bangkok, Thailand.

Bunopas, S., & Vella, P. (1983). *Tectonic and geologic evolution of Thailand.* Paper presented at the Workshop on Stratigraphic Correlation of Thailand and Malaysia, Hat Yai, Thailand.

Bunopas, S., & Vella, P. (1992). *Geotectonic and geologic evolution of Thailand.* Paper presented at the National Conference on Geological Resources of Thailand: Potential for Future Development, Bangkok, Thailand.

Charusiri, P. (1989). *Lithophile metallogenic epochs of Thailand: geological and geochronological syntheses.* (Ph.D.), Queen's University, Kingston, Ontario, Canada.

Charusiri, P., Daorerk, V., Archibald, D., Hisada, K., & Ampaiwan, T. (2002). Geotectonic evolution of Thailand: A new syntesis. *Journal of the Geological Society of Thailand, 1*, 1-20.

Charusiri, P., Kosuwan, S., & Imsamut, S. (1997). *Tectonic evolution of Thailand from Bunopas (1981) to a new scenario.* Paper presented at the International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the south Pacific, Bangkok, Thailand.

Cox, K. G., Bell, J. D., & Pankhurst, R. J. (1993). *The interpretation of igneous rocks* (1 ed.). London, U.K.: Chapman & Hall.

Cumming, G., James, R., Salam, A., Zaw, K., Meffre, S., Lunwongsa, W., & Nuanla-Ong, S. (2008). *Geology and mineralization of the Chatree epithermal gold-silver deposit, Phetchabun Province, Central Thailand.* Paper presented at the of PACRIM Congress, Gold Coast, Australia.

Fitton, J. G., & Upton, B. G. J. (1987). *Alkalic igneous rock.* London, U.K.: Geological Society of London.

Hada, S., Bunopas, S., Ishii, K., & Yoshikura, S. (1999). *Rift-drift history and the* *amalgamation of Shan-Thai and Indochina/East Malaya Blocks*. Paper presented at the Gondwana Dispersion and Asian Accretion – IGCP 321 Final Results Volume.

Hahn, L., Koch, K. E., & Wittekindt, H. (1986). *Outline of the geology and mineral potential of Thailand*. Hannover, German: Geologisches Jahrbuch.

Intasopa, S. (1993). *Petrology and Geochronology of the Volcanic Rocks of the Central Thailand Volcanic Belt.* (Ph.D.), University of New Brunswick, Fredericton, New Brunswick, Canada.

Intasopa, S., & Dunn, T. (1994). Petrology and Sr-Nd systems of the basalts and rhyolites, Loei, Thailand. *Journal of Southeast Asian Earth Sciences, 9*, 177-180.

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

Irvine, T. N., & Baragar, W. R. A. (1971). A Guide to the Chemical Classification of the Common Volcanic Rocks. *Canadian Journal of Earth Sciences, 8*(5), 523-548.

James, R., & Cumming, G. V. (2007). *Geology and mineralization of the Chatree epithermal Au-Ag deposit, Phetchabun Province, Central Thailand.* Paper presented at the International Conference on Geology of Thailand – Towards Sustainable Development and Sufficiency Economy (GEOTHAI ’07), Bangkok, Thailand.

Jungyusuk, N., & Khositanont, S. (1992). *Volcanic rocks and associated mineralization in Thailand.* Paper presented at the National Conference on Geologic Resources of Thailand: Potential for Future Development, Bangkok,Thailand.

Kamvong, T., Charusiri, P., & Intasopa, S. B. (2006). Petrochemical characteristics of igneous rocks from Wang Pong area, Phetchabun, north-central Thailand: Implications for tectonic setting. *Journal of the Geological Society of Thailand, 1*, 9-26.

Limtrakun, P., Panjasawatwong, Y., & Khanmanee, J. (2013). Petrochemistry and origin of basalt breccia from Ban Sap Sawat area, Wichian Buri, Phetchabun, central Thailand. *Songklanakarin Journal of Science and Technology, 35*(4), 469-482.

