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Petrochemistry and Tectonic Setting of the Middle Triassic Arc-Like Volcanic Rocks in the Sayabouli Area, NW Laos

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ABSTRACT: The volcanic rocks from the Sayabouli area in northwestern Laos have been poorly studied. These volcanic rocks are traditionally mapped as the Permian–Early Triassic sequences on the geological map. One basaltic-andesite from the Sayabouli area yields a zircon U-Pb age of 237.7±1.7 Ma, suggesting a Middle Triassic origin. All basalt and basaltic-andesite samples from the Sayabouli area show depletions in HFSEs (e.g., Nb, Ta, Ti) and have high LILE/HFSE ratios, and exhibit the geochemical affinity to the continental arc volcanic rocks and are geochemically similar to the continental arc volcanic rocks from the Phetchabun belt in northeastern Thailand, suggesting a Late Permian–Middle Triassic continental margin in the Sayabouli area of northwestern Laos and Phetchabun area of northeastern Thailand. Our data indicate that the Phetchabun arc volcanic belt through the western Loei sub-belt can be linked to the Sayabouli area in northwestern Laos.

KEY WORDS: volcanic rock, geochemical characteristics, zircon U-Pb age, Middle Triassic, Sayabouli, northwestern Laos.

0 INTRODUCTION

Pre-Jurassic volcanic rocks occur in many parts of Southeast Asia, they are of significance as they provide petrogenetic constraints on the tectonic and metallogenic evolution of Southeast Asia. In northern Thailand and northwestern (NW) Laos, several important suture zones have been recognized including the Nan suture, the Loei fold belt and the Luang Prabang belt in Laos. Volcanic and plutonic rocks are widely distributed along these belts (Fig. 1a) (Qian et al., 2015; Barr and Charusiri, 2011; Panjasawatwong et al., 2006; Chonglakmani and Helmcke, 2001; Intasopa and Dunn, 1994; Intasopa, 1993; Jungyusuk and Khositanont, 1992; Bunopas and Vella, 1983; Bunopas, 1981). According to the three different tectonic belts, northeastern Thailand and adjacent part of northwestern Laos have tectonically been subdivided into the Indochina Block and Sukhothai terrane (Fig. 1a). Researchers pay more attention to the Nan suture and Loei fold belt in Thailand, but investigations on the Loei fold belt in Laos have not been taken into account due to the lack of large scale geological maps and detail geological surveys. The extension of this belt is still debated. Kamvong et al. (2014) and Zaw et al. (2014) proposed that the Loei fold belt (approx. 50–100 km wide and up to 1 500 km long) is situated between the Indochina Block and the Sukhothai terrane and may extend across western Cambodia up through Central Thailand and into Central Laos (Fig. 1a). In NE Thailand, the volcanic rocks in the Loei fold belt can be separated into eastern, central and western sub-belts (Fig. 1b) (Barr and Charusiri, 2011; Boonsoong et al., 2011; Panjasawatwong et al., 2006). The volcanic rocks of the eastern sub-belt are mainly rhyolites. The central sub-belt is mainly composed of pillow basalts and hyaloclastites. The eastern and central rocks are of Silurian to Early Carboniferous age (Udchachon et al., 2011; Khositanont et al., 2008; Intasopa and Dunn, 1994; Sashida et al., 1993). The western sub-belt is largely andesites and has been interpreted to be the products of arc volcanism, which took place during the Permo–Triassic. Volcanic rocks are also reported in the Phetchabun belt, which is the southern extension of the western Loei sub-belt (Fig. 1b) (Kamvong et al., 2014; Salam et al., 2014; Zaw et al., 2014; Boonsoong et al., 2011; Panjasawatwong et al., 2006; Della-Pasqua and Zaw, 2002; Intasopa, 1993; Jungyusuk and Khositanont, 1992; Bunopas and Vella, 1983; Bunopas, 1981). Qian et al. (2015) recently reported that the Loei fold belt could have extended to the northwestern (NW) Laos and have formed a series of Carboniferous arc-volcanic rocks in the Muang Feuang and Pak Lay areas (Fig. 1b). The 323 to 321 Ma volcanic rocks and 310 Ma granitic rocks from the Phetchabun belt are possibly the

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southern extension of the Carboniferous volcanic rocks in NW Laos (Zaw et al., 2014, 2007; Salam et al., 2014). However, the northern extension of the Permian–Middle Triassic volcanic rocks both in the western Loei sub-belt and Phetchabun belt is undefined. For this reason, a geological survey and comparative study were carried out in the Sayabouli area of NW Laos.

