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Tectonic Implication of the Permo-Triassic Khao Yai Mafic Volcanic Rocks in Nakhon Nayok Province, Thailand: Evidence from Geochemistry and Rare Earth Elements (REEs)

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Abstract

The Permo-Triassic Khao Yai Volcanics in Nakhon Nayok Province, Thailand, is a part of the Loei-Phetchabun-Nakhon Nayok Volcanic Belt. The purpose of this study is to clarify the geochemistry and REEs characteristic of Khao Yai Volcanics that is useful for identifying the paleo-environment or tectonic setting eruption in this area. The least-altered, mafic volcanic rocks from the Permo-Triassic Khao Yai volcanics, are seriate-textured to porphyritic, with variable amounts of phenocrysts/microphenocrysts. The mineral compositions include plagioclase, clinopyroxene, orthopyroxene, olivine, minor Fe-Ti oxide mineral, amphibole, apatite, biotite/phlogopite, monazite/zircon, glassy, and quartz. The geochemical characteristic of the Khao Yai Volcanics informed that the rocks had the same parental magma with different degrees of crystal fractionation. Most of the mafic volcanic rocks are subalkalic andesite on the basis of their Zr/TiO_2 and Nb/Y ratios and calc-alkalic on diagrams Ti-Zr, Ti-Zr-Y, Hf-Th-Ta and Y-La-Nb. The least-altered mafic volcanic rocks have (La/Sm)cn and (Sm/Yb)cn ranging from 2.41 to 2.71 and 1.86 to 2.22, respectively. The studied calc-alkalic andesite are analogous to the Quaternary calc-alkalic dacite and andesite from Maca Volcano, Patagonian Andes and the Middle Eocene andesite from Shimokoh cauldron, SW Japan in terms of chondrite-normalized REEs and N-MORB normalized patterns. Accordingly, the studied Khao Yai volcanics have been developed in an active continental margin, formed by eastward underthrusting Paleo-Tethys, the leading edge of Shan-Thai, beneath Indochina in the Late Permian to Early Triassic.

Keywords: Khao Yai mafic volcanic rocks, calc-alkalic magma, volcanic arc, REEs, active continental margin

Introduction

The tectonic implication of Thailand has recognized the continental collision between the Indochina and Shan-Thai terranes [1-13]. The existing discussions include numbers and sources of terranes, locations of suture zones, the timing of terrane collision, and a tectonic model. The geochemistry of mafic volcanic rocks is a branch of geology to ascribe their tectonic settings for tectonic model interpretation. The research area located on the boundary between Indochina and Shan-Thai terranes. The geochemistry as major, trace and REEs are used to clarify the magmatic characters, tectonic setting, and the tectonic model that is useful for understanding the plate amalgamation. The time of amalgamation between Indochina and Shan-Thai terranes still debate by several researchers. It may have taken place in the Middle to Late Permian [1,2], Permo-Triassic [3], Middle Triassic [4], Late Triassic [5-11,13] or Middle Jurassic [12]. Accordingly, pre-Cretaceous felsic to mafic volcanic/hypabyssal rocks are used for the mafic volcanic/hypabyssal rocks that occurred before the Cretaceous period and are particularly interested in this study. The pre-Cretaceous felsic to mafic volcanic/hypabyssal rocks in Thailand may be separated into 5 major belts (**Figure 1(a)**) [14-17] from west to east 1) Chiang Rai - Chiang Mai, 2) Chiang Khong - Tak, 3) Nan - Uttaradit, 4) Loei - Phetchabun - Nakhon Nayok and 5) Sra Kaew - Chanthaburi Volcanic Belts.

The research area is along the Tha Dan (TD) and Bo (KB) creeks, Tha Dan Village, Muang Nakhon Na Yok District, and the Madua creek (MD), Khlong Madua Village, Salika District, Nakhon Nayok Province that appear in the topographic map at a scale of 1: 50,000, series L7017, sheet 5237 I (Ban Salika), approximately between latitudes 14°15′ N and 14°23′ N, and longitudes 101°10′ E and 101°23′ E (**Figure**

1(b)). The research area and vicinity cover sedimentary and igneous rocks that are separated into 3 lithostratigraphic units as Permo-Triassic volcanic rocks, Jurassic sedimentary rocks and Quaternary sediments (**Figure 1(b)**) [18]. The Jurassic sedimentary rocks overlain in the eastern part of the study area and vicinity, and comprise the Phu Kradung and the Phra Wihan Formations of Khorat Group. The Phu Kradung Formation (JKph) unconformably overlies the Permo-Triassic Khao Yai volcanics and consists of red and purple shale, siltstone, and sandstone, with the local conglomerate. The Phra Wihan Formation (JKpw) conformably overlies the Phu Kradung Formation and is composed of white to purplish red claystone, siltstone, and quartz sandstone. The Quaternary sediments (Qc) distribute along drainage patterns as the terrace and alluvial deposits. They are composed of gravel-grade and finer-grade epiclasts of quartz, tuff, rhyolite and andesite.

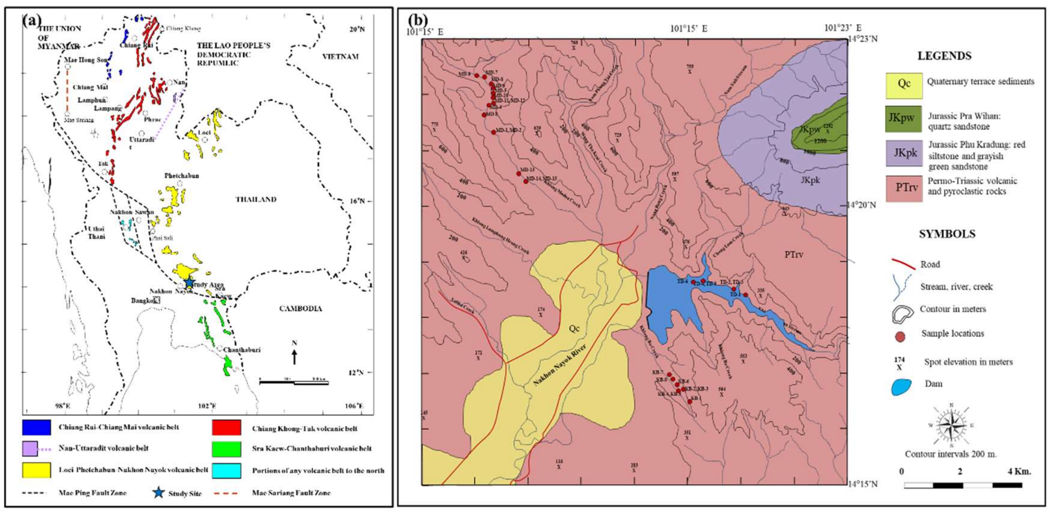

Figure 1 (a) Distribution of pre-Cretaceous volcanic rocks in Thailand (modified from [14-17]). The Mae Ping Fault Zone and the Mae Sariang Fault Zone are taken from Morley [46]. (b) Geologic map of the study area and sample locations (modified from DMR, [18]).

