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Geochemistry and tectonic setting of the Central Loei volcanic rocks, Pak Chom area, Loei, northeastern Thailand

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Abstract

The Central Loei volcanic rocks, as evidenced by those in the Pak Chom area, were formed in the Late Devonian–Early Carboniferous and can be separated into three magmatic groups: transitional tholeiitic basalt, tholeiitic microgabbro and calc-alkalic basalt/andesite on the basis of immobile-element contents and ratios of least altered samples. All the tholeiitic microgabbro possibly occurred as dikes. Chemically, the transitional tholeittic basalt and tholeiitic microgabbro have higher abundances of TiO_2, Ni and Cr relative to the calc-alkalic basalt/andesite at similar values for FeO*/MgO; they also contain higher Ti/Zr but lower Zr/Nb. The transitional tholeiitic basalt has higher concentrations of P_2O_5 and Nb relative to the tholeiitic microgabbro at similar levels of FeO*/MgO, and also has higher ratios of Nb/Y and Ti/V, but lower values for Ti/Zr and Zr/Nb. In terms of chondrite normalized REE and N-MORB normalized patterns, the transitional tholeiitic basalt, tholeiitic basalt and calc-alkalic basalt/andesite are analogous to those from North Atlantic, Southwest Indian Ridge and New Britain Arc. On this basis, the Central Loei volcanic rocks are comprised of MORBs and oceanic island-arc lavas. These arc lavas may have erupted on an oceanic basement in the same ocean basin as those in the Chiang Rai–Chiang Mai volcanic belt.

Keywords: Pak Chom; Loei; Northeastern thailand; MORB; Island-arc lava

1. Introduction

Pre-Jurassic volcanic rocks occur in many parts of Thailand, particularly in the northern Highland, western margin of the Khorat Plateau and the eastern Gulf region (Fig. 1). They are of significance as they provide petrogenetic constraints for the tectonic and metallogenic evolution of Thailand, as well as mainland SE Asia. These volcanic rocks include those along Chiang Mai–Chiang Rai volcanic belt, Tak-Chiang Khong volcanic belt, Nan-Chanthaburi suture zone and Loei-Phetchabun–Sra Kaeo volcanic belt which host major epithermal and skarn gold deposits (e.g. Potisat, 1996; Diemar and Diemar, 1999; Khin Zaw et al., 1999a).

The westernmost Chiang Mai–Chiang Rai volcanic belt runs approximately in a north–south direction from Chiang Rai Province through Chiang Mai Province to Li District, Lamphun Province (Fig. 1). The volcanic rocks of this belt comprise mafic lava, hyaloclastite and pillow breccia that were erupted during the Middle Permian to Permo-Triassic (Chuaviroj et al., 1980; Bunopas, 1981; Bunopas and Vella, 1983; Panjasawatwong, 1999). The mafic rocks in the Chiang Rai region may have formed in a subduction environment (Macdonald and Barr, 1978; Barr et al., 1990), whereas the rest were erupted in an intraplate environment. The intraplate basalts were interpreted to have continental affinities by Barr et al. (1990), whereas Panjasawatwong et al. (1995, 1999) considered that they were erupted in an oceanic setting.

The Tak-Chiang Khong volcanic belt lies east of the Chiang Mai–Chiang Rai volcanic belt (Fig. 1) and is made

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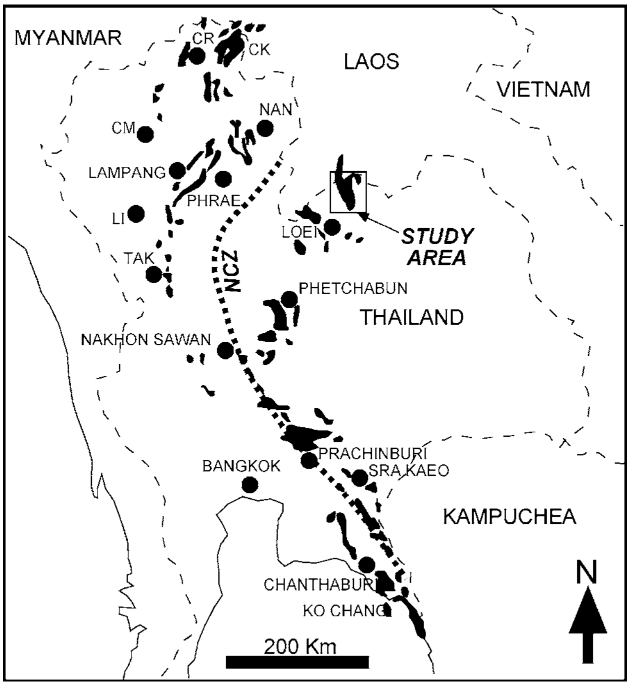

Fig. 1. Distribution of Pre-Jurassic volcanic rocks in Thailand (modified from Jungyusuk and Khositanont, 1992). CR, Chiang Rai; CK, Chiang Khong; CM, Chiang Mai; NCZ, Nan-Chanthaburi suture zone.

up of rhyolite, dacite, andesite and pyroclastic rocks. It extends north from Tak Province through Lampang Province and Phrae Province to the Mae Khong River in the Chiang Khong District, Chiang Rai Province. Two episodes of volcanic activity (Permo-Triassic and possible Late Triassic to Early Jurassic) have been recognized along this belt; products of the older volcanism are predominant over those of the younger (Jungyusuk and Khositanont, 1992). The tectonic settings of these volcanic suites are poorly constrained. However, many workers (e.g. Bunopas, 1981; Bunopas and Vella, 1983; Hutchison, 1989; Barr et al., 1990) postulated that these Permo-Triassic volcanic rocks formed in an arc environment. Barr et al. (2000) recently reported a U–Pb zircon age of 240±1 Ma (early Middle Triassic) for the felsic volcanic rocks at Lampang and considered that these volcanic rocks occurred at a convergent plate margin.

The Nan-Chanthaburi suture zone is situated between the Tak-Chiang Khong volcanic belt and the Loei-Phetchabun-Sra Kaeo volcanic belt (Fig. 1). It is widely accepted that it represents a Late Triassic continental suture between the Shan-Thai (to the present west) and Indochina (to the present east) terranes (e.g. Bunopas, 1981; Hada et al., 1991, 1999; Chaodumrong, 1992; Singharajwarapan, 1994; Singharajwarapan et al., 2000; Crawford and Panjasawatwong, 1996). The pre-Jurassic volcanic rocks along this suture zone occur as variably sized blocks embedded in foliated serpentinite matrix (serpentinite melange?). Recent studies indicate that they are comprised of Early to Middle Permian ocean-island basalt, Carboniferous (?) incipient backarc basin basalt and andesite, Permo-Triassic (?) arc basalt and andesite, and mid-ocean ridge basalt (Yoshikura, 1990; Crawford and Panjasawatwong, 1996).