The purposes of this paper are to probe the tectonic setting of the volcanic rocks from the Sayabouli area in NW Laos and provide evidences for the connection of the Loei fold belt between NE Thailand and NW Laos.

1 GEOLOGICAL SETTINGS

Magmatic rocks in NW Laos are mainly composed of basalt, andesite, rhyolite and some mafic extrusive rocks (Fig. 2). Volcanic rocks are characterized by lava flows, pyroclastic and bedrock outputs, and have been crossed by Permian–Early Triassic granite, monzogranite and granodiorite. Some Late Carboniferous granitic and volcanic rocks could be found in the Pak Lay area (Qian et al. 2015). The sedimentary sequences in the study area include the following units: The Early Silurian–Middle Devonian sedimentary package consists of limestone, mudstone and arenite. The Late Devonian–Early Carboniferous sedimentary sequences comprise muddy limestone and mudstone. The Permian–Early Triassic sedimentary rocks comprise dark grey to light grey limestone, siltstone, mudstone and shale (Fig. 2) (DGM, 1990).

Basalt, basaltic-andesite and andesite samples were collected from the riverside of the Mekong River near the Sayabouli area (Fig. 2), which are mapped as Permian–Early Triassic sequences on the geological map (DGM, 1990). The basalt is mainly composed of phenocrysts of plagioclase and clinopyroxene, and matrix of plagioclase. Basaltic andesite is porphyritic with fine-grained matrix with plagioclase and minor clinopyroxene phenocrysts. Clinopyroxene phenocrysts are subhedral and some of them are partly replaced by chlorite. Plagioclase phenocrysts are euhedral to subhedral, tabular-shaped and variable degrees of sericitization (Figs. 3a and 3b). One basaltic-andesite (LS-22-1) (101°48′12″E, 19°24′20″N) is selected for zircon U-Pb dating and five fresh samples for major elements, trace elements and REE analyses.