The Permo-Triassic volcanic rocks (PTrv), Khao Yai volcanics, are in the southern part of the Loei-Phetchabun-Nakhon Nayok (LPN) volcanic belt that runs in the NNE-SSW direction from Loei through Phetchabun to Nakhon Nayok Provinces. The Khao Yai volcanics consist mainly of pyroclastic rocks, with minor lava flows and hypabyssal rocks (dikes and plugs) of felsic to mafic compositions. The pyroclastic rocks are either fall deposits or flow deposits that are volcanic breccia and agglomerate. The pyroclastic breccia outcrop along the Chong Lom creek is composed largely of andesitic and basaltic blocks that sit in the finer-grained matrix. The matrix constituents are also angular fragments of andesitic and basaltic compositions. Felsic volcanic rocks exposed along the Khlong Tha Dan Dam site include reddish purple, pink, and light grey rhyolites, with local flow bands. Jundee *et al.* [19] reported that the rocks at Khao Yai volcanics at Khun Dan Prakan Chon Dam site, Nakhon Nayok Province are classified as rhyolite, dacite, andesite, and andesitic dikes. In addition, the rocks are indicated as calc-alkalic affinity and have formed in a volcanic-arc setting based on oxide and trace elements. The Khao Yai volcanics may correlate with the Permo-Triassic volcanic rocks and associated plutonic complexes in the Wang Nam Khiao area, Wang Nam Khiao District, Nakhon Ratchasima Province at the eastern part of Khao Yai volcanics for the timing of eruption. Fanka *et al.* [20,21] studied plutonic rocks in the Wang Nam Khiao area, Nakhon Ratchasima, Thailand and point out that the zircon U-Pb geochronology of the Carboniferous biotite granite, Late Permian hornblende granite and Triassic biotite-hornblende granite yielded intrusion ages of 314.6 - 284.9 Ma, 253.4 Ma, and 237.8 Ma, respectively, probably indicating the arc-magmatism related to subduction of Palaeo-Tethys beneath the Indochina Terrane during the Late Carboniferous/Early Permian, Late Permian, and Middle Triassic. Hunyek *et al.* [21] reported that the Permo-Triassic volcanic rocks in the Wang Nam Khiao area are composed of rhyolite, dacite, andesite, and andesite dikes. Their mineral composition, chemistry, and geochemistry showed the hydrous calc-alkalic signature of the continental arc. These volcanic rocks and the adjacent Late Permian hornblende granite were intruded by andesite dikes, a consequence of the Late Permian Palaeo-Tethys subducted beneath the Indochina Terrane. Although the petrochemistry of volcanic and pyroclastic rocks in this research area was previously reported to be comagmatic by Jundee *et al.* [19], in terms of least-mobile elements. the carefully selected least-altered mafic volcanic rocks for REEs, incompatible elements, and modern analogue analyses from this research can confidently depict the tectonic model of Khao Yai Volcanics. The mafic volcanic rock which crystallized from basaltic magma can be indicated the origin of rock and tectonic setting of eruption.

The purpose of this study is to clarify the geochemistry and REEs characteristic of Khao Yai Volcanics. The evidence from REEs interpretation of the Khao Yai Volcanics can exactly identify the paleo-environment or tectonic setting eruption in this area leading to the classification of felsic to mafic volcanic/hypabyssal rocks belts in Thailand. The classification of Thailand's volcanic belt useful for tectonic model interpretation and useful for understand the economic minerals' occurrence such as gold, iron and copper.

Materials and methods

Least-altered samples selection

The chemical composition and mineralogy of primary magma are frequently modified by partial melting of the source rock through fractional crystallization, magma mixing, and contamination, dynamic mixture of several of these processes. The composition of the provenance is a function of the tectonic setting of eruption. The chemical composition changes after the eruption through geological processes such as metamorphism, weathering, and alteration. Ideally, igneous rocks selected for chemical analysis are completely fresh, but sometimes this cannot be achieved [22]. The least-altered samples are generally excluded those with the extensive development of mesoscopic domains of secondary minerals such as quartz resulting from silicification, epidote minerals, and chlorite, well-developed foliation or mineral layering, abundant vugs or druses, xenocrysts, and xenoliths and quartz, epidote, or calcite veining and/or patches totaling more than 5 modal%.

Mineral and texture analysis

Spheroidal weathering has been operated in the Khao Yai Volcanic rocks, giving rise to rounded volcanic clasts either embedded in the rock exposures or present as in situ float. Many of these clasts were transported into streams and creeks. The samples presented in this research were collected from in situ float and float along streams and creeks. The mafic volcanic rock samples were carefully selected for least alteration by petrographic investigation.

Geochemistry analysis

The least-altered mafic volcanic samples (**Figure 1(b)**) were prepared for whole-rock chemical analysis by splitting into conveniently sized fragments and then crushing to small chips, using a Rocklabs Hydraulic Splitter/Crusher. Approximately 50 - 80 g of the cautiously chosen and cleaned chips were pulverized for a few minutes by a Rocklabs Tungsten-Carbide Ring Mill. Loss on ignition was carried out by heating about 1 g of each sample powder at 1000 °C for 12 h [23]. All the described procedures were done at the Department of Geological Sciences, Faculty of Science, Chiang Mai University.

Chemical analyses of major oxides, trace elements, and rare-earth elements (REEs), as listed in **Table 1**, were carried out at the School of Earth Sciences, University of Tasmania, Hobart, Australia. Major oxides (SiO_2, TiO_2, Al_2O_3, total iron as Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5) and a range of trace elements (Ba, Rb, Sr, Y, Zr, Nb, Ni, Cr, V, and Sc) were analyzed on fusion discs and pellets, respectively, using an Automated Philips PW 1480 X-Ray Fluorescence (XRF) Spectrometer with a PW1510 Sample Changer. The standards of major oxides used were synthetic metals, TASBAS, TASGRAN and TASMONZ. Y, Rb, and Ni were measured with a Sc-Mo tube, using the internal and international standards: AWQUARTZ, BHVO-1, BIR-1, DNC-1, FK-N, PM-S, TASBAS and TASGRAN. Nb, Zr, Sr, Cr, Ba, Sc, and V were measured with an Au tube, using the internal and international standards: AWQUARTZ, 2000SR2, BHVO-1, BIR-1, DNC-1, FK-N, PM-S, TASBAS and TASGRAN1. The analyses for major oxides and trace elements of the studied volcanic samples are reported in **Table 1**.

Table 1 Whole-rock analyses of major oxides and some trace elements of the studied least-altered volcanic rocks were analyzed by XRF.