The westernmost Loei-Phetchabun-Sra Kaeo volcanic belt trends NE–SW from Loei Province through Phetchabun, Nakhon Sawan and Prachinburi Provinces to Sra Kaeo Province. It is composed of lava and pyroclastic rocks of a wide range of compositions from felsic to mafic. In the Loei area, the volcanic rocks can be separated into Eastern, Central and Western sub-belts. The volcanic rocks of the Eastern sub-belt are mainly rhyolitic, whereas those of the Western sub-belt are largely andesitic (Jungyusuk and Khositanont, 1992; Della-Pasqua and Khin Zaw, 2002). Rocks of the Eastern and Western sub-belts have been interpreted to be the products of arc volcanism that formed in the Permo-Triassic (e.g. Bunopas, 1981). The rhyolitic samples of the Eastern sub-belt, however, have a Devonian–Carboniferous whole-rock Rb–Sr isochron age of 374±33 Ma (Intasopa and Dunn, 1994). The Central sub-belt is made up mainly of pillow basaltic lava, hyaloclastite and pillow breccia with some intrusions. These volcanic rocks have been assigned to a mid-ocean ridge environment and have a whole-rock Rb–Sr isochron age of 361±11 Ma (Upper Devonian–Lower Carboniferous) (Intasopa and Dunn, 1994). Intasopa (1993) and Intasopa et al. (1995) also reported $^{40}Ar/^{39}Ar$ ages of 225–275 Ma (Permo-Triassic) for volcanic rocks in Phetchabun Province and 9–57 Ma (Tertiary) for alkaline volcanic rocks from the Lop Buri area along the Loei belt. Recent laser ablation Ar/Ar dating of the Lop Buri volcanics also yielded 93±1.0 Ma (Late Cretaceous) for K-feldspar and 44.3 Ma (Eocene) for groundmass of the weakly altered porphyritic trachyandesite from Wat Vachaiport and 16.6±0.05 Ma (Miocene) for Chai Badal basalt (Khin Zaw et al., 1999b).

In this paper, we present detailed geochemical data for least-altered basaltic rocks of the Central sub-belt in the Pak Chom area, Loei Province, northeastern Thailand, in order to constrain the tectonic settings of the eruption of the Central Loei volcanic rocks. We also compare the data with those of modern volcanic suites.

2. Geological background, sample selection and analytical procedure

2.1. Geological background

The least-altered basaltic rocks in this study are part of the Central Loei volcanic belt in the Pak Chom region. They were collected from both outcrop and float in the area lying between latitudes 17° 45′ and 18° 00′ N, and longitudes 101° 45′ and 102° 00′ E on topographic map sheet 5344 I (Ban Na Kho) at a scale of 1:50,000 (Fig. 2). Geological mapping in this area at scales of 1:250,000 and 1:50,000 was undertaken by Charoenpravat et al. (1976) and Chairangsee et al. (1990). More detailed geological mapping at a scale of

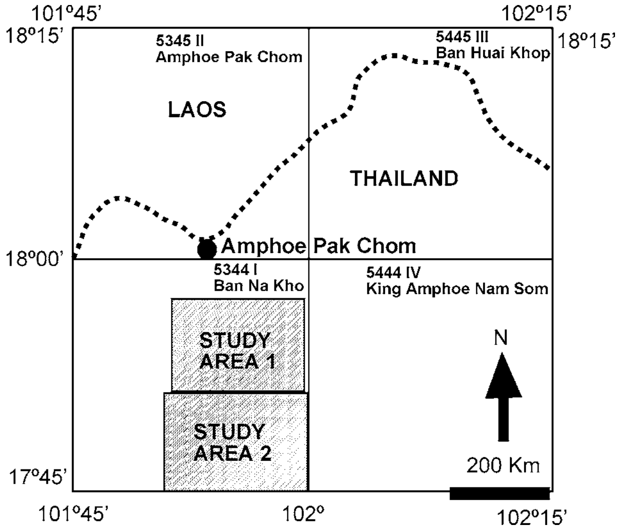

Fig. 2. Map showing the position of map sheet 5344 I (Ban Na Kho), where Central Loei mafic volcanic samples were collected, and the areas where detailed field mapping at scales of 1:50,000 and 1:10,000 was undertaken by Chairangsee et al. (1990) (study area 1), and students and staff of Department of Geological Sciences, Chiang Mai University (Kanpeng et al., 1993; Pattamalai et al., 1993; Paejui et al., 1993; Suriamma et al., 1993) (study area 2).

1:10,000 was done by senior students and staff from the Department of Geological Sciences, Chiang Mai University (Kanpeng et al., 1993; Pattamalai et al., 1993; Paejui et al., 1993; Suriamma et al., 1993). Compilation of the detailed geological maps shows that the rocks in this region can be separated into five main rock units including Upper Devonian volcaniclastic rock, Upper Devonian limestone, Upper Devonian–Lower Carboniferous volcanic rock, Upper Devonian–Lower Carboniferous sedimentary sequence, and Upper Carboniferous limestone (Fig. 3). In addition, mafic plutonic rocks and basaltic dikes that post-date the Upper Devonian–Lower Carboniferous strata locally occur throughout the area.

The Upper Devonian volcaniclastic rock unit consists of tuff, tuffaceous shale/mudstone and silicified tuff that have undergone extensive deformation. The lowermost part is composed largely of tuffaceous shale/mudstone interbedded with a subordinate amount of slightly silicified tuff. The proportion of tuff to tuffaceous sediment and the degree of silicification progressively increase towards the upper part. The uppermost part is made up mainly of black silicified tuff intercalated with minor tuffaceous sediment. The black silicified tuff is generally known as Devonian chert

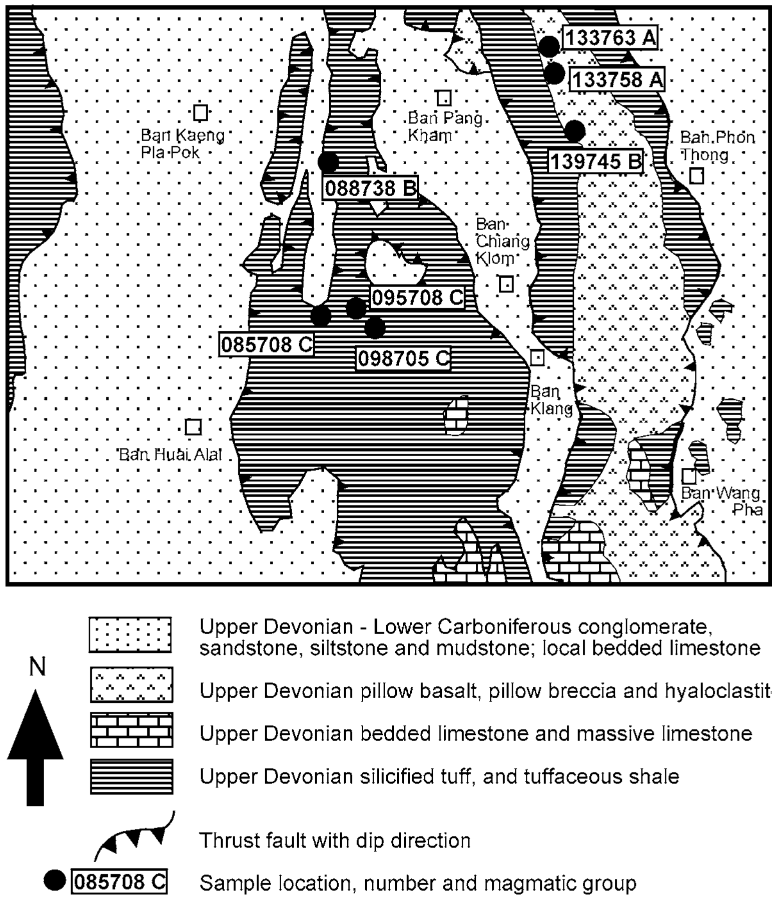

Fig. 3. Simplified geological maps of the study area 1 (modified from Chairangsee et al., 1990) and the study area 2 (compiled from Kanpeng et al., 1993; Pattamalai et al., 1993; Paejui et al., 1993; Suriamma et al., 1993), as shown in Fig. 2, showing the locations of the least altered mafic volcanic samples presented in this study.

