

Island Arc





Petrochemistry and tectonic setting of mafic volcanic rocks in the Chon Daen–Wang Pong area, Phetchabun, Thailand

APICHET BOONSOONG^{*}, YUENYONG PANJASAWATWONG AND KEATISAK METPARSOPSAN Department of Geological Sciences, Faculty of Science, Chiang Mai University, Chiang Mai, Thailand, 50200 (email: apichet@chiangmai.ac.th)

Abstract The mafic volcanic rocks and hypabyssal rocks in the Chon Dean-Wang Pong area are possibly the southern extension of the western Loei Volcanic Sub-belt, Northeast Thailand. They are least-altered, and might have been formed in Permian–Triassic times. The rocks are commonly porphyritic, with different amounts of plagioclase, clinopyroxene, orthopyroxene, amphibole, Fe-Ti oxide, unknown mafic mineral, and apatite phenocrysts or microphenocrysts, and are uncommonly seriate textured. The groundmass mainly shows an intergranular texture, with occasionally hyalophitic, intersertal and ophiticsubophitic textures. The groundmass constituents have the same minerals as the phenocrysts or microphenocrysts and may contain altered glass. The groundmass plagioclase laths may show a preferred orientation. Chemically, the studied rock samples can be separated into three magmatic groups: Group I, Group II, and Group III. These magmatic groups are different in values for Ti/Zr ratios. The averaged Ti/Zr values for Group I, Group II, and Group III rocks are 83 ± 6 , 46 ± 12 , and 29 ± 5 , respectively. In addition, the Group I rocks have higher P/Zr, but lower Zr/Nb relative to Group II and Group III rocks. The Group I and Group II rocks comprise tholeiitic and esite-basalt and microdioritemicrogabbro, while the Group III rocks are calc-alkalic andesite and microdiorite. According to the magmatic affinities and the negative Nb anomalies on normal mid-oceanic ridge basalt (N-MORB) normalized multi-element plot, arc-related lavas are persuasive. The similarity between the studied lavas and the Quaternary lavas from the northern Kyukyu Arc, in terms of chondrite-normalized rare earth element (REE) patterns and N-MORB normalized multi-element patterns, leads to a conclusion that the mafic volcanic rocks and hypabyssal rocks in the Chon Daen–Wang Pong area have been formed in a volcanic arc environment.

Key words: mafic volcanic and hypabyssal rocks, Permian–Triassic, porphyritic, tholeiitic, volcanic arc.

INTRODUCTION

Thailand is generally believed to have been formed by a continental collision of Shan–Thai craton to the present west and the Indochina craton to the present east in the Late Triassic (e.g. Crawford & Panjasawatwong 1996; Singharajwarapan & Berry 2000). The existing problems include numbers and sources of cratons, locations of suture zones,

*Correspondence.

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timing of cratonic collision, and a tectonic model. To solve these problems, many branches of geology are needed. Petrochemistry of mafic volcanic rocks and their hypabyssal equivalents is one such branch that can be used to ascribe their tectonic settings of formation.

The petrochemical studies of volcanic rocks in the research area were previously reported by Kamvong *et al.* (2006), Marhotorn *et al.* (2008) and Tangwattananukul *et al.* (2008). Although they were interpreted as the products of arc volcanism, they had uncommon chemical signatures of

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orogenic and non-orogenic volcanic rocks, in terms of least-mobile elements. Although almost all are comparable to arc volcanic rocks, their Zr/Y ratios are typical of within-plate basalt. Accordingly, the rocks were re-visited, re-collected, and petrochemically re-examined in this study to clarify the tectonic setting of formation. Chemical analyses of the carefully selected sample covered major oxides and a range of trace elements. Rare earth element (REE) analysis was carried out on representative samples. To avoid ambiguous interpretation, discussion of chemical data is focused on the relatively least-mobile elements and their ratios.

GEOLOGICAL SETTING

In the Northern and Upper Western Highlands, and the Loei–Phetchabun Ranges of Thailand, the volcanic rocks and their pyroclastic equivalents formed prior to or immediately after the amalgamation of Shan–Thai and Indochina cratons. The area may be divided into four belts, from west to east, Chiang Rai–Chiang Mai Volcanic Belt, Chiang Khong–Tak Volcanic Belt, Nan–Uttaradit Volcanic Belt, and Loei–Phetchabun–Nakhon Nayok Volcanic Belt, as shown in Figure 1. The study area lies in the central portion of the Loei– Phetchabun–Nakhon Nayok Volcanic Belt.



Fig. 1 Distribution of pre-Cretaceous matic volcanic rocks in Thailand (modified from Jungyusuk & Khositanont 1992; Panjasawatwong *et al.* 2006). The Mae Ping Fault Zone and the Mae Sariang Fault Zone are taken from Morley (2002), and Hisada *et al.* (2004), respectively.

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Fig. 2 Geological map of the Chatree Gold Mine (Nakchaiya M, unpubl. data, 2008).

The Loei-Phetchabun-Nakhon Nayok Volcanic Belt is composed of acidic to basic lavas, and pyroclastic rocks compositionally equivalent to the lavas. In the Loei area, these volcanic rocks may be further separated into eastern, central, and western sub-belts. The volcanic rocks of eastern sub-belt are mainly rhyolitic, whereas those of western sub-belt are largely andesitic (Jungyusuk & Khositanont 1992; Della-Pasqua & Khin 2002). Both have been interpreted to be the products of arc volcanism that took place in the Permo-Triassic (e.g. Bunopas & Vella 1983). The arcrelated rhyolitic samples of eastern sub-belt, however, yielded a whole-rock Rb-Sr isochron age of 374 ± 33 Ma (Late Devonian) (Intasopa & Dunn 1994) and U-Pb zircon ages of 425 ± 7 and 433 ± 4 Ma (Early Silurian) (Khositanont *et al.* 2008). The central sub-belt is composed mainly of pillow lava, hyaloclastite, and pillow breccia. These mafic volcanic rocks have been assigned to be those erupted in a mid-oceanic ridge environment and have a whole-rock Rb-Sr isochron age of 361 ± 11 Ma (Late Devonian) (Intasopa & Dunn 1994). In addition, Panjasawatwong et al. (2006) reported that the mid-ocean ridge basalt (MORB) exists along with oceanic island-arc mafic lava in the central sub-belt. The arc lavas might have been built on an oceanic basement in a major ocean basin or in a mature back-arc basin. The volcanic rocks of western sub-belt in the Phetchabun area have an intercept ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ age of 237 ± 12 Ma (Middle Triassic) and a plateau age of 238 ± 4 Ma (Middle Triassic), and have been geochemically interpreted as the products of volcanism along an active continental margin (Kamvong *et al.* 2006; Marhotorn *et al.* 2008; Tangwattananukul *et al.* 2008; Nakchaiya M, unpubl. data, 2008). The volcanic rocks in the Nakhon Nayok area, in the southern part of the western sub-belt, are also geochemically arc-related magma (Kosuwan P, unpubl. data, 2004).