Sample no.	TD-1	TD-2	TD-3	TD-4	TD-5	TD-6	KB-1	KB-2	KB-3	KB-4	KB-5	KB-6	KB-7	KB-8	MD-1
Major oxide (wt%)															
SiO_2	61.04	57.93	56.00	57.71	57.31	60.44	57.66	55.84	58.59	58.33	58.51	58.10	57.98	58.97	52.66
TiO_2	0.70	0.88	0.89	0.78	0.80	1.06	0.68	0.83	0.66	0.67	0.68	0.66	0.65	0.68	0.90
Al_2O_3	16.80	16.47	16.46	16.87	16.97	16.06	17.25	16.98	17.09	17.08	17.21	17.12	16.85	17.29	17.38
FeO*	5.03	5.36	6.05	5.49	5.75	5.51	5.02	5.81	4.98	5.11	5.10	5.05	4.97	5.17	6.56
MnO	0.10	0.11	0.12	0.11	0.13	0.10	0.10	0.15	0.10	0.12	0.11	0.10	0.10	0.11	0.12
MgO	3.02	3.27	5.62	3.84	3.68	2.43	3.41	3.47	3.48	3.57	3.52	3.51	3.39	3.53	5.62
CaO	5.97	4.08	3.97	4.40	4.39	4.21	5.17	5.96	6.08	5.08	5.33	6.16	6.14	5.73	6.42
Na_2O	3.99	5.18	4.83	4.66	4.44	4.22	3.95	4.61	3.79	4.69	4.57	3.62	3.96	4.61	3.38
K_2O	1.35	2.19	2.03	1.69	2.00	2.21	1.38	1.18	0.92	1.20	1.19	0.99	1.20	0.94	2.48
P_2O_5	0.23	0.33	0.29	0.24	0.24	0.36	0.19	0.33	0.18	0.18	0.18	0.19	0.18	0.19	0.25
LOI	1.34	3.21	3.21	3.10	3.43	2.83	4.21	4.15	3.76	3.23	2.57	3.48	3.73	1.92	3.48
Sum	99.57	99.01	99.46	98.89	99.14	99.42	99.03	99.31	99.63	99.26	98.98	98.97	99.15	99.13	99.25
FeO*/MgO	1.66	1.64	1.08	1.43	1.56	2.27	1.47	1.68	1.43	1.43	1.45	1.44	1.46	1.46	1.17
Trace elements (ppm)															
Ba	304	394	817	333	340	459	320	296	367	402	284	312	267	257	239
Rb	29	61	35	48	53	49	31	24	17	25	31	19	26	24	96
Sr	497	730	1048	701	764	737	678	414	1199	826	587	572	609	551	502
Y	22	28	24	22	24	27	17	23	22	19	17	17	21	17	21
Zr	179	218	172	156	156	203	131	189	127	130	129	129	125	131	144
Nb	3.8	6.5	5.7	4.5	3.7	5.8	3.2	5.2	3.1	2.9	3.5	3.6	2.3	3.3	3
Ni	30	22	113	39	39	5	47	47	50	49	46	49	44	48	107
Cr	42	35	163	54	52	1	56	78	59	58	54	58	49	45	132
V	114	129	140	134	140	140	128	151	124	125	128	123	121	128	149
Sc	17	17	19	17	17	16	17	18	16	16	16	16	17	16	19

Sample no.	MD-2	MD-3	MD-4	MD-5	MD-6	MD-7	MD-8	MD-9	MD-10	MD-11	MD-12	MD-13	MD-14	MD-15
Major oxide (wt%)														
SiO_2	59.76	52.26	60.61	53.35	54.16	52.08	52.52	51.79	58.84	53.63	52.34	54.18	53.73	53.35
TiO_2	0.64	0.86	0.59	0.90	0.91	0.86	0.86	0.85	0.66	0.90	0.86	0.91	0.92	0.87
Al_2O_3	16.80	17.67	16.68	17.55	17.72	17.59	17.37	17.33	16.95	17.35	17.84	17.64	17.66	16.86
FeO*	4.61	6.54	4.27	6.53	6.52	6.44	6.71	6.40	4.82	6.48	6.66	6.44	6.50	6.26
MnO	0.10	0.11	0.09	0.13	0.12	0.11	0.11	0.12	0.09	0.13	0.11	0.13	0.12	0.14
MgO	3.64	6.42	3.09	5.55	5.89	6.36	6.89	6.25	3.54	5.52	6.57	5.65	5.21	6.07
CaO	6.41	8.49	3.81	7.93	7.59	8.54	5.12	8.26	6.78	6.21	8.59	6.63	7.92	5.96
Na_2O	3.28	3.20	4.99	3.23	3.43	3.39	5.19	3.28	3.52	4.01	3.16	3.70	3.49	3.81
K_2O	1.83	0.80	1.99	0.88	1.02	0.78	1.15	0.95	1.16	0.92	0.85	1.18	1.06	1.30
P_2O_5	0.18	0.21	0.14	0.25	0.25	0.21	0.20	0.21	0.14	0.25	0.22	0.25	0.25	0.24
LOI	1.73	2.79	2.94	2.93	2.48	2.50	2.82	3.53	2.57	3.58	2.37	3.06	2.54	4.16
Sum	98.98	99.35	99.19	99.22	100.08	98.87	98.94	98.97	99.07	98.98	99.57	99.76	99.40	99.01
FeO*/MgO	1.26	1.02	1.38	1.18	1.11	1.01	0.97	1.02	1.36	1.17	1.01	1.14	1.25	1.03
Trace elements (ppm)														
Ba	317	194	377	198	275	175	416	209	300	193	198	284	216	246
Rb	47	17	61	18	25	17	25	22	29	26	19	32	23	57
Sr	485	546	709	533	648	546	903	547	593	557	600	616	603	837
Y	19	20	22	21	20	19	19	19	16	21	19	22	20	21
Zr	159	123	150	146	145	123	125	124	119	148	125	147	149	140
Nb	5	3.8	5.3	4.4	3.9	3.4	3	4	2.7	3.5	2.7	4.5	4.7	3.7
Ni	57	168	42	106	119	160	168	159	45	101	170	101	99	101
Cr	45	106	27	133	137	101	105	110	58	135	103	126	121	136
V	111	151	100	153	149	146	143	148	120	144	149	152	148	144
Sc	18	21	15	20	20	21	20	21	17	19	20	21	20	21

FeO* = total iron as FeO; LOI = loss on ignition; and nd = not determined.

REEs analysis

Some certain trace elements (Hf, Ta, Th and U) and REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) were determined on 4 representative least-altered samples, using an HP 4500 Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Solutions for ICP-MS analysis were prepared by Savillex Beaker (HF/HNO_3) digestion technique. Following the method described by Robinson *et al.* [24] the solution for measuring REE was prepared by digesting 100 mg powder sample with 2 mL HF and 0.5 mL HNO_3 at 130 °C for 48 h, and then evaporated to incipient dryness. One mL HNO_3 was added and subsequently evaporated to incipient dryness. The residue was dissolved in 2 mL HNO_3, followed by adding 10 - 20 mL water. The final concentration of the sample was 10 mg/mL. The standards used in ICP-MS analysis were the international standard BHVO-1 (Basalt, Hawaiian volcanic observatory) and the internal standard TASBAS (Tasmania basalt, in-house standard) [23]. The values for REE concentrations in the representative volcanic rocks are given in **Table 2**.

Table 2 REE, Hf, Ta, Th, and U of representatives were analyzed by ICP-MS.

Sample no.	TD-1	TD-4	KB-8	MD-10
La	16.9	16.2	13.6	10.1
Ce	41.1	34.4	29.9	27.6
Pr	4.91	4.79	3.74	3.24
Nd	21.0	20.9	15.5	13.3
Sm	4.36	4.60	3.49	3.11
Eu	1.26	1.33	1.07	0.97
Gd	4.27	4.46	3.42	3.20
Tb	0.70	0.73	0.55	0.53
Dy	3.97	4.10	3.17	3.07
Ho	0.81	0.83	0.64	0.63
Er	2.26	2.28	1.81	1.75
Tm	0.35	0.35	0.28	0.28
Yb	2.33	2.24	1.82	1.81
Lu	0.36	0.34	0.28	0.28
Hf	3.66	3.41	3.01	2.80
Ta	0.77	0.39	0.49	0.48
Th	3.52	2.66	2.65	3.82
U	0.98	0.75	0.73	1.11