(e.g. Charoenpravat et al., 1976; Chairangsee et al., 1990). The age of this rock unit is evidenced by the presence of lower Upper Devonian radiolarians: *Palaeoscenidium* and *Helenifore* (Sashida et al., 1993).

The Upper Devonian limestone is massive in the lower part and bedded, with mudstone intercalation, in the upper part. The limestone is greyish black and has undergone variable degrees of silicification, giving rise to a cherty appearance. They commonly contain corals and unconformably lie on the Upper Devonian volcaniclastic sequence. This rock unit is assigned to the Upper Devonian because of its stratigraphic position and presence of Devonian corals and stromatoporoids in limestone (Fontaine, 1990).

The Upper Devonian–Lower Carboniferous volcanic rock unit comprises mainly pillow basalt, pillow breccia and hyaloclastite, with a whole-rock Rb–Sr isochron age of 361 ± 11 Ma (Upper Devonian–Lower Carboniferous) (Intasopa and Dunn, 1994). They are unconformably underlain by the Upper Devonian volcaniclastic rock and Upper Devonian limestone, and have experienced varying degrees of alteration. The least altered samples of these rocks form the basis of this study.

The Upper Devonian–Lower Carboniferous sediments include sandstone, siltstone and shale/mudstone with local conglomerate and limestone intercalation. They have colors varying from greyish black to greyish green; where weathering has taken place, they are brownish grey to brownish orange. The age of this rock unit is given according to the preserved plant remains in the areas outside the study area (Fontaine et al., 1981). These rocks have partially undergone silicification and are juxtaposed against the older rock units by thrust faults. The sand-sized components of the sandstone are considered to have been derived from a magmatic arc orogen and a subduction complex, and the depositional environment of the sandstone has been interpreted to be a forearc basin (Paejui and Panjasawatwong, 1994).

The Upper Carboniferous limestone lies unconformably on the Upper Devonian–Lower Carboniferous volcanic rocks (Chairangsee et al., 1990). It contains Upper Carboniferous fossils, particularly foraminifera (Vachard, 1990).

2.2. Sample selection

A number of basaltic samples, collected from both outcrop and float, were carefully selected to avoid rocks showing (1) extensive development of mesoscopic domains of secondary minerals such as epidote, albite, chlorite or amphibole, (2) a well-developed foliation and mineral layering, (3) abundant vesicles and amygdales, and (4) quartz, epidote or calcite veining or patches totalling more than approximately 5 modal %. Ten basaltic samples were carefully selected as they are least-altered and most suitable for this study. They include samples from float at grid references 085708, 088738, 095708, 102884, 133758, 133763 and 139745, and outcrops at grid references 094808, 098705 and 087825. The samples at grid references 094808 and 098705 are from subaqueous flows, whereas that at grid reference 087825 forms a dike cross-cutting the Upper Devonian volcaniclastic rocks. The locations of these least altered samples are also shown in Fig. 3.

2.3. Sample preparation and analytical techniques

The samples were prepared for whole-rock analysis by splitting into conveniently sized fragments, and then crushing into small chips, using a Rocklabs hydraulic crusher/breaker. The crushed fragments were cleaned with an air hose; 30–50 g aliquots of the rock chips displaying no sign of weathered surfaces, veins or amygdale minerals were pulverised for 2–3 min in a tungsten–carbide Rocklabs ring mill. All the procedures described above were carried out in the Department of Geological Sciences, Chiang Mai University. The powdered samples were analysed for 11 major oxides (SiO_2, TiO_2, FeO, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5 and loss on ignition) and 10 trace elements (Ba, Sr, Rb, Zr, Y, Nb, Cr, Ni, V and Sc). Three representative samples were analyzed for rare-earth elements (La, Ce, Nd, Sm, Eu, Tb and Yb). All the analyses were carried out at Chemex Labs (Vancouver, Canada). All the major oxides and Ba, Nb, Rb, Sr, Y and Zr were analyzed by XRF and the detection limits for Ba, Nb, Rb, Sr and Y are 2 ppm, and Zr is 3 ppm. Cr, Ni and V were measured by Atomic Absorption Spectrometry (AAS) with detection limits of 2, 1 and 5 ppm, respectively. Rare earth elements (REE) were determined by NAA (detection limits: 2 ppm for Ce, 0.05 ppm for Dy, 0.05 ppm for Er, 0.01 ppm for Eu, 0.05 ppm for Gd, 1 ppm for La, 5 ppm for Nd, 5 ppm for Pr, 0.1 ppm for Sm and 0.1 ppm for Yb). The results of analyses and some selected ratios are reported in Tables 1 and 2.

3. Geochemistry

3.1. Magmatic grouping

Igneous rocks, in particular volcanic rocks, are susceptible to alteration. Accordingly, their present compositions are unlikely to be primary. However, it has been well documented that carefully selected samples can be informative with regard to their primary composition if due care is taken for the selection of elements and elemental ratios. The mafic volcanic rocks presented in this study have been subjected to very low- to low-grade metamorphism. Therefore, only relatively immobile elements such as Ti, P, Zr, Y, Nb, Ni, Cr, V, Sc and REE (see Cann, 1970; Pearce and Cann, 1973; Coish, 1977; Floyd and Winchester, 1975; Winchester and Floyd, 1977; Shervais, 1982; Holm, 1985; Whitford et al., 1988), and FeO*/MgO ratio (see Miyashiro,

Table 1
Whole rock analysis of least altered mafic volcanic rocks from the Pak Chom area, Loei, northeastern Thailand

Magmatic group	A	A	B	B	B	C	C	C	C	C
Sample no.	133758	133763	139745	087825	088738	085708	094808	095708	098705	102884
SiO2	51.07	51.76	50.03	50.25	48.87	51.78	56.15	51.56	52.13	59.17
TiO2	1.41	1.32	0.57	1.23	1.13	0.89	0.78	0.87	0.88	0.93
Al2O3	16.04	15.65	11.02	15.15	15.78	17.48	15.93	17.29	17.57	19.63
FeO*	10.54	10.06	10.06	11.61	10.57	9.67	8.20	9.52	9.82	6.62
MnO	0.16	0.17	0.18	0.19	0.16	0.2	0.15	0.19	0.29	0.08
MgO	6.78	6.62	12.38	7.13	10.8	6.98	5.74	6.84	6.99	4.88
CaO	8.7	9.17	13.98	9.71	9.48	7.41	8.66	7.92	5.63	2.09
Na2O	4.39	4.67	1.6	4.45	2.68	3.51	2.79	3.89	5.07	4.6
K2O	0.66	0.36	0.09	0.15	0.4	1.78	1.4	1.65	1.3	1.79
P2O5	0.25	0.22	0.09	0.12	0.14	0.31	0.19	0.28	0.32	0.23
LOI	4.47	3.89	3.85	3.71	3.97	4.13	1.08	4.07	4.1	6.19
FeO*/MgO	1.55	1.52	0.81	1.63	0.98	1.39	1.43	1.39	1.41	1.36
Ba	197	184	99	151	270	955	592	740	775	538
Sr	228	202	55	130	188	614	351	631	573	92
Rb	7	4	4	6	7	33	28	33	27	46
Zr	108	103	40	74	72	84	101	92	90	120
Y	22	19	12	21	16	20	24	19	22	23
Nb	18	19	5	7	9	5	7	3	7	8
Cr	146	132	710	122	450	48	112	48	46	14
Ni	52	44	80	42	178	10	<2	9	12	<2
V	310	250	305	338	260	330	230	320	310	75
Sc	27	35	59	44	39	41	33	39	38	16
Ti/Zr	78	77	85	100	94	63	46	57	59	46
Zr/Nb	6	5	8	11	8	17	14	31	13	15
Zr/Y	5	5	3	4	5	4	4	5	4	5
Nb/Y	0.818	1	0.417	0.333	0.563	0.25	0.292	0.158	0.318	0.348
Ti/V	27	32	11	22	26	16	20	16	17	74

FeO* = total iron as FeO, LOI = loss on ignition. Major elements have been normalized to 100 wt % on the basis of volatile free.