The geological map of the Phetchabun area on a scale of the 1:250 000 was compiled by Chonglakmani and Sattayarak (1984). More detailed geological maps in the Chatree Gold Mine (Fig. 2) and the Chon Daen–Wang Pong area (Fig. 3) were compiled by Akara Mining Co. Ltd. (Nakchaiya M, unpubl. data, 2008) and Panjasawatwong Y (2006, unpubl. data), respectively. The Chatree Gold Mine is exclusively underlain by pyroclastic and hypabyssal rocks. The Chon Daen–Wang Pong area is largely underlain by sedimentary, plutonic, and volcanic rocks that can be separated into nine major lithostratigraphic units from older to younger as follows: Carboniferous sedimentary rocks, Lower Permian sedimentary rocks, Upper Permian sedimentary



Fig. 3 Geological map of the Wang Pong–Chon Daen area (Panjasawatwong Y, unpubl. data, 2006).

rocks, Permo–Triassic sedimentary and volcanic rocks, Triassic sedimentary and volcanic rocks, Triassic volcanic rocks, Triassic plutonic rocks, Jurassic plutonic rocks, and Quaternary colluvial deposits. The inferred ages, obtained from stratigraphic correlation, are however needed to ascertain the basis of informative data.

SAMPLE SELECTION

A number of the Permian–Triassic mafic volcanic rocks and hypabyssal rocks were collected from many localities in the Chon Daen–Wang Pong area. However, the samples presented in this study are only those considered to be least-altered, under the petrographic microscope. The least-altered samples in this account generally exclude the samples with

- 1. extensive development of mesoscopic domains of secondary minerals such as quartz resulted from silicification, epidote minerals and chlorite
- 2. well-developed foliation or mineral layering
- 3. abundant vesicles or amygdales, xenocrysts, and xenoliths
- 4. quartz, epidote, or calcite veining and/or patches totaling more than 5 mod.%.

Using the above criteria, 30 least-altered mafic volcanic samples and mafic hypabyssal samples were selected to examine their chemistry in this study.

MAGMATIC GROUPS

The studied rocks can be chemically separated into three magmatic groups as Group I, Group II, and Group III. The Group I rocks remarkably have the highest values for Ti/Zr ratios (83 ± 6 average). The Ti/Zr values (46 ± 12 average) for Group II rocks are significantly higher than those for Group III rocks (29 ± 5 average). Also obviously recognized are the higher P/Zr values (9.2 ± 0.5 on average) and the lower Zr/Nb values (32 ± 5 on average) for the Group I rocks relative to Group II (P/Zr = 6.9 ± 1.4 average and Zr/Nb = 37-71) and Group III rocks (P/Zr = 5.1 ± 1.1 average, and Zr/Nb = 52-68).

OCCURRENCE AND PETROGRAPHY

The Permian–Triassic mafic igneous rocks in the Chon Daen–Wang Pong area cover an area of approximately 400 km² (Figs 2,3).

GROUP I ROCKS

The Group I mafic igneous rocks are those of the Permo–Triassic unit (sedimentary, volcaniclastic, volcanic rocks) and Triassic rock unit (volcanic rocks) as shown in Figure 3. They include samples of mafic lava flows (samples CD-1, CD-5, WP-11, WP-12) and hypabyssal rock (sample number CD-11). Almost all the lava samples are slightly porphyritic, with partly altered plagioclase as the common phenocrysts or microphenocrysts. Additional phenocrysts or microphenocrysts may include clinopyroxene, unknown mafic mineral, and Fe–Ti oxides. The groundmass is commonly intergranular and uncommonly hyalophitic and intersertal. It consists of abundant plagioclase laths, with subordinate or minor interstitial clinopyroxene, devitrified glass and/or Fe–Ti oxide. The non-porphyritic lava sample is seriate textured, and consists mainly of plagioclase and clinopyroxene. The hypabyssal sample is seriate textured and fine-grained, with plagioclase as the principal constituent, and clinopyroxene and Fe–Ti oxide as the minor constituents.

GROUP II ROCKS

The Group II mafic volcanic rocks are those assigned to the Permo-Triassic unit (sedimentary, volcaniclastic, volcanic rocks), and Triassic units (sedimentary and volcaniclastic rocks with minor volcanic rocks, volcanic rocks) as shown in Figures 2 and 3. They are from mafic lava flows (samples CD-2, CD-3, CD-4, CD-6, CD-10, CD-12, CD-13, CD-14, WP-1, WP-7, WP-9, WP-10, OP-1, OP-3, CS-1, CS-2) and are non-porphyritic to highly porphyritic. The phenocrysts or microphenocrysts may include plagioclase, amphibole, orthopyroxene, clinopyroxene, unknown mafic mineral, apatite, and Fe-Ti oxide; apatite microphenocrysts are present only in the more evolved samples. The groundmass is commonly intergranular and uncommonly ophitic or subophitic. It comprises abundant felty plagioclase laths, clinopyroxene, orthopyroxene, and/or amphibole. Fe-Ti oxide occurs as an additional, major or minor constituent. The non-porphyritic rock is seriate textured, compositionally similar to the porphyritic rocks.