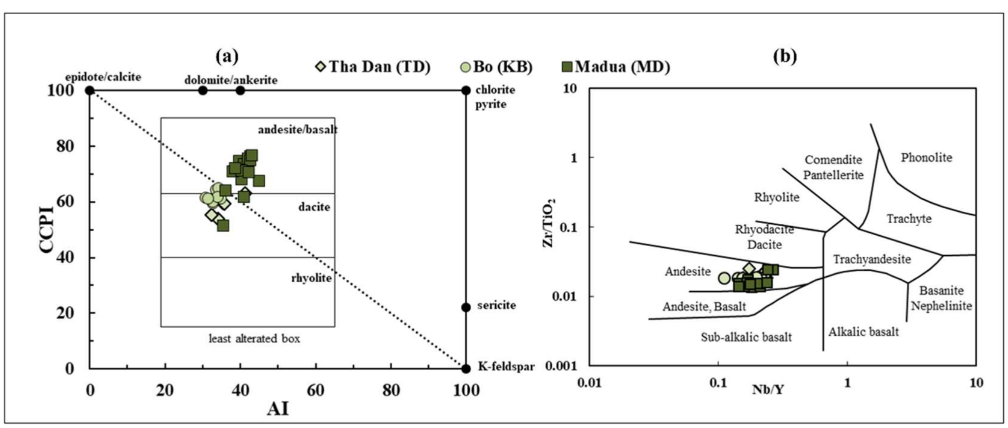

Figure 2 (a) The alteration box plot [24] for studied, least-altered mafic volcanic rock samples. (b) Plot of Zr/TiO_2 against Nb/Y [26] for the studied, least-altered mafic volcanic rocks.

In addition, the alteration box plot [25] was used for confirmed least-altered samples selection (**Figure 2(a)**). The data for major oxides, in terms of weight %, were used to calculate Ishikawa alteration index (AI) (Eq. (1)) and chlorite-carbonate-pyrite index (CCPI) (Eq. (2)), following the equations:

$$AI = (100(MgO+K_2O))/(FeO+K_2O+MgO+Na_2O) \quad (1)$$

$$CCPI = (100(FeO+MgO))/(FeO+K_2O+MgO+Na_2O) \quad (2)$$

Based on above criteria, the 29 least-altered mafic volcanic samples (**Figure 1(b)**) were suitable for geochemical interpretation.

Results and discussion

Petrography

The studied mafic volcanic samples almost totally show slightly to highly porphyritic textures. The phenocrysts in these samples are whitish to greenish plagioclase crystals (sizes up to 2.0 mm across), and dark brown to dark green and black mafic minerals (sizes up to 2.5 mm across). The groundmass constituents are generally fine-grained and dense, and have colors varying from gray to green with different hues and tones. Specks of pyrite have been sporadically observed in a few samples. Veinlets of different hues and tones of white, green, brown, red and black may occasionally exist. The phenocrysts/microphenocrysts are abundant plagioclase, subordinate clinopyroxene and orthopyroxene, and minor olivine, Fe-Ti oxide, amphibole and apatite. Apatite microphenocrysts are present as inclusions in plagioclase phenocrysts/microphenocrysts. These phenocrysts/ microphenocrysts are embedded in the holocrystalline groundmass with a felty texture or a trachytic texture, but for sample number TD-3 that has altered glassy groundmass. In general, the groundmass constituents are largely composed of plagioclase laths and may contain minor clinopyroxene, orthopyroxene, amphibole, biotite/phlogopite flakes, Fe-Ti oxide, interstitial quartz, apatite and monazite/zircon. Secondary patches of chlorite/serpentine, brown amphibole, epidote minerals (zoisite/clinozoisite and epidote), pumpellyite, calcite, brucite, alunite, quartz, Fe-Ti oxide, hematite/iron hydroxide, sphene/leucoxene and/or pyrite are rarely present. Veinlets of chlorite, epidote minerals (zoisite/clinozoisite and epidote), pumpellyite, calcite, alunite, quartz, Fe-Ti oxide, hematite/iron hydroxide, sphene/leucoxene, fine white mica and/or pyrite are also sporadically existent. Tiny cavities that may be sealed by chlorite, epidote, pumpellyite, quartz and/or Fe-Ti oxide have been observed in very few samples.

Magmatic affinity

The secondary processes may lead to the removal and addition of mobile elements. The concentrations of immobile elements may be changed, due to the dilution or enrichment of the mobile elements, however, the ratios of immobile elements in the primary rock and altered rock remain constant. Accordingly, only the elements considered as immobile elements, and immobile-element ratios are used to interpret the geochemical data presented in this study.

Almost all the major oxides, excluding some certain minor oxides, in igneous rocks are sensitive to alteration/metamorphic processes. It is, however, generally agreed that the values of total iron and MgO in the carefully selected samples of altered/metamorphosed igneous suites are little removed from primary values [22]. According to the little mobility of total iron and MgO, and their significant abundances in mafic volcanic rocks, total iron as FeO (herein FeO*)/MgO ratios are used as a fractionation parameter for the studied least-altered volcanic samples. Following the work pioneered by Pearce and Cann [26], numerous studies have shown that the high-field-strength elements (herein HFSE) Ti, Zr, Y, Nb, Ta, Th, U and P, and also the transitional elements Ni, Cr, V and Sc are relatively immobile during the alteration of basaltic and more evolved lavas and intrusive. In addition, although occasional reports have appeared of REEs-, especially light REEs (herein LREEs), mobility during hydrothermal alteration and low-grade metamorphism [27], the overwhelming consensus of opinion is that the REE patterns of carefully selected igneous samples are probably slightly shifted from their primary patterns, but remain parallel/ sub-parallel to the primary patterns. Consequently, in attempting to determine the geochemical affinities and tectonic significance of the studied least-altered mafic volcanic rocks, concentration has focused on the relatively immobile elements, namely HFSE, REEs and transition elements [22].

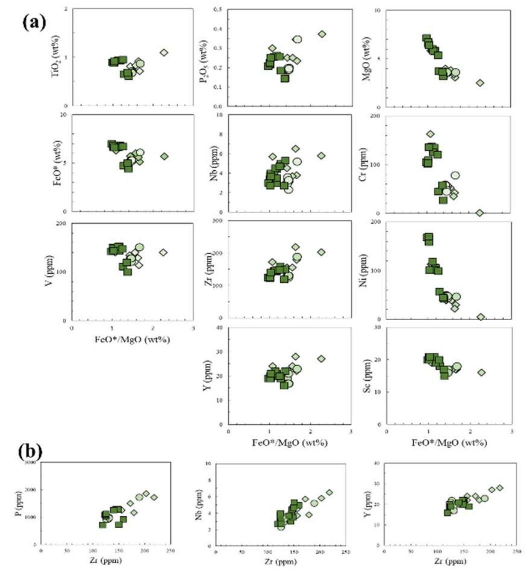

Figure 3 (a) FeO*/MgO variation diagrams for the studied, least-altered volcanic rocks. (b) Plots of P, Nb and Y against Zr for the studied, least-altered volcanic rocks. Symbols are as in **Figure 2**.

The studied, least-altered volcanic rocks span the ranges in Zr/TiO_2 and Nb/Y from 0.014 to 0.025 and 0.11 to 0.26, respectively. The rocks are classified as subalkalic andesite since almost all are plotted in the compositional field of subalkalic andesite on the Zr/TiO_2-Nb/Y diagram of Winchester and Floyd [28] (**Figure 2(b)**). The The FeO*/MgO variation diagrams for immobile major oxides and trace elements (**Figure 3(a)**) show that the values for FeO*, TiO_2 and V of the studied subalkaic andesite are relatively constant throughout the fractionation. Therefore, the diagrams cannot specify whether the rocks are calc-alkalic or tholeiitic. P_2O_5, Nb, Zr and Y form broadly positive trends against FeO*/MgO, typical of incompatible element behavior. The trends for MgO, Ni, Cr and Sc descend relative to FeO*/MgO, typical of olivine, pyroxene and chrome-spinel removal from liquid in early stages of crystallization that is index of crystal fractionation [22]. The olivine and pyroxene fractionation are in agreement with the occurrences of olivine and pyroxene phenocrysts/microphenocrysts in the petrographic investigation.