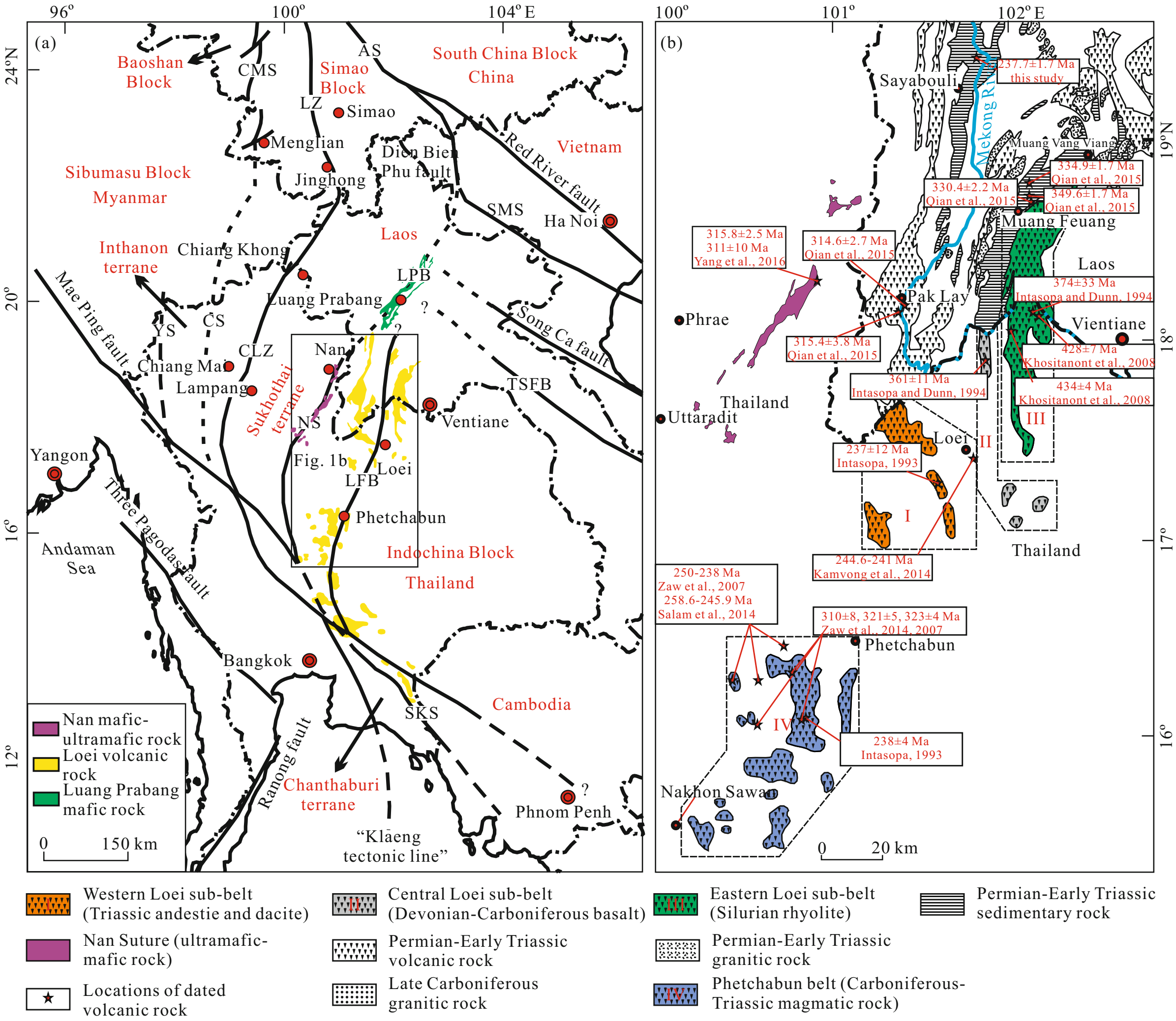

Figure 1. (a) Tectonic map and distribution of the volcanic belts in Laos and NE Thailand (Qian et al., 2015). AS. Ailaoshan-Jingshajiang suture; LB. Lancangjiang belt; CMS. Changning-Menglian suture; SMS. Song Ma suture; TSFB. Truong Son fold belt; LFB. Loei fold belt; LPB. Luang Prabang belt; SKS. Sa Kaeo suture; NS. Nan suture; CLB. Chiang Kong-Lampang-Tak belt; CS. Chiang Mai suture; YS. Yuam suture. (b) Distribution of the Paleozoic and Mesozoic magmatic rocks along the Loei fold belt (modified from Qian et al., 2015; Panjasawatwong et al., 2006; Jungyusuk and Khositanont, 1992; DGM, 1990).