1973, 1975a–c; Beccaluva et al., 1979; Grenne and Roberts, 1980; Crawford and Keays, 1987; Hawkins and Evans, 1983) are taken into consideration.

The least-altered Central Loei mafic volcanic rocks have a wide compositional range in terms of relatively immobile elements and their ratios. They can be separated into three magmatic groups, i.e. Group A basalt (sample nos. 133758 and 133763), Group B microgabbro (sample nos. 139745, 087825 and 088738) and Group C basalt/andesite (sample nos. 085708, 094808, 095708, 098705 and 102884). The rocks classified as Group A and Group B have higher TiO_2, Ni and Cr abundances than those of Group C samples at similar values for FeO* (total iron as FeO)/MgO (Figs. 4 and 5), and also contain higher Ti/Zr ratios relative to those of Group C (Table 1, Fig. 6a). Group A samples are differentiated from Group B samples by their higher P_2O_5 and Nb contents at similar levels of the fractionation parameter (Figs. 4 and 5), and higher Nb/Y (Table 1, Figs. 7 and 8a) and Ti/V values (Table 1, Fig. 6b).

3.2. Group A

Basalts of Group A are greenish grey to dark greenish grey; weathered portions are yellowish brown to moderate brown. They are fine-grained, with microporphyritic texture. Their microphenocrysts include altered plagioclase and olivine with sizes up to 0.3 mm across. The groundmass is made up mainly of altered plagioclase and chloritic materials (largely altered from glass). Plagioclase grains are subhedral–anhedral and partly altered to sericite and epidote; chlorite may occur as an additional alteration product. Olivine exhibits euhedral to subhedral outlines and is totally pseudomorphed by chlorite and serpentine. Secondary fibrous amphibole, pumpellyite, leucoxene, iron sulfides

Table 2
REE analysis of some least altered mafic volcanic samples from the Pak Chom area, Loei, northeastern Thailand

Magmatic group	A	B	C
Sample no.	133758	139745	102884
La	17	13	14
Ce	46	6	30
Nd	15	<5	<5
Sm	3.8	1.5	3.9
Eu	1	0.5	1.5
Tb	0.8	0.4	0.6
Yb	2.1	1.5	2.1
[La/Sm]cn	4.47	2	3.43
[Sm/Yb]cn	1.8	1	1.94
[La/Yb]cn	8.09	2	6.67

cn = chondrite normalized.

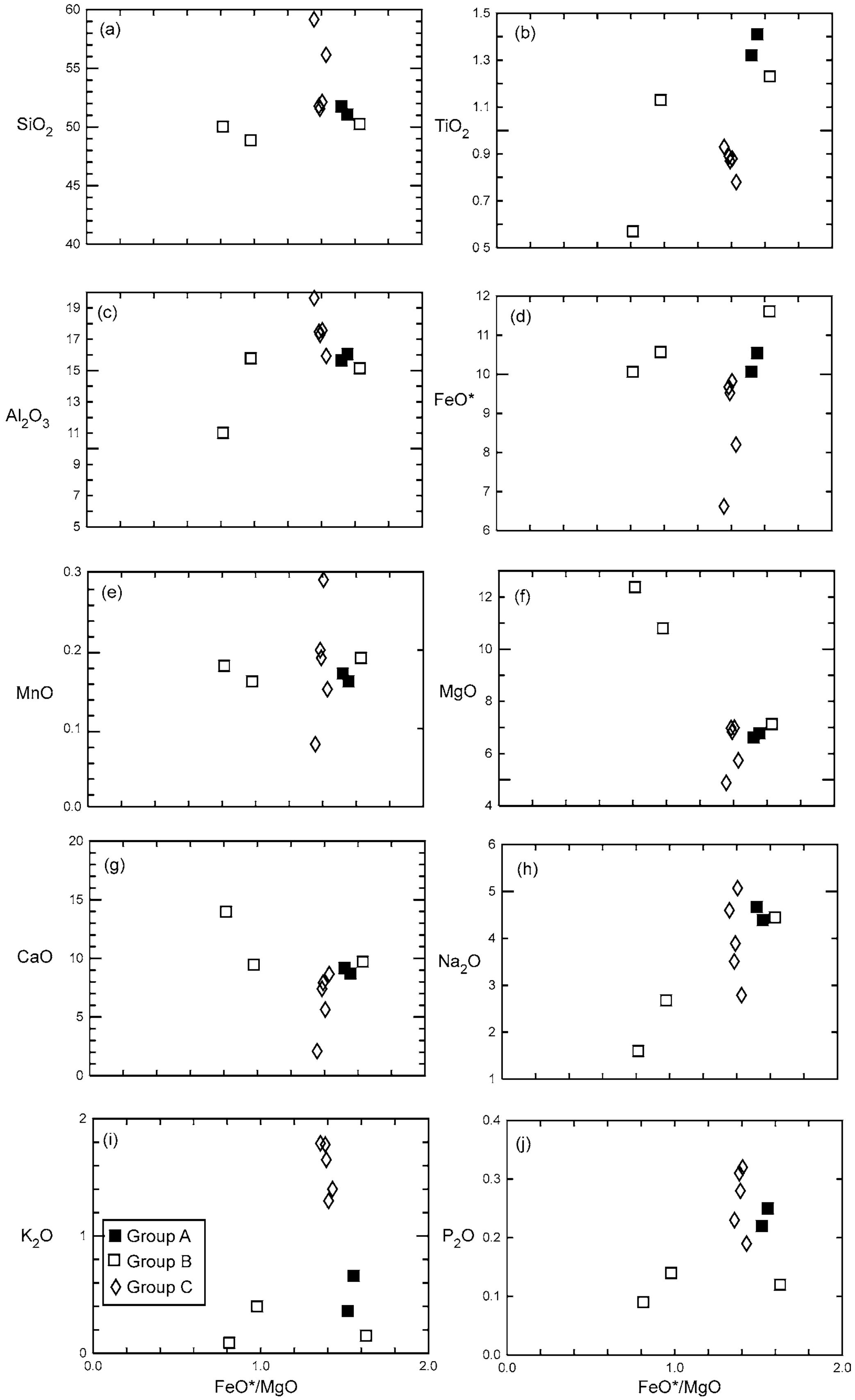

Fig. 4. Variation of major oxides in relation to FeO*/MgO for the least altered central Loei mafic volcanic rocks.