The incompatible -elements were used for indicating the magmatic origin of rock because they prefer in melt phase. The relationships between incompatible-element pairs for the studied andesite samples, such as P-Zr, Nb-Zr and Y-Zr (**Figure (3b)**) are linear. The P/Zr, Nb/Zr and Y/Zr ratios are 6.7±0.9, 0.27±0.004 and 0.14±0.01, with correlation coefficient (r) of 0.80, 0.83, and 0.83, respectively. These signify that all the rocks are essentially co-magmatic. They might have formed by different degrees of partial melting of a common source rock or by different degrees of crystal fractionation of the same parental magma. The former is unlikely as the patterns for the incompatible-element pairs do not trace back to the origin.

REEs are the elements with atomic number 57-71 (La-Lu) that have similar geochemical behavior. The REEs in igneous rock are incompatible in the mineral structure. REEs concentration in rocks are usually normalized to a common reference standard, which most commonly comprises the values for chondritic meteorites [22]. The chondritic meteorites are thought to be relatively unfractionated samples of the solar system. Chondrite normalization eliminates the abundance variation between odd and even atomic number elements, and allows any fraction of REEs relative to chondritic meteorites to be identified. The REEs presented on a concentration vs atomic number diagram on which concentrations are normalized to the chondritic reference values. Trends on REEs diagrams are REE patterns and the shape of REEs pattern is of considerable petrological interest. Four representatives of the studied andesite suite have chondrite-normalized values for La and Yb in ranges of 32 - 54 and 8 - 12, respectively. Chondrite-normalizing values used are those of Taylor and Gorton [29]. Their REE patterns are LREEs slightly enrichment and relatively flat heavy REEs (herein HREEs) with chondrite-normalized La/Sm [herein (La/Sm)cn] and Sm/Yb [herein (Sm/Yb)cn] ranging from 1.98 to 2.38 and 1.85 to 2.25, respectively (**Figure 4(a)**), and weak or absent Eu anomalies. The chondrite normalized REEs pattern of samples are parallel that interpret as co-magmatic character and is typical of calc-alkalic series [30]. The samples have a slight degree of fractionation and europium anomalies are chiefly controlled by plagioclase removal.

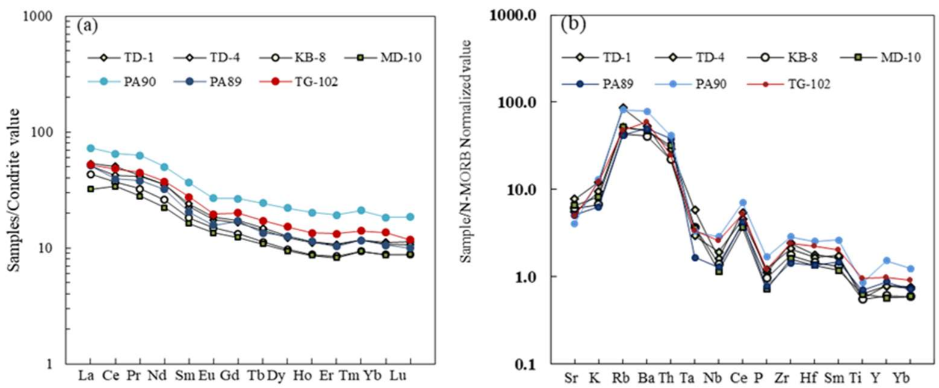

Figure 4 Plots of (a) chondrite-normalized REE [28] and (b) N-MORB normalized multi-elements [30] for the representatives of andesite presented in this study and their modern analogs, calc-alkalic dacite (sample number PA90) and andesite (sample number PA 89) from the Quaternary Maca Volcano, Patagonian Andes (~ 45° S, Chile) [43] and Middle Eocene andesite (sample number TG-102) from Shimokoh cauldron, SW Japan [45].

Normalized multi-element diagrams or spider diagrams for igneous rocks are based upon a grouping of elements incompatible and compatible with respect to a typical mantle mineralogy. The large ion lithophile (LIL) elements (Cs, Rb, K, Ba, Sr, Eu) concentrations may be a function of the behavior of a fluid phase, whilst the HFSE (Y, Hf, Zr, Ti, Nb, Ta) concentrations are controlled by the chemistry of source and the crystal/melt process. In different tectonic environments with different physical conditions and mineral assemblages, the order of element incompatibility may change significantly. Therefore, the degree of incompatibility of trace elements in oceanic basalts during magma generation can be indicting primitive magma composition. The trace-element data of a sample for the purpose of pattern recognition it is convenient to normalize these data to the trace-element abundances of the primitive mantle composition. The primitive mantle is the composition of mantle before the continental crust formed. The mantle normalizing diagram was established by Sun and McDonough [31] that used N-type mid oceanic ridge basalt (N-MORB) for primitive mantle representation. In terms of N-MORB normalized multi-element patterns, the rocks generally show more LIL and less HFS elements concentrations with negative Ta and Nb anomalies (**Figure 4(b)**). Ta and Nb anomalies controlled by ilmenite, rutile and sphene removal and also characteristic of continental crust and may indicator of crustal involvement in magma process. The N-MORB-normalized pattern of this study is typical of island arc calc-alkalic rocks [32].

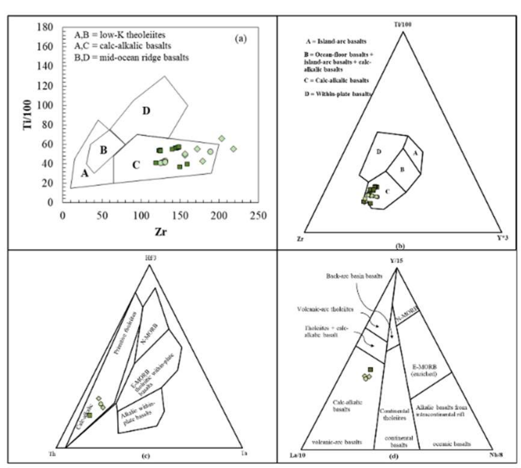

Figure 5 Tectonic discrimination diagrams (a) Ti-Zr and (b) Ti-Zr-Y [25] for the studied, least-altered volcanic rocks. (c) Hf-Th-Ta [32] and (d) Y-La-Nb [33] for the studied, least-altered volcanic rocks. Symbols are as in **Figure 2**.

The REEs and N-MORB patterns indicated the crustal contamination in magma that is the typical of island arc calc-alkalic rocks. The calc-alkalic nature is well supported by their positions on a binary diagram of Ti-Zr [26] (**Figure 5(a)**), and ternary diagrams Ti-Zr-Y [26] (**Figure 5(b)**), Hf-Th-Ta [33] (**Figure 5(c)**) and Y-La-Nb [34] (**Figure 5(d)**), although the applied diagrams were designed for basalts.