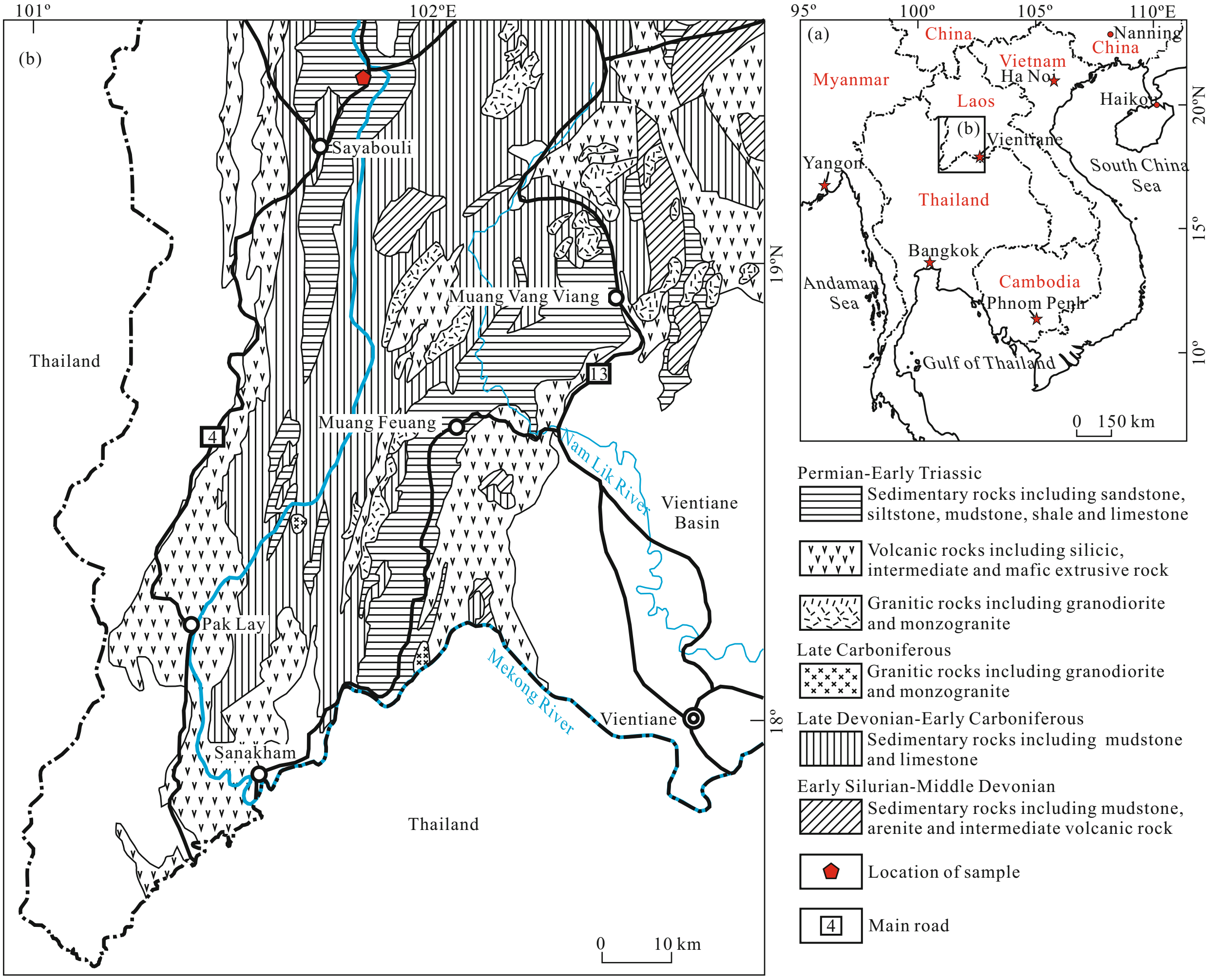

Figure 2. Geographical map (a) and geological map (b) of the study area (modified from DGM, 1990).