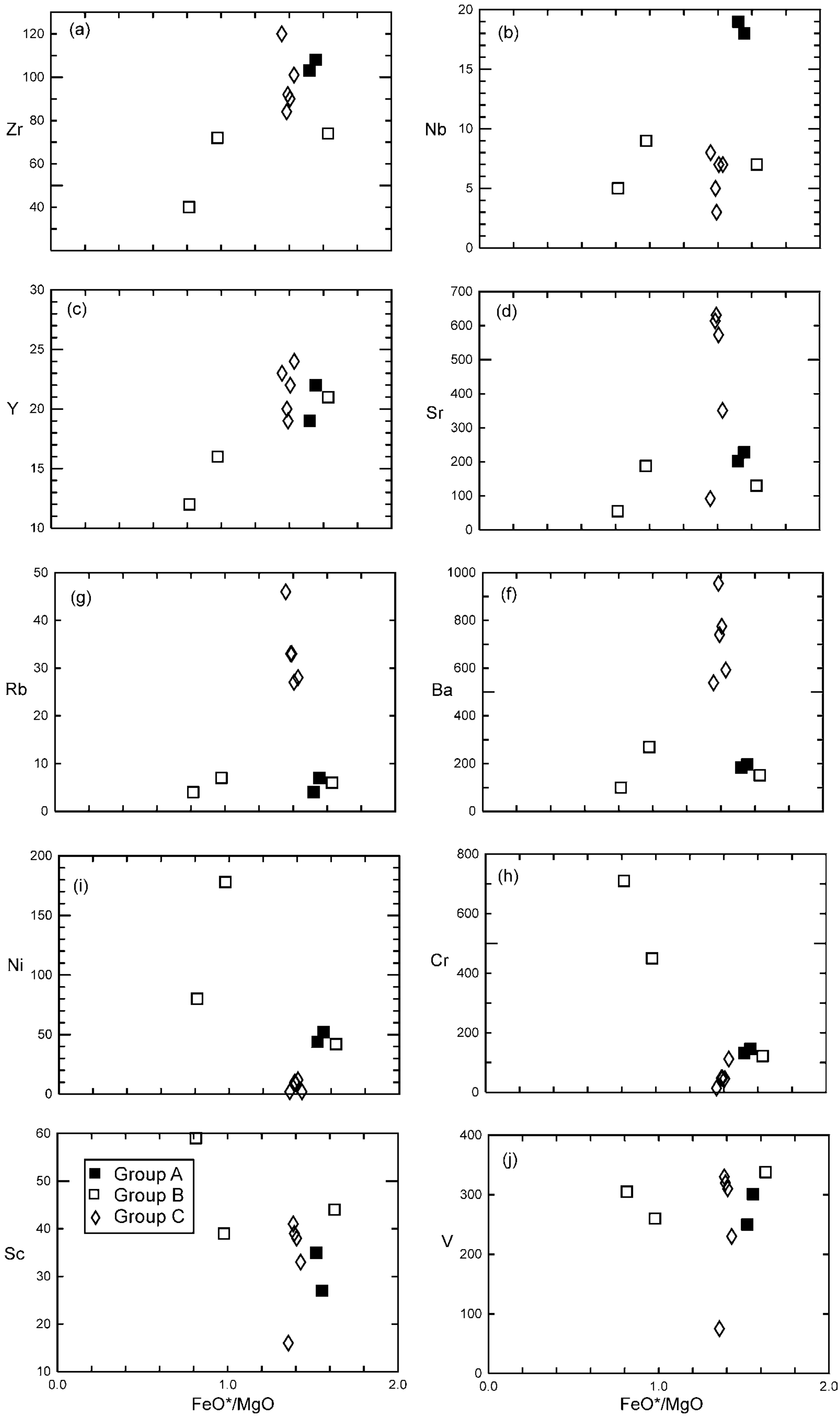

Fig. 5. Variation of trace elements in relation to FeO*/MgO for the least altered central Loei mafic volcanic rocks. Symbols as in Fig. 4.

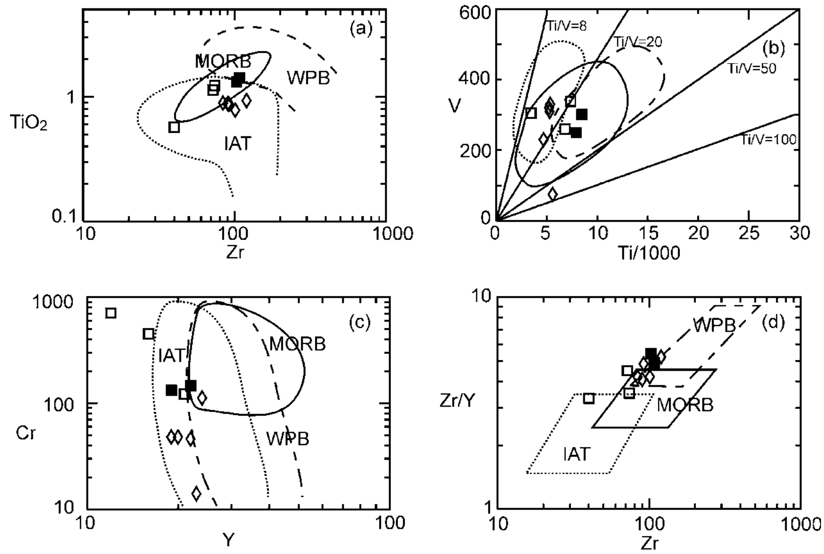

Fig. 6. Plots of (a) TiO_2 against Zr, (b) V against Ti, (c) Cr against Y and (d) Zr/Y against Zr for the least altered central Loei mafic volcanic rocks (symbols as in Fig. 4). Field boundaries of basalts from different tectonic settings in (a) and (c), (b), and (d) are after Pearce (1980), Shervais (1982), and Pearce and Norry (1979), respectively. HA, Hawaiian alkalic basalt: HT, Hawaiian tholeiite; MORB, mid-ocean ridge basalt; BABB, backarc basin basalt; IAT, island arc tholeiite; WPB, within-plate basalt. A chondritic Ti/V ratio of 8 is taken from Nesbitt and Sun (1976).

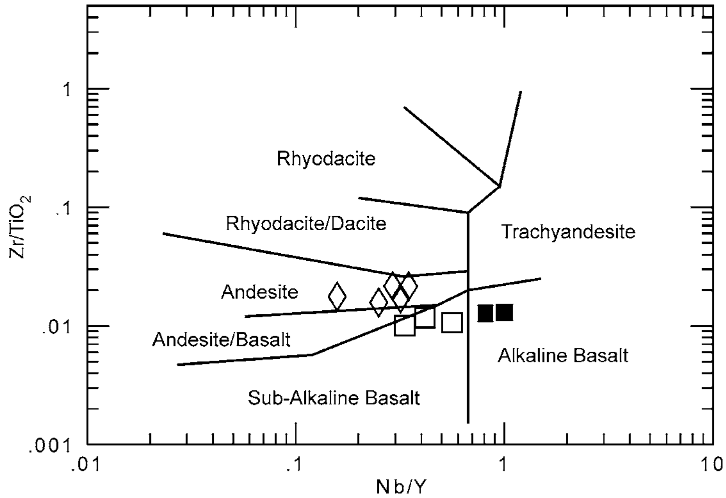

Fig. 7. Variation of Zr/TiO_2 with Nb/Y for the least altered central Loei mafic volcanic rocks. Symbols same as in Fig. 4.