GROUP III ROCKS

The Group III mafic volcanic rocks are associated with the Permo-Triassic unit (sedimentary, volcaniclastic, volcanic rocks), the Triassic unit (sedimentary and volcaniclastic rocks, with minor volcanic rocks) and the Jurassic unit (gabbrodiorite, microgabbro-microdiorite) as shown in Figure 3. They are almost totally from mafic lava flows (samples CD-7, CD-8, CD-9, WP-2, WP-3, WP-5, WP-6, WP-8); only one is from a mafic hypabyssal rock (sample WP-4). The lava samples show slightly to highly porphyritic textures, with phenocrysts or microphenocrysts of plagioclase, amphibole, clinopyroxene, orthopyroxene, and/or Fe-Ti oxide. The groundmass is commonly felty and intergranular, but rarely ophitic or subophitic and trachytic. It is constituted of abundant plagioclase and subordinate to minor amphibole,

clinopyroxene, apatite and/or Fe–Ti oxide. The hypabyssal sample is seriate textured, made up of plagioclase and amphibole.

GEOCHEMISTRY

SAMPLE PREPARATION AND ANALYTICAL TECHNIQUES

The 30 carefully selected mafic volcanic rocks and hypabyssal rocks were prepared for whole-rock chemical analysis by splitting into conveniently sized fragments, and then crushing to small chips (approximately 5 mm across), using a hydraulic splitter-crusher (Rocklabs, Auckland. New Zealand). The chips were chosen to avoid those containing vesicles, amygdale minerals, veinlets, xenoliths, and weathering surfaces. Compressed air was used to remove dusty materials from the selected chips. Approximately 50-80 g of the cleaned chips was pulverized for a few minutes by a tungsten carbide ring mill (Rocklabs).

Chemical analyses of major oxides $(SiO_2, TiO_2, TiO_2,$ Al₂O₃, total iron as Fe₂O₃, MnO, MgO, CaO, Na₂O, K_2O , P_2O_5) and a range of trace elements (Rb, Sr, Y, Zr, Nb, Ni, Cr, V, Sc, Th) were carried out using a wavelength dispersive sequential X-ray spectrometer (MagixPro PW2400; Philips, Almelo, Netherlands) at the Department of Geological Sciences, Faculty of Science, Chiang Mai University. The major oxides were measured from fusion discs, prepared by mixing 1.0 g powder with 5.0 g $\text{Li}_2\text{B}_4\text{O}_7$ and 0.1 g LiBr. The trace elements were determined from pellets made by pressing mixes of 5.0 g sample powder and 1.0 g $C_6H_8O_3N_2$ wax at 200 kN pressure. The net (background-corrected) intensities were measured, and the concentrations were calculated against the calibrations derived from eight international standard reference rock samples (AGV-2, BIR-1, RGM-1, BCR-2, DNC-1, W-2, BHVO-2, GSP-2). The inter-element matrix corrections were done by SuperQ v3.0 programs (Philips). The reporting detection limits are about 0.01 wt% for major oxides, 6 ppm for Cr and V, 5 ppm for Ni and Sc, 3 ppm for Rb, and 2 ppm for Sr, Y, Zr, Nb. and Th.

REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb) and Hf were determined on six representative samples, using an inductively coupled plasma mass spectrometer (ICP-MS), installed at the School of Earth Sciences, Royal Holloway College, University of London. Realistic working detection limits are approximately 1 ppm for most REE, but 2 ppm and 10 ppm are likely to be better estimates of detection limits for Er and Pr, respectively. Precision is estimated to be 5-10%.

The analytical results for major oxides and trace elements of the studied mafic volcanic samples and hypabyssal samples are reported in Table 1, and the REE and Hf analyses of representative samples are given in Table 2.

ELEMENT MOBILITY

Although the studied mafic volcanic rocks and hypabyssal rocks were carefully selected, their chemical compositions are unlikely to represent those in the magma since the rocks have undergone variable degrees of alteration. 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 incompatible elements in the primary rocks and altered rocks remain constant. Accordingly, only the immobile elements and immobile incompatible element ratios are used in interpreting the geochemical data presented in this study.

Following the work pioneered by Pearce and Cann (1973), numerous studies have shown that the high field strength elements (HFSE; Ti, Zr, Y, Nb, Th, P) and also the transitional elements Ni, Cr, V, and Sc are relatively immobile during alteration. In addition, although occasional reports have appeared concerning REE, especially light REE (LREE), mobility during hydrothermal alteration and low-grade metamorphism (e.g. Hellman & Henderson 1979; Whitford et al. 1988), 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 to subparallel to the primary patterns. Consequently, in attempting to determine the geochemical affinities and tectonic significance of the studied mafic volcanic rocks and hypabyssal rocks, concentration has focused on the relatively immobile elements, which are HFSE, REE, and transition elements.

MAGMATIC AFFINITIES

The studied mafic samples contain the values for loss on ignition varying from 1.20 to 6.17 wt% $(3.05 \pm 1.25 \text{ average})$, implying that they are