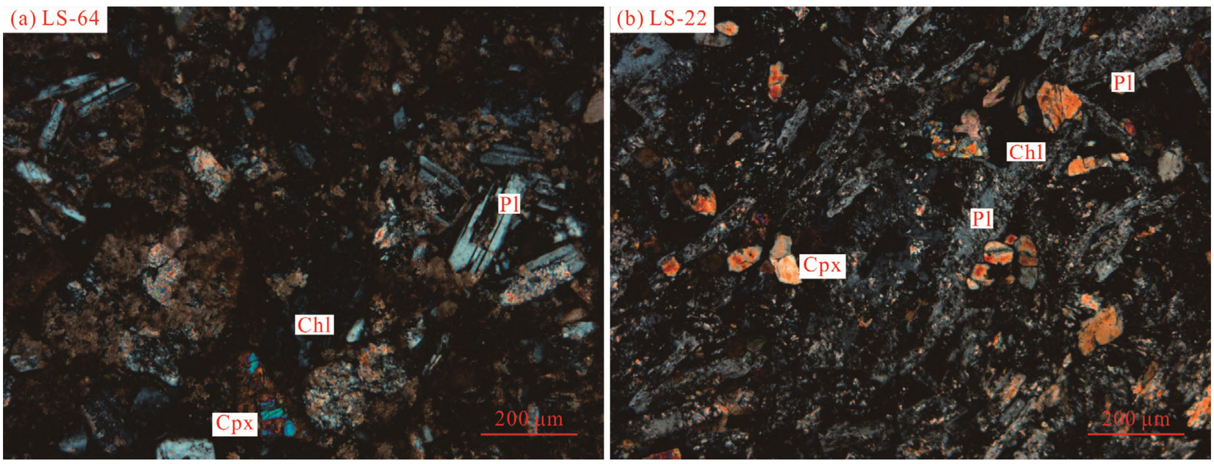

Figure 3. Microscope photographs for the Sayabouli volcanic rocks in NW Laos. (a) Basaltic andesite (LS-64) and (b) basaltic andesite (LS-22-1). Chl. chlorite; Pl. plagioclase; Cpx. clinopyroxene.

2 ANALYTICAL METHODS

Zircons were separated from the sample (LS-22-1) by standard techniques, mounted in epoxy, and polished. Optical microscopy and cathodoluminescence (CL) images outlined the morphology and internal structure of the grains. CL images were obtained on a JEOL JXA-8100 electron microprobe. Zircon U-Pb dating was undertaken on an LA-ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan. The detailed analytical procedure followed Yuan et al. (2004) and involved a 193 nm Geolas 2005M laser-ablation system coupled to an Agilent 7500a ICP-MS. Helium was used as the carrier gas to enhance the transport efficiency of the ablated material. The sport diameter was 32 μm. The data acquisition mode involved peak jumping and raw count rates were measured for ^{29}Si, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, and ^{235}U, U, Th and Pb concentrations were calibrated using ^{29}Si as an internal standard and NIST SRM 610 as reference standard. Each analysis consists of 30 s gas blank and 40 s signal acquisition. Off-line selection and integration of background, analyte signals, time-drift correction, and quantitative calibration were conducted by ICPMSDataCal (Liu et al., 2010a, b). Common Pb correction was in accordance with the method of Andersen (2002). U-Pb ages and concordia diagrams were prepared using ISOPLOT3.00 (Ludwig, 2003). All measurements were normalized relative to standard zircon GJ-1 and 91500. Individual analyses in the data table and concordia plots are presented with 1σ errors, and uncertainties in ages are quoted at the 95% confidence level (2σ). The analytical results are listed in Table 1.

Five fresh samples were powdered into 200 meshes for elemental analysis. All samples were processed at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan. Major elements were analyzed by XRF method, the analysis precision is generally better than 5%. Trace elements and REE analysis were carried out by an Agilent 7500a ICP-MS. The analytical precision is better than 5% for elements >10 ppm, less than 8% for those <10 ppm, and 10% for transition metals. The analytical results for the typical samples are shown in Table 2.

3 RESULTS

3.1 LA-ICP-MS Zircon Age

The LA-ICP-MS zircon U-Pb analytical results for the basaltic-andesite sample (LS-22-1) are shown in Table 1. ^{206}Pb/^{207}Pb ages were used for older (>1 000 Ma) zircon grains, and ^{206}Pb/^{238}U ages were used for younger zircons. Most grains are transparent, euhedral and light brown with elongation ratios varying from 1.5 : 1 to 3 : 1. Zircons exhibit oscillatory magmatic zoning in CL images (Wu and Zheng, 2004; Corfu et al., 2003) (Fig. 4). Th and U concentrations of 22 spots give a relatively wide range from 74 ppm to 454 ppm and 102 ppm to 2 846 ppm, respectively. Their Th/U ratios range from 0.14 to 0.89. Twelve spots yield a weighted ^{206}Pb/^{238}U mean age of 237.7±1.7 Ma (MSWD=1.5) (Fig. 4), representing the formation age of the basaltic andesite. The apparent ages of the remaining spots range from 308 to 1 856 Ma, most zircon grains of these older ages exhibit oscillatory magmatic zoning (Fig. 4), which can be interpreted as the ages of the xenocrysts.