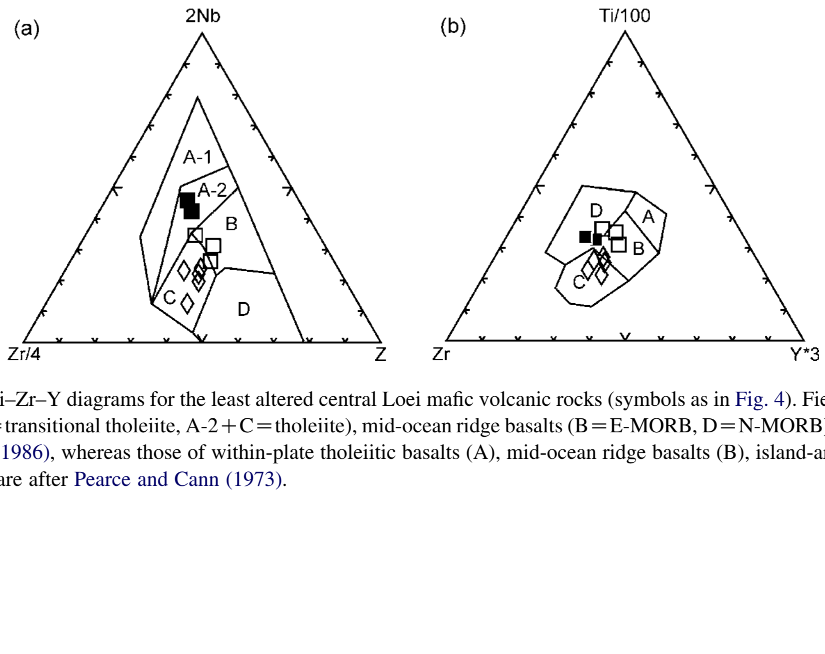

Fig. 8. (a) Nb–Zr–Y and (b) Ti–Zr–Y diagrams for the least altered central Loei mafic volcanic rocks (symbols as in Fig. 4). Fields of within-plate basalts (A-1 + A-2 = alkalic basalt, A-2 = transitional tholeiite, A-2 + C = tholeiite), mid-ocean ridge basalts (B = E-MORB, D = N-MORB) and volcanic arc basalts (C + D) in (a) are after Meschede (1986), whereas those of within-plate tholeiitic basalts (A), mid-ocean ridge basalts (B), island-arc tholeiites (B + C), and calc-alkalic basalts (C + D) in (b) are after Pearce and Cann (1973).

and Fe–Ti oxide (magnetite) are present in small to trace amounts. Tiny vesicles with amygdale zeolites and chlorite occurs locally in minor amounts. The secondary mineral assemblage is indicative of low-grade regional subgreenschist facies metamorphism. The secondary mineral assemblage is indicative of low-grade regional subgreenschist facies metamorphism and deformation, and the effect is possibly related to the Himalayan Orogeny. Recent K–Ar dating of Group A sample (133763) gives an age of 63±24 Ma (Paleocene) (Khin Zaw and Sue Golding, unpublished data, 2001), and this age is consistent with the interpretation.

Although SiO_2 is considered to be a mobile element, the lavas of Group A have SiO_2 (51.07 and 51.76 wt %) in the compositional range of basalt. They plot in the field of alkalic basalts in a Zr/TiO_2–Nb/Y plot (Fig. 7). However, their Nb/Y ratios, 0.818 and 1.000, signify that they could possibly have tholeiitic or alkalic affinities (Pearce and Cann, 1973; Floyd and Winchester, 1975; Pearce, 1982). The transitional nature is supported by their positions in a Nb–Zr–Y diagram (Fig. 8a). These basalts have the following values for relatively immobile elements: TiO_2= 1.32 and 1.41 wt %, P_2O_5=0.22 and 0.25 wt %, Zr=103 and 108 ppm, Y=19 and 22 ppm, Nb=18 and 19 ppm, Ni=44 and 52 ppm, Cr=132 and 146, V=250 and 310 ppm, and Sc=35 and 37 ppm, and limited ratios of least-mobile, incompatible elements (e.g. Ti/Zr=77 and 78, Zr/Nb=5 and 6 and Zr/Y=5), implying that they are all essentially comagmatic. The rare-earth-element (REE) pattern for one sample (Fig. 9) shows relatively flat heavy rare-earth elements (HREEs) (from Yb to Sm) with chondrite-normalized Sm/Yb (herein (Sm/Yb)cn)=1.80, and slight light rare-earth-element (LREE) enrichment (from Sm to La) with chondrite-normalized La/Sm (herein (La/Sm)cn)=4.47.

In terms of empirical diagrams for discriminating tectonic settings of eruption, the rocks are consistent with intraplate basalts on Nb–Zr–Y (Fig. 8a) and Ti–Zr–Y (Fig. 8b) diagrams, mid-ocean ridge basalts (MORB) and backarc basin basalts on the Ti–V plot (Fig. 6b), island arc tholeiites on the Cr–Y diagram (Fig. 6c), and MORB and within-plate basalts on the Zr/Y–Zr diagram (Fig. 6d). The discrepancies might be attributable to the transitional nature of Group A samples. A similar transitional tholeiitic suite from a modern setting may be the enriched mid-ocean ridge basalts (E-MORBs) (sample nos. 410-1 and 413-1) from the North Atlantic (Wood et al., 1979), when ratios of least mobile incompatible elements are taken into consideration, i.e. the REE and normal mid-ocean ridge basalt (N-MORB) normalized multi-element patterns as shown in Figs. 9a and 10a. By comparison, Group A basalts could also be E-MORBs.

3.3. Group B

The Group B microgabbro samples are non-ophitic/subophitic textured (sample no. 139745) and

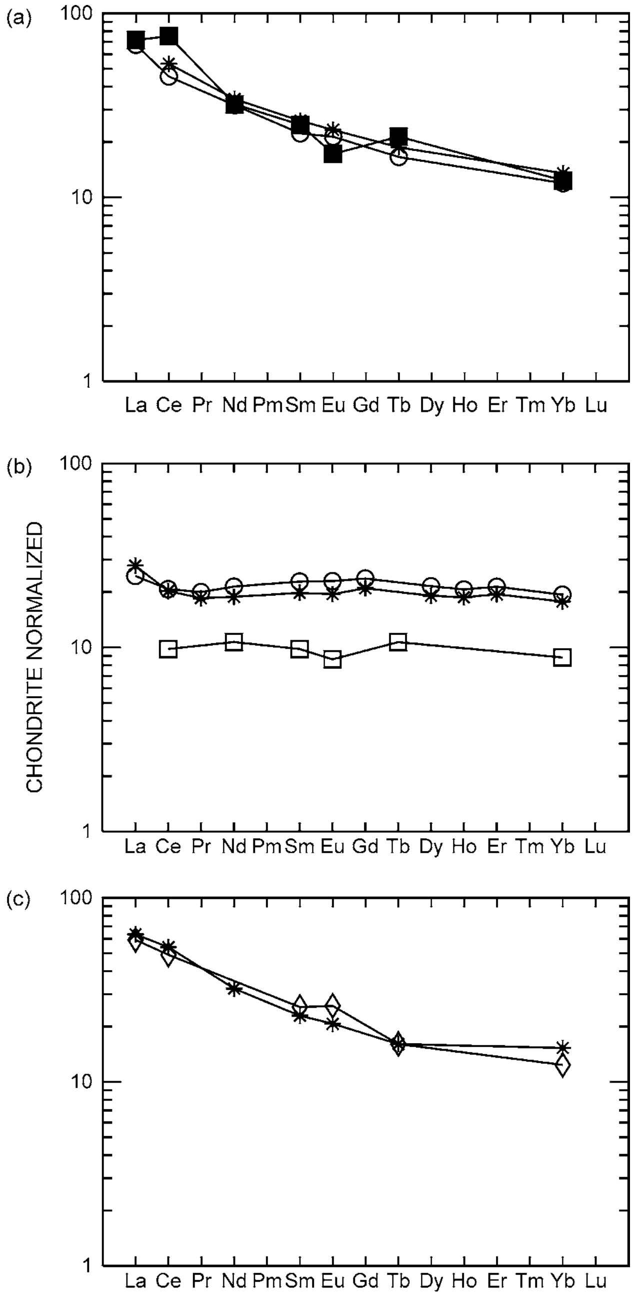

Fig. 9. Chondrite-normalized REE patterns for the representatives of (a) Groups A (sample no. 133758-filled square), (b) B (sample no. 139745-open square) and (c) C (sample no. 102884-diamond). Also plotted are their modern analogs: (a) E-MORBs (sample nos. 410-1-star and 413-1-circle) from the North Atlantic (data from Wood et al., 1979), (b) T-MORBs (sample nos. P 41–49-star and P 20–33-circle) from the Southwest Indian Ridge (data from Le Roux et al., 1989) and (c) a calc-alkalic lava (sample no. 29-star) from the New Britain Arc (data from Johnson and Arculus, 1978). Normalising values are those of Taylor and Gorton (1977).

ophitic/subophitic-textured (sample nos. 087825 and 088738). Petrographic features of individual rock types are separately described below.