Table 1 Who.	le-rock ans	alyses and a	some selec	ted ratios o	of the studi	ied, least-a	ltered mafi	ie volcanie	rocks and]	nypabyssal	rocks				
Sample number Lat. (°N) Long. (°E)	${ m CD-1^{\dagger}}$ 16°12'43″ 100°58'36″	WP-11 [†] 16°15′9″ 100°58′17″	WP-12 [†] 16°15′6″ 100°58′17″	CD-5 [†] 16°13′19″ 100°57′56″	${ m CD-11}^{\dagger}$ 16°9'20" 100°49'29"	${ m CD-2^{\ddagger}}$ 16°12'40″ 100°58'36″	WP-1 [‡] 16°16'10″ 100°49'59″	WP-7* 16°16'41″ 100°54'22″	CD-3 [‡] 16°14′21″ 100°58′17″	WP-9 [‡] 16°16'27" 100°57'55"	WP-10 [‡] 16°15′13″ 100°58′4″	CD-4 [‡] 16°13′39″ 100°58′16″	CD-6 [‡] 16°10′50″ 100°56′20″	CD-10 [*] 16°10′37″ 100°50′27″	$CD-12^{*}$ 16°9'45″ 100°50'40″
Major oxides															
SiO_2	47.82	49.13	48.48	47.88	48.83	53.02	51.99	49.42	52.54	50.64	55.27	53.60	54.58	54.18	52.35
${ m TiO_2}$	2.24	2.60	2.72	2.23	2.21	1.73	0.91	1.00	1.04	0.66	0.86	0.81	0.98	0.66	1.46
Al_2O_3	16.11	15.71	15.28	16.50	17.28	18.39	18.76	20.34	18.82	15.53	19.16	20.33	20.15	20.03	18.55
FeO^*	13.81	13.95	14.91	13.04	13.28	7.99	10.43	10.57	8.86	8.69	7.81	8.34	8.61	6.84	9.88
MnO	0.17	0.15	0.24	0.17	0.24	0.13	0.08	0.19	0.14	0.13	0.12	0.12	0.13	0.10	0.19
MgO	5.20	4.84	4.89	7.32	7.02	5.86	6.26	5.33	5.31	10.56	5.36	4.39	3.12	3.73	4.17
CaO	10.90	7.97	7.75	10.13	6.65	8.53	8.39	9.13	9.58	10.36	5.65	8.01	7.69	9.71	8.08
Na_2O	3.21	4.33	4.03	2.30	3.93	3.72	2.50	2.98	2.83	2.34	5.23	3.62	3.83	3.99	4.13
$ m K_2O$	0.16	0.96	1.30	0.11	0.17	0.71	0.54	0.93	0.65	0.85	0.31	0.64	0.72	0.57	0.80
P_2O_5	0.38	0.37	0.38	0.33	0.38	0.27	0.14	0.12	0.24	0.23	0.23	0.15	0.19	0.19	0.40
LOI	2.51	3.05	1.55	3.63	3.17	4.10	2.39	1.20	1.60	2.83	6.17	3.30	2.67	3.22	2.38
Original Sum.	101.81	99.61	99.92	101.38	101.42	79.67	99.65	98.92	100.75	101.03	99.87	99.55	99.52	100.89	100.29
FeO*/MgO	2.66	2.88	3.05	1.78	1.89	1.36	1.67	1.98	1.67	0.82	1.46	1.90	2.76	1.83	2.37
Trace elements															
Ba	164	367	399	173	292	234	141	176	187	189	226	238	290	148	491
Rb	6.7	14.4	20.5	5.2	7.8	15	18	24	14	24	13	16	20	16	19
\mathbf{Sr}	452	648	636	246	374	539	314	435	354	443	692	644	609	532	582
Υ	48	48	44.7	44	46	54	24	20	31	19	20	23	36	21	53
Zr	182	184	185	153	167	200	87	75	129	101	128	113	143	113	202
Nb	5.5	4.8	6.1	4.3	6.7	5.4	Y	Y	3.1	Y	3.3 2	2.1	~ 2	2.2	4.2
Ni	49	29	24.	100	101	61	48	20	76	282	49	24	19	23	46
Cr	177	147	157	318	286	242	235	124	215	962	236	120	124	101	174
Λ	351	461	516	354	394	243	277	254	195	231	216	196	242	153	256
Sc	36	42	41	35	34	27	35	27	25	36	27	2.8	21	14	27
Th	5.1	6.2	6.4	5.8	5.3	8.7	6.7	6.2	6.9	6.6	6.8	6.8	7.5	7.0	7.2
Selected Ratios Zr/TriO ₆	0.008	200.0	0.006	0.006	0.007	0 014	0.010	0.008	0.019	0.015	0.015	0.014	0.015	0.017	0.014
Nb/Y	0.115	0.099	0.137	0.099	0.145	0.101	<0.055	<0.027	0.009	0.097	0.161	0.092	<0.041	0.104	0.080
N0/Zr Y/Zr	0.26	0.26	0.03	0.29	0.04 0.28	0.05	10.0	0.01	0.02	0.19	0.16	0.20	0.01	0.19	0.26