3.2 Geochemical Characteristics

Major and trace element compositions of all samples are listed in Table 2. All major oxides are volatile-free normalized to 100%. In addition, the data of volcanic rocks in the Phetchabun belt are selected from Boonsoong et al. (2011) and Intasopa (1993).

Five samples from the Sayabouli area are basalt and basaltic andesite with 49.99 wt.%–56.87 wt.% of SiO_2, 4.80 wt.%–7.52 wt.% of MgO and are characterized by low TiO_2

Table 1 LA-ICP-MS zircon U-Pb data of the Sayabouli volcanic rocks

Spot No.	Concentration		Th/U	Isotope ratio						Calculated apparent age (Ma)					
	Th	U		^{207}Pb/^{206}Pb		^{207}Pb/^{235}U		^{206}Pb/^{238}U		^{207}Pb/^{206}Pb		^{207}Pb/^{235}U		^{206}Pb/^{238}U	
	(ppm)			Ratio	1σ	Ratio	1σ	Ratio	1σ	Age	1σ	Age	1σ	Age	1σ
LS22-1-1	205	301	0.68	0.055 94	0.001 51	0.453 64	0.011 64	0.058 88	0.000 71	450	36	380	8	369	4
LS22-1-2	184	373	0.49	0.050 52	0.001 66	0.263 73	0.008 69	0.037 68	0.000 36	219	59	238	7	238	2
LS22-1-3	345	601	0.57	0.054 74	0.002 97	0.287 49	0.015 40	0.038 09	0.000 33	402	125	257	12	241	2
LS22-1-4	454	701	0.65	0.051 92	0.001 40	0.266 26	0.006 95	0.037 16	0.000 29	282	45	240	6	235	2
LS22-1-5	318	598	0.53	0.051 20	0.001 27	0.269 20	0.006 66	0.038 21	0.000 48	250	34	242	5	242	3
LS22-1-6	197	397	0.50	0.052 29	0.001 50	0.274 90	0.008 28	0.038 06	0.000 47	298	46	247	7	241	3
LS22-1-7	210	731	0.29	0.064 01	0.001 11	1.119 93	0.019 03	0.126 70	0.000 78	742	25	763	9	769	4
LS22-1-8	138	581	0.24	0.052 04	0.001 46	0.267 82	0.007 39	0.037 35	0.000 28	287	50	241	6	236	2
LS22-1-9	388	2 846	0.14	0.056 18	0.001 18	0.289 83	0.005 40	0.037 42	0.000 37	459	48	258	4	237	2
LS22-1-10	238	807	0.29	0.052 78	0.001 91	0.275 04	0.009 55	0.037 79	0.000 39	319	84	247	8	239	2
LS22-1-11	182	498	0.36	0.114 23	0.002 20	5.223 34	0.090 23	0.331 65	0.002 81	1 868	36	1 856	15	1 846	14
LS22-1-12	312	772	0.40	0.056 23	0.001 26	0.285 59	0.006 58	0.036 73	0.000 27	461	38	255	5	233	2
LS22-1-13	98	303	0.32	0.084 49	0.001 34	2.394 22	0.055 67	0.204 46	0.003 54	1 304	21	1 241	17	1 199	19
LS22-1-14	181	234	0.77	0.062 87	0.001 32	1.109 71	0.023 96	0.127 65	0.001 05	704	32	758	12	774	6
LS22-1-15	356	806	0.44	0.054 36	0.001 17	0.368 15	0.008 09	0.048 93	0.000 36	386	36	318	6	308	2
LS22-1-16	144	755	0.19	0.051 37	0.001 36	0.268 98	0.006 90	0.037 93	0.000 33	258	43	242	6	240	2
LS22-1-17	328	544	0.60	0.063 29	0.001 08	1.046 96	0.019 01	0.119 58	0.001 04	718	24	727	9	728	6
LS22-1-18	253	1 101	0.23	0.051 45	0.001 00	0.267 80	0.005 43	0.037 63	0.000 29	261	32	241	4	238	2
LS22-1-19	113	344	0.33	0.056 43	0.001 64	0.398 81	0.010 93	0.051 53	0.000 55	469	42	341	8	324	3
LS22-1-20	74	102	0.73	0.111 44	0.004 16	5.130 59	0.196 36	0.333 53	0.005 21	1 823	47	1 841	33	1 855	25
LS22-1-21	187	209	0.89	0.066 87	0.001 87	1.228 89	0.035 92	0.132 98	0.001 59	834	41	814	16	805	9
LS22-1-22	85	165	0.52	0.050 60	0.002 63	0.256 82	0.013 47	0.037 01	0.000 57	223	93	232	11	234	4