The non-ophitic/subophitic textured microgabbro is dark greenish grey (weathered portions: moderate brown)

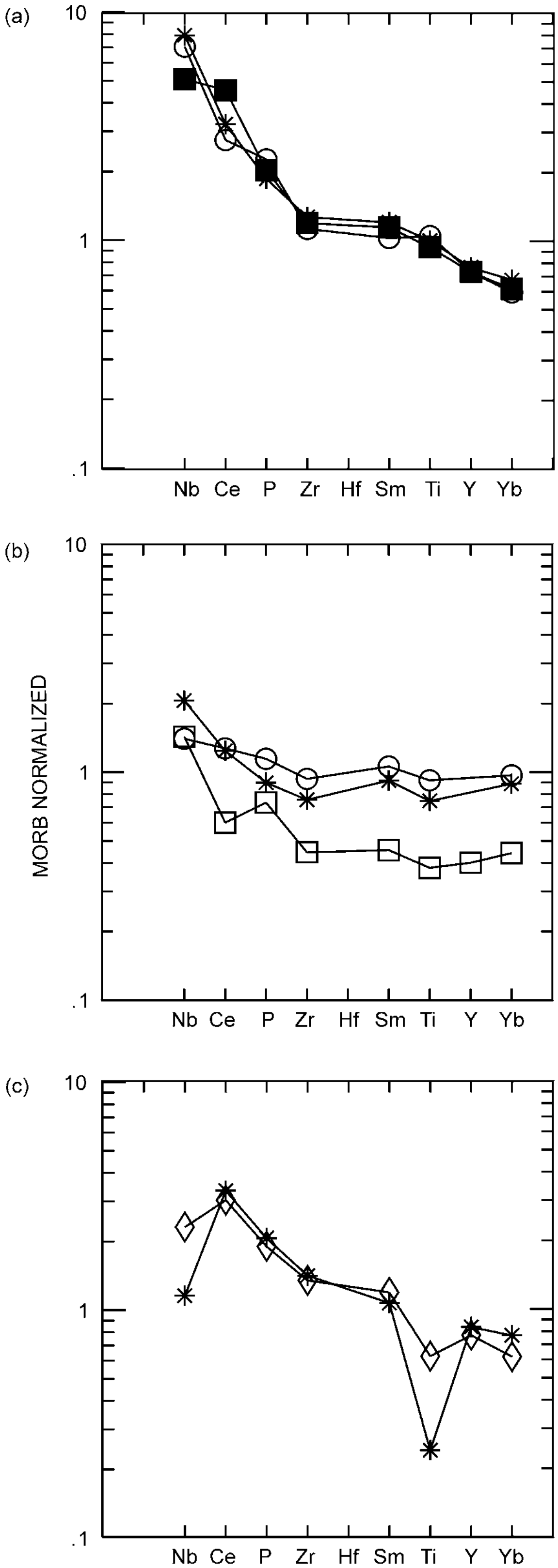

Fig. 10. A subset of the MORB-normalized multi-element diagram of Pearce (1982, 1983) showing the patterns for representatives of (a) Groups A (sample no. 133758-filled square), (b) B (sample no. 139745-open square) and (c) C (sample no. 102884-diamond) compared with those of (a) E-MORBs (sample nos. 410-1-star and 413-1-circle) from the North Atlantic (data from Wood et al., 1979), (b) T-MORBs (sample nos. P 41–49-star and P 20–33-circle) from the Southwest Indian Ridge (data from Le Roux et al., 1989) and (c) a calc-alkalic lava (sample no. 29-star) from the New Britain Arc (data from Johnson and Arculus, 1978). Normalizing values are those of Sun and McDonough (1989).

and exhibits a seriate texture. It is composed predominantly of clinopyroxene (ca. 43.5 modal %) with subordinate plagioclase (ca. 29.0 modal %) and amphibole (ca. 20 modal %), and accessory Fe–Ti oxides. Clinopyroxene occurs either as clusters of grains or as isolated grains. The grains are subhedral to anhedral, with zonal patterns, and are less than 0.6 mm across. Plagioclase grains are largely to be totally replaced by abundant sericite, and minor epidote, pumpellyite and chlorite. Amphibole is light brown to brown hornblende and generally shows euhedral–anhedral outlines. It is commonly altered to chlorite and titanite/leucoxene. Fe–Ti oxides (magnetite) mainly have irregular outlines and are partly altered to leucoxene and hematite. The metamorphic assemblage present is typical of very low- to low-grade regional metamorphism (subgreenschist facies).

The ophitic/subophitic-textured microgabbro samples are medium bluish grey, fine-grained rocks; where weathering has taken place, they turn moderate brown. One sample is non-porphyritic and the other is porphyritic. Phenocrysts/microphenocrysts in the porphyritic sample are of subhedral–anhedral plagioclase with sizes up to 1.3 mm across. The non-porphyritic microgabbro and the groundmass of the porphyritic sample are dominated by plagioclase and clinopyroxene that commonly occur as ophitic/subophitic relationships, with trace Fe–Ti oxide. Plagioclase is partly or largely replaced by sericite, epidote, pumpellyite, titanite/leucoxene and/or clay minerals, whereas clinopyroxenes is partly transformed to chlorite, titanite/leucoxene, quartz and/or epidote minerals. Fe–Ti oxides (magnetite) are mostly irregular, anhedral, and may be partially pseudomorphed by leucoxene and hematite. The metamorphic minerals in these samples are indicative of very low- to low-grade regional metamorphism.

The Group B microgabbro samples have values for TiO_2 (0.57–1.23 wt %), Zr (40–74 ppm), Y (12–21 ppm), Ni (42–178 ppm), Cr (122–710 ppm), V (260–338 ppm) and Sc (39–59 ppm) comparable to those in Group A basalts at similar values for FeO*/MgO (Figs. 4 and 5). However, they contain lower P_2O_5 (0.09–0.14 wt %), Nb (5–9 ppm), Nb/Y (0.33–0.56) and Ti/V (11–26) and higher values for Ti/Zr (85–100) and Zr/Nb (8–11) relative to Group A samples (Figs. 4–6).

The microgabbro samples have Zr/TiO_2 and Nb/Y ratios consistent with subalkalic basalts (Fig. 7). The representative sample for this suite shows a relatively flat chondrite-normalized REE pattern with chondrite-normalized La/Yb = 2 (Fig. 9b). These microgabbros are consistent with MORBs and backarc basin basalts on Ti–V and Nb–Zr–Y diagrams (Figs. 6b and 8a), island-arc tholeiites on the Cr–Y plot (Fig. 6c), arc lavas and MORBs on TiO_2–Zr and Zr/Y–Y diagrams (Fig. 6a and d), and arc tholeiites, mid-ocean ridge tholeiite and within-plate basalts on the Ti–Zr–Y plot (Fig. 8b). These trace element patterns, excluding that on the Cr–Y plot, are suggestive of MORB.