Major oxides55.0054.0263.19Si0255.0054.0263.19Ti021.171.140.40AlgO318.4919.6015.69FeO*9.948.286.24MnO0.190.130.28MgO5.247.532.95CaO5.247.532.95NagO1.541.336.28CaO5.247.532.95CaO5.241.131.13KgO1.541.336.28P2050.350.290.09LOI4.992.945.80Original Sun.100.8099.52100.40P2050.782.945.80Crigenal Sun.100.8099.52100.40Trace elements332.95100Sr672585131Y323.63.6Sr672585100Nb3.63.62.94Sr672585100Sr672585131Y3.63.62.63Nb3.63.62.64Nb3.63.63.6Sr672585131Y3.63.63.6Y3.63.63.6Sr672585131Y3.63.63.6Sr6723.63.6Sr6723.63.6	$\begin{array}{c} 65.65\\ 0.46\\ 14.84\\ 5.64\\ 5.64\\ 0.26\\ 1.26\\ 0.28\\ 0.28\\ 0.08\\ 0.08\\ 0.08\\ 2.03\\ 2.03\\ 1120\\ 100.33\\ 1120\\ 105\end{array}$	$\begin{array}{c} 61.95\\ 0.41\\ 16.43\\ 6.79\\ 0.29\end{array}$	10.38.01	$16^{\circ}16'26''$ $100^{\circ}54'59''$	$16^{16'16'7'}$ $100^{6}4'5''$	$16^{\circ}16'1''$ $100^{\circ}54'9''$	$16^{\circ}17'17''$ $100^{\circ}51'41''$	$16^{\circ}17'26''$ $100^{\circ}51'51''$	$16^{\circ}16'44''$ $100^{\circ}54'48''$	$16^{\circ}10'18''$ $100^{\circ}56'27''$	UD-8° 16°11′57″ 100°53′60″	16°12'32″ 100°54'17″
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} 65.65\\ 0.40\\ 14.84\\ 5.64\\ 5.64\\ 0.26\\ 0.26\\ 0.28\\ 0.08\\ 0.08\\ 0.08\\ 0.08\\ 0.08\\ 0.08\\ 0.08\\ 0.08\\ 0.08\\ 0.08\\ 100.33\\ 1120\\ 100.33\\ 105\end{array}$	$\begin{array}{c} 61.95\\ 0.41\\ 16.43\\ 6.79\\ 0.29\end{array}$										
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} 0.40\\ 14.84\\ 5.64\\ 5.64\\ 0.26\\ 1.26\\ 0.08\\ 0.08\\ 0.08\\ 0.08\\ 2.26\\ 100.33\\ 120\\ 100.33\\ 1120\\ 105\end{array}$	$\begin{array}{c} 0.41 \\ 16.43 \\ 6.79 \\ 0.29 \end{array}$	53.51	62.01	58.64	57.70	60.04	53.30	63.14	53.47	62.71	59.65
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	14.84 5.64 0.26 3.93 1.66 1.29 6.25 0.08 3.80 1.20 3.80 1.20 3.80 100.33 2.03 1120	16.43 6.79 0.29	0.54	0.75	0.78	0.84	0.57	0.56	0.87	0.75	0.83	0.99
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	5.64 0.26 3.93 1.66 1.29 6.25 6.25 6.25 0.08 3.80 1.20 2.03 2.03 105	$6.79 \\ 0.29$	19.46	16.28	18.46	18.99	19.02	21.40	17.91	20.62	18.15	18.48
	0.26 3.93 1.66 1.29 6.25 6.25 6.25 6.25 1.29 1.20 2.03 2.03 1120	0.29	10.03	7.18	6.56	7.04	5.74	7.25	6.19	8.11	6.26	7.58
	3.93 1.66 1.29 6.25 6.25 6.25 3.80 3.80 3.80 3.80 100 33 2.03 1120 105		0.16	0.11	0.12	0.11	0.13	0.15	0.13	0.11	0.13	0.15
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	1.66 1.29 6.25 6.25 0.08 3.80 3.80 3.80 1.00 3.3 2.03 1120 1120	4.25	4.94	3.19	3.64	3.59	2.96	3.84	2.13	4.25	2.14	2.62
NagO 4.42 3.57 1.13 K_2O 1.54 1.33 6.28 P_2O_5 0.35 0.29 0.09 D_2O_5 0.09 0.09 0.09 $LO1$ 4.99 2.94 5.80 D_1O1 1.99 2.94 5.80 D_1O2 0.09 9.552 100.40 $FeO*/MgO$ 2.53 2.01 1.60 Trace elements 4.44 366 1036 Ba 4.44 366 1036 Sr 6.72 5.85 131 Y 83 2.4 100 Sr 6.72 3.3 5.0 Nb 3.6 3.6 2.8 Nb 3.6 3.6 2.8 Ni 1.7 4.4 2.7	1.29 6.25 0.08 3.80 100.33 2.03 1120 1120	1.42	7.97	6.00	7.26	7.16	7.58	8.69	3.80	8.29	3.46	5.25
Kz0 1.54 1.33 6.28 P_20_5 0.35 0.29 0.09 LOI 4.99 2.94 5.80 Original Sum. 100.80 99.52 100.40 FeO*/MgO 2.53 2.01 1.60 Trace elements 2.53 2.01 1.60 Rb 33 2.4 100 Sr 672 585 131 Y 32 33 2.4 100 Sr 672 585 131 Y Y 3.6 3.6 < 2 Ni Ni 1.57 Nb 3.6 3.6 3.6 < 2 Ni 2.6 < 2	$\begin{array}{c} 6.25\\ 0.08\\ 3.80\\ 100.33\\ 2.03\\ 2.03\\ 1120\\ 105\end{array}$	1.59	2.74	2.95	3.80	3.84	3.47	3.83	4.84	3.80	5.29	4.58
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	0.08 3.80 100.33 2.03 1120 105	6.77	0.53	1.39	0.53	0.51	0.29	0.83	0.71	0.48	0.78	0.45
LOI 4.99 2.94 5.80 Original Sum. 100.80 99.52 100.40 Trace elements 2.53 2.01 1.60 Ba 444 366 1036 Rb 33 2.4 100 Sr 672 585 131 Y 3.6 3.6 2.61 Nb 3.6 3.6 2.61 Ni 1.7 4.4 2.61	3.80 100.33 2.03 1120 105	0.10	0.12	0.15	0.21	0.22	0.19	0.15	0.27	0.122	0.25	0.24
	$\begin{array}{c} 100.33 \\ 2.03 \\ 1120 \\ 105 \end{array}$	4.20	က္	1.25	1.50	2.13	1.52	2.37	3.98	2.51	3.71	3.88
	2.03 1120 105	100.44	101.01	100.99	100.05	09.66	99.75	99.59	99.88	100.35	99.63	99.93
	$\frac{1120}{105}$	1.67	1.44	2.25	1.80	1.96	1.94	1.89	2.91	1.91	2.93	2.89
	$1120 \\ 105$											
Rb 33 24 100 Sr 672 585 131 Y 32 533 5.0 Zr 157 164 61 Nb 3.6 3.6 <2 Ni 17 44 23	105	1221	190	327	230	219	122	228	199	136	340	219
Sr 672 585 131 Y 32 53 5.0 Zr 157 164 61 Nb 3.6 3.6 3.6 <2 Ni 17 44 23		113	16	39	14	14	14	25	26	53	22	16
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	173	209	443	378	609	617	688	745	1138	603	1629	1089
Zr 157 164 61 Nb 3.6 3.6 -2 Ni 17 -44 -23	7.6	6.5	11	37	26	58	24	19	53	21	50	42
Nb 3.6 3.6 <2 Ni 17 44 23	68	68	60	178	142	141	135	111	206	131	228	184
Ni 17 44 23	Y	Y	Y	3.4	2.7	2.0	Y	Y	3.0	Y	2.1	3.0
	8	73	26	32	34	58	22	30	16	25	17	15
Cr 116 155 137	135	141	146	195	159	135	122	138	107	135	102	107
V 261 248 163	160 97	1/16 97	787	179 81	171	195 00	131	148	211	102	115	159 00
Th 7.9 7.7 8.7	2.5 7.5	8.8	33 8.0	9.6	6.7	67 8.0	01 8.4	6.9	01 8.8	ou 7.4	6"L	6 2 2
Selected Ratios												
Zr/TiO_2 0.013 0.014 0.015	0.013	0.017	0.015	0.024	0.018	0.017	0.023	0.020	0.024	0.018	0.027	0.019
Nb/Y 0.113 0.108 <0.197	7 <0.159	<0.162	<0.050	0.092	0.105	0.073	<0.079	<0.083	0.056	<0.040	0.043	0.072
Nb/Zr 0.02 0.02 0.02 0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Y/Zr 0.20 0.20 0.08	0.11	01.0	0.18	12.0	0.18	070	0.18	0.17	0.26	0.16	7770	0.23