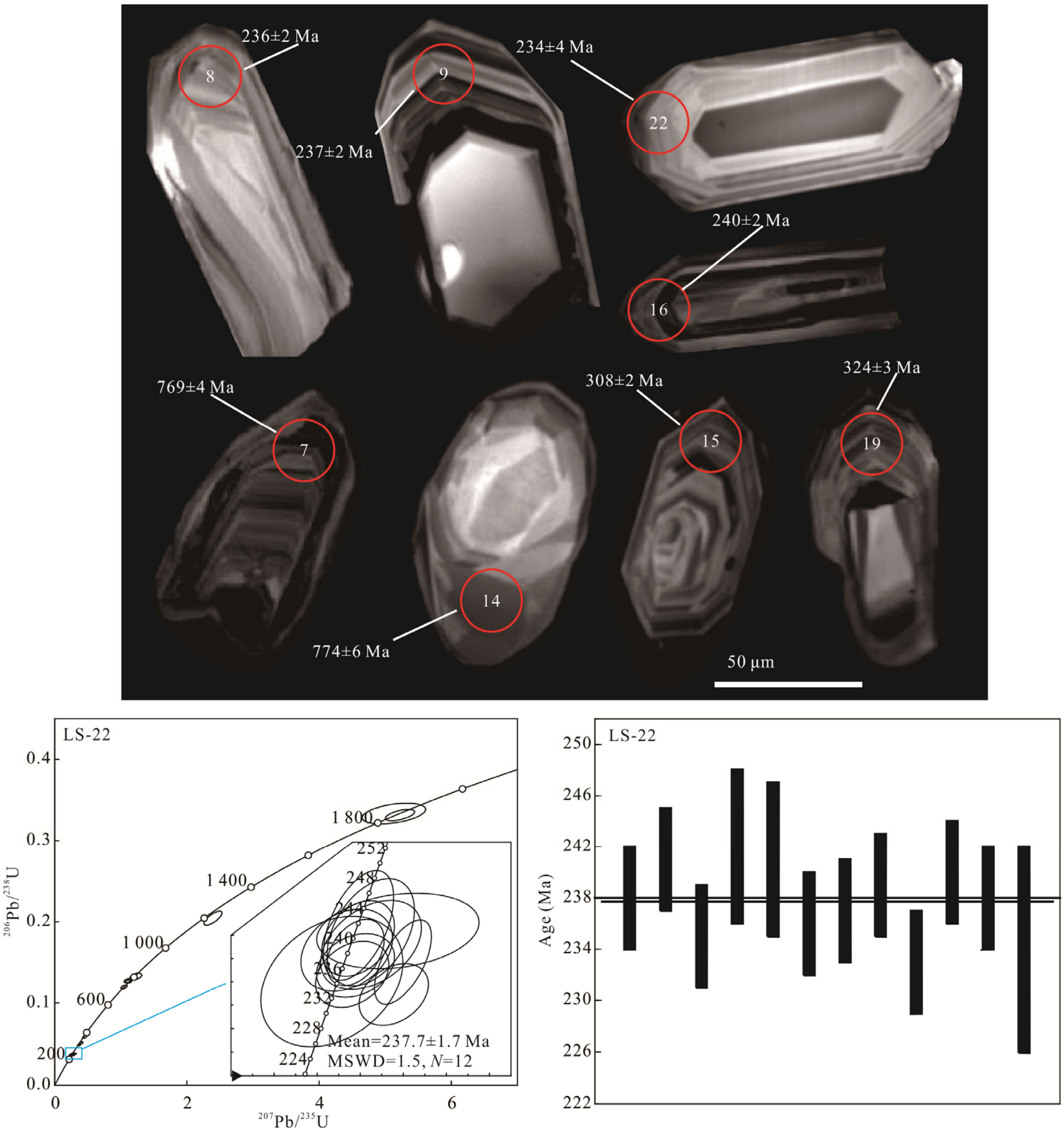

Figure 4. Cathodoluminescence (CL) images and LA-ICP-MS zircon U-Pb concordia diagram for the Sayabouli volcanic rocks (sample LS-22-1) in NW Laos.

(0.52 wt.%–1.44 wt.%), Mg# (molar Mg×100/(Mg+Fe)=52–59 and high Al_2O_3 content (14.55 wt.%–22.96 wt.%). In the Co-Th diagram (Fig. 5a) (Hastie et al., 2007), these samples fall in the field of basalt or basaltic andesite, and in the Nb/Y-Zr/TiO_2 diagram (Fig. 5b) (Winchester and Floyd, 1977), these samples fall in the field of sub-alkaline basalt with one sample in the field of andesite/basalt. In the SiO_2-K_2O diagram (Fig. 5c) (Le Maitre et al., 1989), samples plot in the fields of low-K calc-alkaline to medium-K calc-alkaline series.

Volcanic rocks from the Sayabouli area show similar chondrite-normalized REE patterns (Fig. 6a) and have moderately fractionated light rare-earth elements (LREEs) relative to heavy rare-earth elements (HREEs), with La_N/Yb_N (N herein refers to chondrite-normalized value)=2.55–6.71. The Gd_N/Yb_N ratios range from 1.48 to 2.00 and Eu/Eu* ratios range from 0.91 to 1.13 (Fig. 6a). In the primitive mantle-normalized multielement spidergram (Fig. 6b), these samples show depletions in Nb, Ta and Ti and high LILE/HFSE ratios, similar to those of arc volcanic rocks (Tatsumi and Maruyama, 1989). Nb_N/La_N ratios are in the