Tectonic setting of eruption

Many tectonic discrimination diagrams have been applied to the studied least-altered andesite. The studied volcanic rocks appear to be plate-margin basalt (erupted along an active continental margin, an oceanic island arc and a mid-oceanic ridge) on a Ti/Y against Zr/Y diagram [35] (**Figure 6(a)**). The volcanic-arc environments are supported by their positions on the plots of Ti-Zr (Fig. 5a), Ti-Zr-Y (**Figure 5(b)**), Hf-Th-Ta (**Figure 5(c)**), Y- La-Nb (**Figure 5(d)**), Cr-Y [36] (**Figure 6(b)**), Nb-Zr-Y [37] (**Figure 6(c)**), Zr-Zr/Y [38] (**Figure 6(d)**) and Ti/Y-Nb/Y [36] (**Figure 6(e)**).

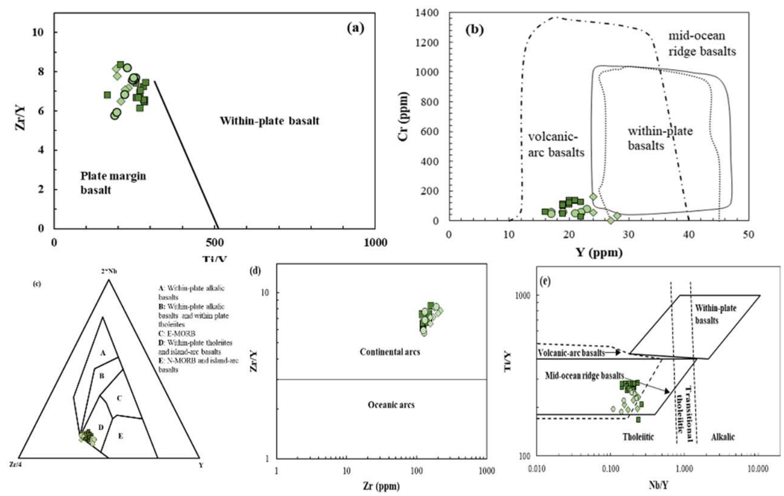

Figure 6 Tectonic discrimination diagrams for the studied, least-altered volcanic rocks (a) Zr/Y-Ti/Y [35], (b) Cr-Y [35], (c) Zr-Nb-Y [36], (d) Zr-Zr/Y [37] and (e) Ti/Y-Nb/Y [35]. Symbols are as in **Figure 2**.

Up to now, many tectonic discrimination diagrams for either mafic or felsic volcanic rocks have been constructed. However, several studies [39-42] have demonstrated that these diagrams may often fail to unequivocally classify the tectonic setting of the formation of altered lavas. For example, Duncan [39] studied the Mesozoic basalt of Karoo igneous province, one of the world's classic continental flood basalt. He found that the southern Karoo basalt appeared to be a calc-alkalic affinity and erupted in a subduction-related environment, whereas the northern Karoo basalt erupted in a within-plate environment when tectonic discrimination diagrams had been applied.

Modern analog

In order to solve the problem, the classical principle of geology "Present is the key to the past" has been applied. The REE patterns of carefully selected igneous samples are probably slightly shifted from their primary patterns but remain parallel/sub-parallel to the primary patterns. The comparison of the modern rock which has an exactly known tectonic environment to the studied rock samples can be interpreted as the tectonic environment of samples. In the other words, if the tectonic interpretation is correct, there should be modern analogs [5,9,17,43]. Extensive searches for modern analogs have been made in terms of chondrite (**Figure 4(a)**) and N-MORB (**Figure 4(b)**) normalized multi-element patterns. The chondrite and N-MORB REEs patterns of the rock samples are analogs to the younger rock still in the original tectonic environment. In doing so, the representatives of the andesite presented in this study are analogous to the calc-alkalic dacite (sample number PA90) and andesite (sample number PA89) from the Quaternary Maca Volcano, Patagonian Andes (~45° S, Chile) that erupted in an active continental margin. The Maca Quaternary volcanoes, Patagonian Andes (~45° S, Chile) are large, adjacent stratovolcanoes that rise from the Chiloe block at the southern end of the southern volcanic zone of the Andes [44]. In addition, the representatives of the andesite presented in this study are analogous to the Middle Eocene andesite (sample number TG-102) from Shimokoh cauldron, SW Japan [45] that is a typical arc-trench system composed of a volcanic arc, fore arc basins, and an accretionary complex. Accordingly, the studied andesite is interpreted to have erupted in an active continental margin.

Tectonic implication

Although the volcanic belts in northern Thailand are clearly classified based on location, geochemistry and tectonic setting, and continue from the north to the south, the continuous volcanic rocks in central Thailand are difficult to classify because the outcrops are covered with thick sediments in the central basin. The Khao Yai Volcanics is located at the rim of central Thailand and has the effect of the Mae Ping strike-slip fault. However, the model of the Tertiary evolution of strike-slip faults and rift basins in SE Asia of Morley [46] may imply that the Khao Yai Volcanics is not effected by the Mae Ping strike-slip fault (**Figure 1(a)**). The geochemistry and REEs significances lead the Khao Yai Volcanics to be a part of the LPN volcanic belt that runs from Loei though Phetchabun to Nakhon Nayok provinces. The Khao Yai Volcanics is the end of the LPN volcanic belt that occurred as an arc volcanic environment. The age dating of the Khao Yai Volcanics is absent so the correlations with nearby arc-related igneous rocks were used. These arc-related magmatic rocks are most likely to have formed in the Late Permian as the nearby plutonic and volcanic rocks. The zircon U-Pb ages performed on arc-related plutonic rocks in Loei-Phetchabun Volcanics by Khositanont *et al.* [13] are 254 - 250 Ma, and those on volcanic rocks by Salam *et al.* [8] are 258.6 - 245.9 Ma. In addition, the Late Permian hornblende granite, and hornblendite and hornblende gabbro in the Wang Nam Khiao area have zircon U-Pb ages of 253.4±4.3 Ma and 257.1±3.4 Ma [4,21], respectively. These imply the multiple continental arc magmatism along the LPN volcanic belt. The distribution of arc-related volcanic rocks and dikes in the area of Khun Dan Prakarn Chon Dam site [19] implies that arc magmatism has been extensively operated in the study area. The tectonic model of the Khao Yai area was not previously presented and has been done in this study. The REEs signature is precision evidence for tectonic interpretation. The schematic tectonic model and arc magmatism in the Khao Yai Volcanics in this study, the Khun Dan Prakan Chon Dam site [19], and the Wang Nam Khiao area [21] are illustrated in **Figure 7**. In the Late Permian, the east-west cross-section was used described the magmatism of LPN volcanic belt. The Wang Nam Khiao area in the east was intruded by the Late Permian hornblende granite, hornblendite, hornblende gabbro, and volcanic rock and dike that have arc-related signatures. The Khao Yai Volcanics in the areas of Tha Dan and Salika villages, Nakhon Nayok Province, and the Khun Dan Prakan Chon Dam site in the west are volcanic rock and shallow intrusive dikes that have an arc-related signature. These magmatic rocks in Nakhon Nayok Province, the southern end of the LPN volcanic belt, might have crystallized at different depths above the eastward subducted slab of Paleo-Tethys, the leading edge of Shan-Thai Terrane, beneath the Indochina terrane in the Late Permian to Early Triassic [4,8,13,21] before the collision and the amalgamation were formed in the Late Triassic [4,13]. The Khao Yai Volcanics age dating should be performed for further studies.