It has been shown that empirical diagrams for discriminating tectonic settings of eruption may often fail to unequivocally classify the tectonic settings of formation for altered lavas (e.g. Holm, 1982; Prestvik, 1982; Duncan, 1987; Myers and Breitkopf, 1989). To avoid this problem, geochemical comparisons between the Group B samples and modern suites have been made to define the tectonic setting. The result shows that the Group B microgabbros are analogous to transitional-type MORBs (T-MORBs) (sample nos. P20–33 and P41–49) from the southwest Indian Ridge (Le Roux et al., 1989) in terms of chondrite-normalized REE (Fig. 9b) and N-MORB normalized multi-element patterns (Fig. 10b).

3.4. Group C

The basaltic/andesitic rocks assigned to Group C are very fine-grained to fine-grained, and have dark greenish grey, green, to medium bluish grey colors. Their weathered surfaces are greenish brown, moderate brown or brownish black. They are slightly to highly porphyritic, and contain clinopyroxene ± plagioclase phenocrysts/microphenocrysts. The matrix consists largely of altered plagioclase and may contain clinopyroxene and chlorite as subordinate constituents, and magnetite (largely as irregular patches), ?hydrogarnet, titanite, leucoxene, epidote, pumpellyite, amphibole, calcite and quartz (both primary interstitial and secondary) as minor to trace constituents. Plagioclase grains have anhedral to euhedral outlines and are partly or almost entirely pseudomorphed by secondary minerals that may include sericite, clay minerals, epidote, calcite and chlorite. Clinopyroxene grains are anhedral to euhedral, and may have chlorite, amphibole, ?hydrogarnet, leucoxene and titanite/calcite as alteration products. Plagioclase and clinopyroxene phenocrysts and microphenocrysts have sizes up to 3 mm across. Some clinopyroxene phenocrysts/microphenocrysts display disequilibrium features (e.g., corroded outlines and rounded edges). Fracture-infillings by minerals such as chlorite, calcite and zeolites are rare.

The Group C basalt/andesite have fairly constant FeO*/MgO (1.36–1.43). However, values for the least-mobile elements, such as TiO_2 (0.78–0.93 wt %), P_2O_5 (0.19–0.32 wt %), Zr (84–120 ppm), Nb (3–8 ppm), Y (19–24 ppm), Ni (<2–12 ppm), Cr (14–112 ppm), V (75–330 ppm) and Sc (16–41 ppm), are variable (Figs. 4 and 5). They have lower values for TiO_2, Ni and Cr, at similar FeO*/MgO, and Ti/Zr (46–63) but higher Zr/Nb (13–31) than the basaltic rocks of Groups A and B (Table 1, Figs. 4 and 5). These basaltic and andesitic rocks have subalkalic affinities as revealed by their Nb/Y ratios (0.16–0.35). The chondrite-normalized REE and N-MORB normalized multi-element patterns of a representative sample (Figs. 9c and 10c) are typical of calc-alkalic basalt/andesite. Consequently, they might have erupted within an oceanic island arc system, active continental margin, incipient backarc basin or post-orogenic environments. The interpretation is in agreement with their positions on Nb–Zr–Y (Fig. 8a), Ti–Zr–Y (Fig. 8b) and TiO_2-Zr (Fig. 6a) diagrams. Their chondrite-normalized REE and N-MORB normalized multi-element patterns are mostly comparable with those of calc-alkalic andesite (sample no. 29) from the New Britain Arc (Johnson and Arculus, 1978) as illustrated in Figs. 9c and 10c, suggesting that they erupted in an oceanic arc environment.

4. Discussion

The mafic volcanic rocks presented in this study are from the Central Loei volcanic sub-belt and occur mainly as pillow basalt, hyaloclastite and pillow breccia that erupted during the Late Devonian–Early Carboniferous; a few formed as dikes that cut through Upper Devonian volcaniclastic rocks. The subaqueous lavas rest unconformably on the Upper Devonian volcaniclastic rocks and Upper Devonian limestone, and are juxtaposed against Upper Devonian–Lower Carboniferous epiclastic strata by thrust faults. The studied rocks can be chemically divided into three magmatic groups, i.e. Group A (transitional tholeiitic basalt), Group B (tholeiitic microgabbro) and Group C (calc-alkalic basalt/andesite). The transitional tholeiitic basalt of Group A and the calc-alkalic basalt/andesite of Group C occur as subaqueous lava flows, whereas all the tholeiitic microgabbro samples of Group B are possibly dike rocks.

Chemical comparisons with modern volcanic suites have been undertaken in terms of chondrite-normalized REE and N-MORB normalized multi-element patterns. The results show that the Groups A and B basaltic rocks have MORB affinities, i.e. the former is analogous to E-MORB from North Atlantic and the latter is very similar to T-MORB from the Southwest Indian Ridge, and the Group C samples are closely comparable to calc-alkalic lavas from the New Britain Arc. Accordingly, it is interpreted that the Central Loei volcanic rocks are comprised of MORBs and oceanic island-arc mafic lavas. This interpretation is in accordance with the inference made by Intasopa and Dunn (1994), except for the additional arc affinity in this study. The MORB affinities might have formed in a major ocean basin or a mature backarc basin as mafic volcanic rocks in the Chiang Rai–Chiang Mai volcanic belt as mentioned by Sashida and Igo (1999). The arc lavas might have erupted on an oceanic basement, as represented by MORB samples.

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, many different tectonic models accounting for the continent–continent (Shan-Thai-Indochina) collision in Thailand and vicinity have been proposed. The widely different opinions reflect both the complex tectonic evolution and inadequate data. Accordingly, detailed studies in various geological aspects should be further carried out to solve the problems.

5. Conclusions

The Loei-Phetchabun-Sra Kaeo volcanic belt in Thailand trends NE–SW from Loei Province through Phetchabun, Nakhon Sawan and Prachinburi Provinces to Sra Kaeo Province. The Loei volcanic rocks can be separated into Eastern, Central and Western sub-belts. The Central sub-belt is composed of pillow basaltic lava, hyaloclastite and pillow breccia with some intrusions. They were formed in the Late Devonian–Early Carboniferous and can be separated into three magmatic groups: Group A (transitional tholeiitic basalt), Group B (tholeiitic microgabbro) and Group C (calc-alkalic basalt/andesite). The transitional tholeiitic basalt of Group A and the calc-alkalic basalt/andesite of Group C occur as subaqueous lava flows, whereas all the tholeiitic microgabbro samples of Group B are possibly dike rocks. Chemically, the transitional tholeittic basalt and tholeiitic microgabbro have higher abundances of TiO_2, Ni and Cr relative to the calc-alkalic basalt/andesite at similar values for FeO*/MgO; they also contain higher Ti/Zr but lower Zr/Nb. The transitional tholeiitic basalt has higher concentrations of P_2O_5 and Nb relative to the tholeiitic microgabbro at similar levels of FeO*/MgO, and also has higher ratios of Nb/Y and Ti/V, but lower values for Ti/Zr and Zr/Nb. In terms of chondrite normalized REE and N-MORB normalized patterns, the transitional tholeiitic basalt, tholeiitic basalt and calc-alkalic basalt/andesite are analogous to those from the North Atlantic, Southwest Indian Ridge and New Britain Arc. The chemical evidence suggest that the Central Loei volcanic rocks consist of MORBs and oceanic island-arc lavas. These arc lavas might have erupted on an oceanic environment, and have an exploration potential for volcanic-hosted massive sulphide (VHMS) deposits of Zn-Cu-Pb-Ag-Ba association.

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