Metcalfe, I. (1996). Pre-Cretaceous evolution of SE Asian terranes. In R. Hall & D. J. Blundell (Eds.), *Tectonic Evolution of Southeast Asia. Geological Society* (pp. 97-122). London, U.K.: Geological Society.

Metcalfe, I. (1997). *The Paleotethys and Paleozoic-Mesozoic tectonic evolution of Southeast Asia.* Paper presented at the GEOTHAI ’97.

Metcalfe, I. (2002). Permian tectonic framework and paleogeography of SE Asia. *Journal of Asian Earth Sciences, 20*, 551-556.

Morley, C. K. (2002). A tectonic model for the Tertiary evolution of strike-slip faults and rift basins in SE Asia. *Tectonophysics, 347*, 189–215.

Morley, C. K., Ampaiwan, P., Thanudamrong, S., Kuenphan, N., & Warren, J. (2013). Development of the Khao Khwang Fold and Thrust Belt: Implications for the geodynamic setting of Thailand and Cambodia during the Indosinian Orogeny. *Journal of Asian Earth Sciences, 62*, 705-719.

Morley, C. K., Charusiri, P., & Watkinson, I. (2011). Structural geology of Thailand during the Cenozoic. In M. F. Ridd, A. J. Barber, & M. J. Crow (Eds.), *The Geology of Thailand* (pp. 273–334). London, U.K.: Geological Society.

Panjasawatwong, Y., Chataramee, S., Lintrakun, P., & Porarai, K. (1997). *Geochemistry and tectonic setting of eruption of central Loei volcanics in the Pak Chom area, Loei, northeast Thailand.* Paper presented at the International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific, Bangkok, Thailand.

Panjasawatwong, Y., Zaw, K., Chantaramee, S., Limtrakun, P., & Pirarai, K. (2006). Geochemistry and tectonic setting of eruption of central Loei volcanic rocks, Pak Chom area, Loei, northeastern Thailand. *Journal of Asian Earth Sciences, 26*, 77-90.

Salam, A., Zaw, K., Mefre, S., Golding, S., Mcphie, J., Suphananthi, S., & James, S. (2008). *Mineralisation and oxygen isotope zonation of Chatree epithermal gold-silver deposit, Phetchabun Province, central Thailand.* Paper presented at the PACRIM Congress, Gold Coast, Australia.

Sone, M., & Metcalfe, I. (2008). Parallel Tethyan sutures in mainland Southeast Asia: new insights for Paleotethys closure and implications for the Indosinian orogeny. *Comptes Rendus Geoscience, 340*, 166-179.

Sutthirat, C., Charusiri, P., Pongsapitch, W., Ferrar, E., & Landgridge, R. (1995). *A Late Pliocene Ko Kha-Sop Prap and Nam Cho basaltic eruption, northern Thailand: evidence from geology and 40Ar/39Ar geochronology.* Paper presented at the The international Conference on Geology, Geotechnology and Mineral Resources of Indochina, Khon Kaen, Thailand.

Vichit, P. (1992). *Gemstones in Thailand.* Paper presented at the National Conference on Geologic Resources of Thailand, Potential for Future Development, Bangkok, Thailand.

Vichit, P., Udompornvirat, S., Titra-ngan, A., & Jariyawat, P. (1988). *A Report on Gem Deposits in Wichian Buri Area, Phetchabun Province*. Retrieved from

Wielchowsky, C. C., & Young, J. D. (1985). *Regional facies variations in Permian rocks of the Phetchabun fold and thrust belt, Thailand.* Paper presented at the The Conference on Geology and Mineral Resources Development of Northeast, Thailand, Khon Kaen, Thailand.

Yang, K., Mo, X., & Zhu, Q. (1994). Tectono-volcanic belts and late Paleozoic-early Mesozoic evolution of southwestern Yunnan, China. *Journal of Southeast Asian Earth Sciences, 10*, 245-262.