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Sample no.	$WP-12^{\dagger}$	WP-1 [‡]	$CD-12^{\ddagger}$	$\mathrm{CS} ext{-}2^{\ddagger}$	$WP-3^{\$}$	WP-6 [§]
La	12.3	5.00	12.4	3.50	9.60	5.40
Се	31.1	10.8	29.1	5.90	21.3	11.9
Pr	4.20	1.60	4.10	0.90	2.90	1.70
Nd	24.0	9.00	20.6	4.50	14.7	8.30
Sm	6.26	3.16	6.09	1.63	3.21	2.23
Eu	1.95	0.86	1.68	0.51	0.95	0.82
Gd	6.29	2.79	5.89	1.68	3.83	2.12
Tb	1.16	0.55	1.17	0.23	0.50	0.41
Dv	6.67	3.32	6.16	1.38	2.84	2.26
Ho	1.39	0.63	1.29	0.36	0.56	0.42
Er	3.52	1.77	3.25	1.07	1.36	1.17
Tm	0.52	0.29	0.53	0.15	0.22	0.15
Yb	3.51	2.09	3.62	1.17	1.65	1.25
Hf	3.96	1.75	4.18	0.77	2.51	1.69
Selected ratios						
(La/Sm) _{cn}	1.23	0.99	1.28	1.35	1.87	1.52
(Sm/Yb) _{cn}	1.97	1.67	1.86	1.54	2.15	1.97

Table 2REE and Hf analyses (ppm) and some selected chondrite-normalized ratios of the studied, least-altered maficvolcanic rocks

[†] Group I.

[‡] Group II.

§ Group III.

cn, chondrite-normalized values (Anders & Grevesse 1989).



Fig. 4 Plots of (a) SiO₂ and (b) FeO^{*} against FeO^{*}/MgO in the studied, least-altered andesite-basalt and microdiorite-microgabbro. Group I (\bigcirc), Group II (\square), Group III (\square), FeO^{*} denotes total iron as FeO. Field boundaries between tholeiitic and calc-alkalic fields are taken from Miyashiro (1974).

somewhat altered. Keeping the alteration effects in mind, the rocks have a wide spectrum of silica content, ranging 47–66 wt%. The Group I rocks appear to be totally tholeiitic, while the Group II and Group III rocks straddle the field boundaries between calc-alkalic and tholeiitic fields on SiO₂ and FeO* vs FeO*/MgO diagrams (Fig. 4). Figures 5 and 6 are the zirconium variation diagrams for the least-mobile minor oxides (TiO₂, P₂O₅) and trace elements (Nb, Y, Th, Ni, Cr, V, Sc) in the studied mafic volcanic rocks and hypabyssal rocks. The data points for the studied samples are scattered on the variation diagrams other than Y–Zr plot. The abundances of Y systematically increase with increasing Zr values, forming a clearly defined positive trend, with average Zr/Y ratios of 5.2 ± 2.0 . This phenomenon signifies that Y is a least-mobile, incompatible element as expected. The scatters of data points on the other variation diagrams reflect either primary



Fig. 6 Zirconium variation diagrams for (a) Nb, (b) Y, (c) Th, (d) Ni, (e) Cr, (f) V, and (g) Sc in the studied least-altered andesite-basalt and microdiorite-microgabbro. All the trace elements are in ppm, and the symbols used are as in Figure 4. The data points for Nb below the detection limit (2 ppm) are omitted.



Fig. 7 Plot of $Zr/TiO_2 vs Nb/Y$ for the studied least-altered andesitebasalt and microdiorite-microgabbro (symbols as in Fig. 4). Field boundaries for different magma types are taken from Winchester and Floyd (1977). Data points for rocks with Nb content below the detection limit are omitted.

compositions or modified compositions resulting from alteration.

The presented Group I rocks have Zr/TiO₂ and Nb/Y ratios in the ranges of 0.006–0.008 and 0.098– 0.146, respectively, corresponding to sub-alkalic andesite-basalt compositions as illustrated in a Zr/TiO₂-Nb/Y diagram (Fig. 7). The Group II rocks are all mafic lava flows and have Nb contents ranging from below the detection limit (2 ppm) up to 5.4 ppm. Those with Nb content at or above the detection limit lie almost totally in the sub-alkalic andesite field, very close to the demarcation that separates andesite-basalt from andesite on the Zr/TiO₂-Nb/Y plot. In contrast, those with Nb content below the detection limit have Zr/TiO₂ in a range of 0.008–0.017, implying that they are almost totally and esitic-basaltic in composition. Almost all the Group III rocks are mafic lava flows; only one sample (sample CD-9) is a mafic hypabyssal rock. Similar to the Group II rocks, their Nb content varies from below the detection limit up to 3.4. Keeping those with Nb content less than the detection limit in mind, the Group III rocks appear to be sub-alkalic andesite on the basis of their Zr/TiO_2 (0.017–0.027) and Nb/Y (up to 0.072) ratios.