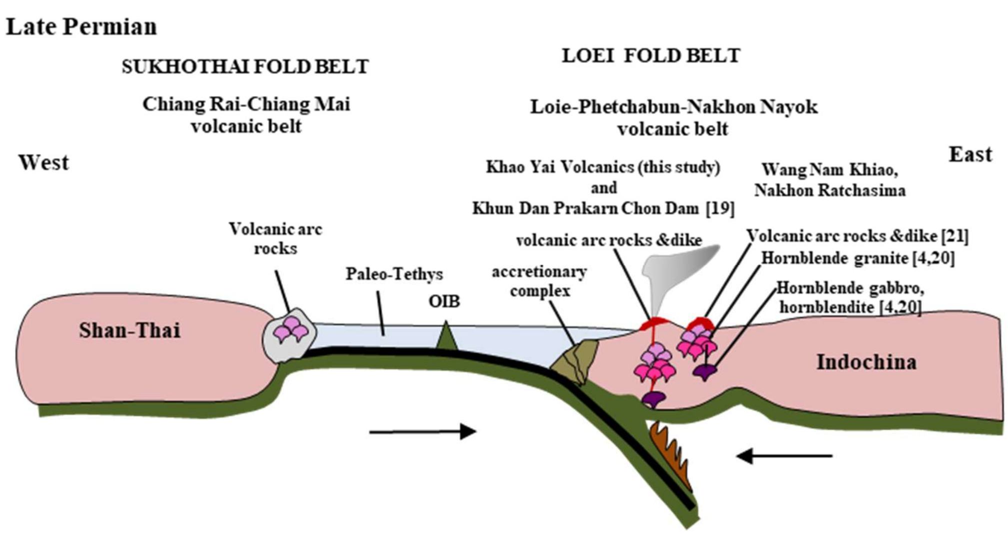

Figure 7 Schematic tectonic model for arc magmatism at Khao Yai Volcanics (the Tha Dan and Salika areas) and vicinity in Loei Fold Belt during the Late Permian.

Conclusions

The studied mafic volcanic samples mostly show porphyritic textures. The microphenocryst assemblages include plagioclase, clinopyroxene, orthopyroxene, olivine, Fe-Ti oxide, amphibole, and/or apatite. These microphenocrysts are embedded in the groundmass, consisting of plagioclase, clinopyroxene, orthopyroxene, amphibole, biotite/phlogopite flakes, Fe-Ti oxide, interstitial quartz, apatite, monazite/zircon and/or altered glass in variable proportions.

The studied least-altered volcanic rocks on Zr/TiO_2-Nb/Y diagram are andesite with sub-alkalic series. The incompatible elements in binary plots are suggestive of co-magmatic nature that, and have formed by different degrees of crystal fractionation of the same parental magma. The calc-alkalic nature is well supported by their positions on a binary diagram of Ti-Zr, and ternary diagrams Ti-Zr-Y, Hf-Th-Ta and Y-La-Nb. The chondrite normalized representative andesite samples show LREE enrichment and relatively flat HREE. Furthermore, the representative andesite samples are analogous to the calc-alkalic dacite and andesite from the Quaternary Maca Volcano, Patagonian Andes and the Middle Eocene andesite from Shimokoh cauldron, SW Japan in terms of chondrite and N-MORB normalized multi-element patterns. Therefore, on the basis of geochemistry and REEs evidences Khao Yai Volcanics formed an active continental margin environment. Based on petrography and geochemistry significances, the Khao Yai Volcanics is assigned to be the southern end of the Loei-Phetchabun-Nakhon Nayok volcanic belt. The continental magmatic arc might have resulted from the eastward subduction of the leading edge of the Shan-Thai terrane (Paleo-Tethys) beneath the Indochina terrane in the Late Permian to Early Triassic.

Acknowledgments

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References

[1] SM Barr and AS Macdonald. Nan River suture zone, Northern Thailand. *Geology* 1987; **15**, 907-10.
[2] K Manila, C Chonglakmani, Q Feng and D Helmcke. Provenance and tectonic setting of the Permian Nam Duk Formation, north - central Thailand - implications for geodynamic evolution. *ScienceAsia* 2008; **34**, 7-22.
[3] SM Barr, C Tantisukrit, W Yaowanoiyothin and AS Macdonald. Petrology and tectonic implications of Late Paleozoic volcanic rocks of the Chiang Mai belt, Northern Thailand. *J. Southeast Asian Earth Sci.* 1990; **4**, 37-47.
[4] A Fanka, T Tsunogae, V Daorerk, Y Tsutsumi, Y Takamura and C Sutthirat. Petrochemistry and zircon U-Pb geochronology of granitic rocks in the Wang Nam Khiao area, Nakhon Ratchasima, Thailand - Implications for petrogenesis and tectonic setting. *J. Asian Earth Sci.* 2018; **157**, 92-118.
[5] SM Barr, AS Macdonald, GR Dunning, P Ounchanum and W Yaowanoiyothin. Petrochemistry, U-Pb (zircon) age, and paleotectonic setting of the Lampang volcanic belt, northern Thailand. *J Geol. Soc.* 2000; **157**, 553-63.
[6] S Intasopa and T Dunn. Petrology and Sr-Nd isotopic systems of the basalts and rhyolites, Loei, Thailand. *J. Southeast Asian Earth Sci.* 1994; **9**, 167-80.
[7] Y Kamata, K Ueno, H Hara, I Ichise, T Charoentitirat, P Charusiri, A Sardsud and K Hisada. Classification of the Sibumasu and Paleo-Tethys tectonic division in Thailand using chert lithofacies. *Island Arc* 2009; **18**, 21-31.
[8] A Salam, K Zaw, S Meffre, J McPhie and CK Lai. Geochemistry and geochronology of epithermal Au-hosted Chatree volcanic sequence - Implication for tectonic setting of the Loei fold belt in central Thailand. *Gondwana Res.* 2014; **26**; 198-217.
[9] S Singharajwarapan, R Berry and Y Panjasawatwong. Geochemical characteristics and tectonic significance of the Permo-Triassic Pak Pat volcanics, Uttaradit, northern Thailand. *J. Geol. Soc. Thai*. 2000; **1**, 1-7.
[10] M Sone and I Metcalfe. Parallel Tethyan sutures in mainland Southeast Asia - new insights for Palaeo-Tethys closure and implications for the Indosinian orogeny. *Compt. Rendus Geosci*. 2008; **340**, 166-79.
[11] W Srichan, AJ Crawford and RF Berry. Geochemistry and geochronology of Late Triassic volcanic rocks in the Chiang Khong region, northern Thailand. *Island Arc* 2009; **18**, 32-51.