One sample of the Group I sub-alkalic rocks (sample WP-12) was selected for REE analysis. The analytical results as a chondritenormalized REE pattern are shown in Figure 8a. The REE pattern, which is slightly enriched light REE, with chondrite-normalized La/Sm [(La/ Sm)_{en}] = 1.23 and chondrite-normalized Sm/Yb

 $[(Sm/Yb)_{cn}] = 1.97$, is typical of tholeiitic series (Hess 1989; Wilson 1989). Accordingly, the Group I rocks are inferred to be tholeiitic andesite-basalt and microdiorite-microgabbro. REE analyses were carried out on sample numbers WP-1, CD-12. and CS-2 of Group II sub-alkalic andesite-basalt. The results show that they have subparallel, slightly light REE enriched patterns, with similar (La/Sm)_{cn} values (0.99-1.35) and slightly lower (Sm/Yb)_{cn} values (1.54–1.86) relative to the representative Group I andesite-basalt (Fig. 8b). Similarly to the Group I rocks, the Group II rocks are assigned to be tholeiitic series. The chondritenormalized REE patterns for Group III subalkalic andesite are represented by sample numbers WP-3 and WP-6 (Fig. 8c). They have subparallel, slightly light REE enriched patterns, with $(La/Sm)_{cn}$ values = 1.52–1.87 and $(Sm/Yb)_{cn}$ values = 1.97-2.15, characteristic of calc-alkalic rocks (Hess 1989; Wilson 1989). Therefore, the Group III rocks are calc-alkalic andesite and microdiorite.

TECTONIC SETTING OF ERUPTION

The least-altered mafic lava flows and hypabyssal rocks presented in this study have been plotted in many tectonic discrimination diagrams, using least-mobile elements and/or least-mobile-element ratios. The diagrams include Zr/Y–Ti/Y (Fig. 9a), Ti–V (Fig. 9b), Ti–Zr (Fig. 9c), Cr–Y (Fig. 9d), Zr/Y–Zr (Fig. 9e) and Ti/Y–Nb/Y (Fig. 9f) bivariate plots, and Ti–Zr–Y (Fig. 10a), Nb–Zr–Y (Fig. 10b) and Y–La–Nb (Fig. 10c) ternary plots.

The Group I tholeiitic andesite/basalt and microdiorite/microgabbro appear to be platemargin basalt on the basis of Zr/Y – Ti/Y diagram (Fig. 9a). The plate-margin magmatic rocks are not supported by their positions in the field of within-plate basalt on Ti–Zr (Fig. 9c) and Zr/Y–Zr diagrams (Fig. 9e), but are well supported by their positions in the fields of volcanic arc basalt on Ti/Y–Nb/Y (Fig. 9f), Ti–Zr–Y (Fig. 10a), Nb–Zr–Y (Fig. 10b), and Y–La–Nb (Fig. 10c) diagrams, midocean ridge basalt on Ti–V (Fig. 9b), Ti–Zr (Fig. 9c), Cr–Y (Fig. 9d), Ti/Y–Nb/Y (Fig. 9f), Ti–Zr–Y (Fig. 10a), and Nb–Zr–Y (Fig. 10b) diagrams, and back-arc basin basalt on Ti–V plot (Fig. 9b).

The Group II tholeiitic and esite-basalt form a compositional field across the field boundary between plate-margin basalt and within-plate basalt on the Zr/Y-Ti/Y plot (Fig. 9a). They are,



Fig. 8 Chondrite-normalized patterns for the representatives of (a) Group I, (b) Group II, and (c) Group III and esite-basalt and microdioritemicrogabbro. Chondrite normalizing values are those of Anders and Grevesse (1989).

however, largely in the field of plate-margin basalt that could have been formed in a volcanic arc as shown by Ti–V (Fig. 9b), Ti–Zr (Fig. 9c), Cr–Y (Fig. 9d), Ti/Y–Nb/Y (Fig. 9f), Ti–Zr–Y (Fig. 10a), Nb–Zr–Y (Fig. 10b), and Y–La–Nb (Fig. 10c), a mid-ocean ridge as shown by Ti–V (Fig. 9b) and Cr–Y (Fig. 9d) plots or a back-arc basin as shown by Ti–V plot (Fig. 9b). The appearance of withinplate affinity as shown by the Zr/Y–Ti/Y diagram (Fig. 9a) is in accordance with the values for Zr and Zr/Y as shown in Figure 9e.

The Group III calc-alkalic and esite-basalt and microdiorite-microgabbro are plotted in the field of plate-margin basalt as the Group I rocks on the Zr/Y-Ti/Y plot (Fig. 9a). They might have also been formed in a volcanic arc environment as shown by Ti-V (Fig. 9b), Ti-Zr (Fig. 9c), Cr-Y (Fig. 9d), Ti/Y-Nb/Y (Fig. 9f), Ti-Zr-Y (Fig. 10a), Nb–Zr–Y (Fig. 10b), and Y–La–Nb (Fig. 10c) diagrams, a mid-ocean ridge environment as shown by Ti–V (Fig. 9b) and Ti/Y–Nb/Y (Fig. 9f) diagrams, a back-arc basin as shown by Ti–V plot (Fig. 9b) and/or a within-plate environment as shown by the Cr–Y (Fig. 9d) and Zr/Y–Zr (Fig. 9e) diagrams.

It is obvious that the above tectonic discrimination diagrams yield inconsistent results. The discrepancy is partly due to the evolved nature of the studied mafic volcanic rocks and the fact that the fields for back-arc basin basalt are almost totally absent from the applied discrimination diagrams. Moreover, several studies (Holm 1982; Prestvik 1982; Duncan 1987; Myers & Breitkopf 1989) have demonstrated that these diagrams may often fail to unequivocally classify tectonic setting of formation of altered lavas. In order to solve the problem,



Fig. 9 (a) Zr/Y-Ti/Y (after Pearce & Gale 1977), (b) V-Ti (after Shervais 1982), (c) Ti-Zr (after Pearce 1982), (d) Cr-Y (after Pearce 1982), (e) Zr/Y-Zr (after Pearce & Norry 1979), and (f) Ti/Y-Nb/Y (after Pearce 1982) discrimination diagrams for the least-altered andesite-basalt and microdioritemicrogabbro. Symbols used are as in Figure 4. AB, alkalic basalt; AT, arc tholeiite; BABB, back-arc basin basalt; CAB. calc-alkaline basalt: CFB. continental flood basalt; MORB, mid-ocean ridge basalt; OIB, ocean-island basalt; plate-margin basalt; PMB. VAB volcanic-arc basalt; and WPB, withinplate basalt.

the classical principle of geology 'present is the key to the past' has been applied. In other words, if the tectonic interpretation is correct, there should be modern analogs (Panjasawatwong et al. 1995, 2006; Panjasawatwong 1999; Phajuv et al. 2005; Singharajwarapan & Berry 2000). Extensive searches for modern analogs have been made in terms of chondrite-normalized REE and N-MORB normalized multi-element patterns. In doing so, the representatives of Group I, Group II, and Group III rocks are analogous to the Quaternary basalt (samples HOKU34, KIM1, MKR2) from the northern Ryukyu Arc (Shinjo et al. 2000), as illustrated in Figures 11, 12, and 13. They have negative Nb anomalies and similar immobile incompatible element ratios as shown by the parallelism of the study patterns and those for the modern analog. Accordingly, a deduction can be drawn here that the studied andesite-basalt and microdiorite-microgabbro have been formed in a volcanic arc.

CONCLUSION AND TECTONIC IMPLICATIONS

The mafic samples presented here comprise Group I, Group II, and Group III rocks with Ti/Zr values of 83 ± 6 , 46 ± 12 and 29 ± 5 , respectively. The Group I and Group II are tholeiitic and esite-basalt and microdiorite-microgabbro, whereas the Group III is calc-alkalic andesite and microdiorite. The chemical differences among the three magmatic groups might have been attributed to the heterogeneity of source rocks just before partial melting. These rocks have contemporaneously formed in a volcanic arc environment as evidenced by their lithostratigraphy and modern analogs. In constructing the plate tectonic evolution of any fold belt, reliable data from many different branches of geology are needed. So far, although many informative facts were obtained, the tectonic evolution of Thailand is still a subject of debate, particularly in terms of the location of suture zone, timing of collision, paleo-environments, post-orogenic



Fig. 11 Plots of (a) chondrite-normalized REE, and (b) N-MORB normalized multi-elements for the representative of Group I andesite-basalt and microdiorite-microgabbro, and its modern analog, tholeiitic basalt (sample HOKU34) from the volcanic front of northern Ryukyu Arc and southern Kyushu, Japan (Shinjo et al. 2000). Chondrite-normalizing values are those of Anders and Grevesse (1989), whereas N-MORB normalizing values are those of Sun and McDonough (1989).

adjustment, and a tectonic model. The widely different opinions reflect either the complicated tectonic history or inadequate data. The tectonic settings of volcanic rocks in the Chon Daen–Wang Pong area are part of the important fact to elucidate the tectonic evolution.

Thailand is widely believed to be constituted by Shan-Thai and Indochina cratons to the west and east. Based on recent data, the tectonic model can be shown in Figure 14. In the Silurian–Devonian, the Shan-Thai and Indochina cratons were separated by a major ocean basin, represented by the

(b)

Yb

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Fig. 12 Plots of (a) chondrite-normalized REE, and (b) N-MORB normalized multi-elements for the representatives of Group II andesite—basalt, and their modern analog, tholeiitic basalt (sample KIM1) from the volcanic front of northern Ryukyu Arc and southern Kyushu, Japan (Shinjo *et al.* 2000). Chondrite-normalizing values are those of Anders and Grevesse (1989), whereas N-MORB normalizing values are those of Sun and McDonough (1989).



Fig. 13 Plots of (a) chondrite-normalized REE, and (b) N-MORB normalized multi-elements for the representatives of Group III andesite-basalt and microdiorite-microgabbro, and their modern analog, tholeiitic andesite (sample MKR2) from the back-arc basin of northern Ryukyu Arc (north Ryukyu), Japan (Shinjo *et al.* 2000). Chondrite-normalizing values are those of Anders and Grevesse (1989), whereas N-MORB normalizing values are those of Sun and McDonouch (1989).

mid-ocean ridge basalt of the Central Loei Volcanic Sub-belt (Intasopa & Dunn 1994; Panjasawatwong *et al.* 2006). A west-dipping subduction formed at the leading edge of the Shan–Thai craton, leading to a volcanic arc. This arc may have been rifted to form an immature back-arc basin in the Silurian (Fig. 14a), represented by the immature back-arc basin basalt and andesite in the Chiang Rai–Chiang Mai Volcanic Belt (Phajuy B, unpubl. data, 2008), and then a mature back-arc basin in the Devonian (Fig. 14b), as evidenced by Devonian radiolarian chert represented by Wonganan and Caridroit (2005). The mature back-arc basin might have continued spreading, leading to a major ocean basin in the Carboniferous to Middle Permian (Fig. 14c). These lead to the occurrences of ocean-island basalt and mid-ocean ridge and esite-basalt in the Chiang Rai-Chiang Mai Volcanic Belt (Phajuy B, unpubl. data, 2008).

In the Devonian – Middle Permian, while the back-arc basin became wider to be a major ocean basin, the older major ocean basin became narrower and then closed. The closure of the older

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Fig. 14 Schematic diagrams showing tectonic evolution of Shan–Thai and Indochina cratons. ST, Shan–Thai craton; IC, Indochina craton; IAB, islandarc basalt; OIB, ocean-island basalt; BABB, back-arc basin basalt.

major ocean basin resulted in changing the spreading center of the new ocean basin to a new subduction with reverse polarity to the extinct older one in the Late Permian (Fig. 14d). Subsequently, the new major ocean basin became narrower, and a new arc, as represented by the rocks presented in this study, formed above the subduction in the Late Permian–Middle Triassic (Fig. 14e). The polarity of subduction in this period is in agreement with that of Kamvong *et al.* (2006), whereas the presence of contemporaneous arc is consistent with the interpretation made by Kamvong *et al.* (2006), Marhotorn *et al.* (2008), Tangwattananukul *et al.* (2008) and Nakchaiya M (2008, unpubl. data). Finally, the Shan–Thai and Indochina cratons might have been completely collided in a period of the Middle–Late Triassic and then immediately followed by post-orogenic eruption that gave rise to Chiang Khong–Tak Volcanic Belt (Srichan *et al.* 2009) as shown in Figure 14f. The report of Upper Triassic radiolarians by Kamata *et al.* (2002) supports the Late Triassic collision.

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