[12] P Nualkhao, R Takahashi, A Imai and P Charusiri. Petrochemistry of granitoids along the Loei Fold Belt, northeastern Thailand. *Resour. Geol.* 2018; **68**, 395-424.
[13] S Khositanont, Y Panjasawatwong, P Ounchanum, T Thanasuthipitak, K Zaw and S Meffre. Petrochemistry and zircon age determination of Loei Phetchabun volcanic rocks. *In*: Proceedings of the International Symposia on Geoscience Resources and Environments of Asian Terranes, 4th IGCP 516 and 5th APSEG. Bangkok, Thailand. 2008, p. 272-8.
[14] A Boonsoong, Y Panjasawatwong and K Metparsopsan. Petrochemistry and tectonic setting of mafic volcanic rocks in the Chon Daen-Wang Pong area, Phetchabun, Thailand. *Island Arc* 2011; **20**, 107-24
[15] PK Jundee, P Limtrakun, A Boonsoong and Y Panjasawatwong. Petrography and REE geochemical characteristics of felsic to mafic volcanic/hypabyssal rock in Nakhon Sawan and Uthai Thani Provinces, central Thailand. *Chiang Mai J. Sci.* 2017; 4, 1722-34.
[16] B Phajuy, Y Panjasawatwong and P Osataporn. Preliminary geochemical study of volcanic rocks in the Pang Mayao area, Phrao, Chiang Mai, northern Thailand - Tectonic setting of formation. *J. Asian Earth Sci.* 2005; **24**, 765-776.
[17] Y Panjasawatwong, S Chantaramee, P Limtrakun and K Pirarai. Geochemistry and tectonic setting of eruption of central Loei volcanics in the Pak Chom area, Loei, Northeast Thailand. *J. Asian Earth Sci.* 2006; **26**, 77-90.
[18] Department of Mineral Resources. *Geological Map of Changwat Nakhon Nayok, scale 1:250,000*. Department of Mineral Resources, Bangkok, Thailand, 2007.
[19] PK Jundee, W Hansakulcharoenchai, B Phajuy and P Sangtong. Geochemistry of extrusive rocks at Khun Dan Prakan Chon Dam site, Nakhon Nayok Province, Thailand. *ScienceAsia* 2021; **47S**, 103-11.
[20] A Fanka, T Tsunogae, V Daorerk, Y Tsutsumi, Y Takamura and T Endo. Petrochemistry and mineral chemistry of Late Permian hornblendite and hornblende gabbro from the Wang Nam Khiao area, Nakhon Ratchasima, Thailand - Indication of palaeo-tethyan subduction. *J. Asian Earth Sci.* 2016; **130**, 239-55.
[21] V Hunyek, C Sutthirat and A Fanka. Magma genesis and arc evolution at the Indochina terrane subduction: petrological and geochemical constraints from the volcanic rocks in Wang Nam Khiao area, Nakhon Ratchasima, Thailand. *Front. Earth Sci.* 2020; **8**, 271.
[22] HR Rollinson. *Using geochemical data: Evaluation, presentation, interpretation. Longman* Scientific & Technical. Harlow, England, 1993.
[23] PJ Lechler and MO Desilets. A review of the use of loss on ignition as a measurement of total volatiles in whole-rock analysis. *Chem. Geol*. 1987; **63**, 341-4.
[24] P Robinson, AT Townsend, Z Yu and C Munker, Determination of scandium, yttrium and rare earth elements in rocks by high resolution inductively coupled plasma mass spectrometry. *J. Geostandard. Geoanal.* 1999; **23**, 31-46.
[25] RR Large, JB Gemmell, H Paulick and DL Huston. The alteration box plot - A simple approach to understanding the relationship between alteration mineralogy and lithogeochemistry associated with volcanic-hosted massive sulfide deposits. *Econ. Geol.* 2001; **96**, 957-71.
[26] JA Pearce and JR Cann. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth Planet. Sci. Lett.* 1973; **19**, 293-300.
[27] DJ Whitford, MJ Korsch, PM Porritt and SJ Craven. Rare-earth mobility around the volcanogenic polymetallic massive sulphide deposit at Que River, Tasmania, Australia. *Chem. Geol.* 1988; **68**, 105-19.
[28] JA Winchester and PA Floyd. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chem. Geol.* 1977; **20**, 325-43.
[29] SR Taylor and MK Gorton. Geochemical application of spark-source mass spectrometry; III - Element sentivity, presition and accuracy. *Geochim. Cosmochim. Acta* 1977; **41**, 1375-80.
[30] A Fujinawa. Distinctive REE patterns for tholeiitic and calc-alkaline magma series co-occurring at Adatara volcano, Northeast Japan. *Geochem. J*. 1992; **26**, 395-409.
[31] SS Sun and WF McDonough. Chemical and isotopic systematics of oceanic basalt: Implications for mantle composition and processes. *Geol. Soc. Publ.* 1989; **42**, 313-45.
[32] M Wilson. *Igneous petrogenesis: A global tectonic approach*. Chapman and Hall, London, England 1989, p. 153-90.
[33] DA Wood. The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. *Earth Planet Sci. Lett.* 1980; **50**, 11-33.

[34] B Cabanis and M Lecolle. *Le diagramme La/10-Y/15-Nb/8: un outil pour la discrimination des series volcaniques et la mise en evidence des processus de mélange et/ou de contamination crustale*. Gauthier-Villars, Paris, France, 1989.
[35] JA Pearce and GH Gale. Identification of ore-deposit environment from trace element geochemistry of associated igneous host rocks. *Geol. Soc. Spec. Publ*. 1977; **7**, 14-24.
[36] JA Pearce. *Trace element characteristics of lavas from destructive plate boundaries*. *In*: RS Thorpe (Ed.). Andesites-orogenic andesites and related rocks. John Wiley and Sons, Chichester, England, p. 528-48.
[37] MA Meschede. method of discriminating between different types of mid-oceanic ridge basalts and continental tholeiites with the Nb-Zr-Y diagram. *Chem. Geol.* 1986; **56**, 207-18.
[38] JA Pearce. *Role of the sub-continental lithosphere in magma genesis at active continental margins*. *In*: CJ Hawkesworth and MJ Norry (Eds.). Continental basalts and mantle xenoliths. Shiva Publications, Chandigarh, India, 1983, p. 230-49.
[39] RA Duncan. The Karoo igneous province - A problem area for inferring tectonic setting from basalt geochemistry. *J. Volcanol. Geoth. Res.* 1987; **32**, 13-34.
[40] PE Holm. Non-recognition of continental tholeiite using the Ti-Zr-Y diagram. *Contrib. Mineral. Petr.* 1982; **79**, 308-10.
[41] R Myers and JH Breitkopf. Basalt geochemistry and tectonic setting - A new approach to relate tectonic and magmatic processes. *Lithos* 1989; **23**, 53-62.
[42] T Prestvik. Basic volcanic rocks - A discussion of the Zr-Ti-Y discrimination diagram and its suitability for classification purposes. *Lithos* 1982; **15**, 241-7.
[43] Y Panjasawatwong, B Phajuy and S Hada. Tectonic setting of the Permo-Triassic Chiang Khong volcanic rocks, northern Thailand based on petrochemical characteristics. *Gondwana Res.* 2003; **6**, 743-55.
[44] MD Orazio, F Innocenti, P Manetti, M Tamponi, S Tonarina, O Gonzalez-Ferran, A Lahsen and R Omarini. The Quaternary calc-alkaline volcanism of the Patagonian Andes close to the Chile triple junction - Geochemistry and petrogenesis of volcanic rocks from the Cay and Maca volcanoes (~ 45° S, Chile). *J. S. Am. Earth Sci.* 2003; **16**, 219-42.
[45] T Imaoka, K Kiminami, K Nishida, M Takemoto, T Ikawa, T Itaya, H Kagami and S Iizumi. K-Ar age and geochemistry of the SW Japan Paleogene cauldron cluster: Implications for Eocene-Oligocene thermo-tectonic reactivation. *J. Asian Earth Sci.* 2011; **40**, 509-33.
[46] CK Morley. A tectonic model for the Tertiary evolution of strike-slip faults and rift basins in SE Asia. *Tectonophysics* 2002; **347**, 189-215.