range of 0.15–0.70, indicative of a geochemical affinity to arc volcanic rocks and are geochemically similar to continental arc volcanic rocks from the Phetchabun belt (Boonsoong et al., 2011; Intasopa, 1993). However, compared with those of typical continental arc volcanic rocks from the Lancangjiang tectonic zone (Peng et al., 2008), these samples exhibit lower Th/Nb (0.17–1.24), Th/Yb (0.34–1.83) and higher La/Ta (20.67–107.50) ratios. All samples both from the Sayabouli area and Phectchabun belt have lower Nb and Ta contents and higher Th/Nb, Th/Yb and La/Yb ratios than those of average MORB (Sun and McDonough, 1989).

4 DISCUSSION

4.1 Age of Volcanic Rocks in Sayabouli Area

The LA-ICP-MS zircon U-Pb age of the basaltic-andesite sample from the Sayabouli area yields a crystallization age of 237.7±1.7 Ma at Middle Triassic, representing the formation age of the volcanic rocks. Intasopa (1993) firstly reported the similar age of 237±12 Ma for the andesite from the western

Table 2 Major and trace element analytical data for the Sayabouli and Phetchabun volcanic rocks

Sample	LS-22-1	LS-22-2	LS-27-1	LS-64	LS-4
Major oxide (wt.%)					
SiO_2	51.65	50.85	48.12	55.26	51.06
TiO_2	0.51	0.52	0.89	1.40	0.63
Al_2O_3	20.52	22.38	18.18	17.94	14.17
$Fe_2O_3^T$	8.27	7.49	9.09	12.25	9.79
MnO	0.15	0.13	0.12	0.22	0.17
MgO	5.23	4.68	6.48	5.51	7.32
CaO	6.23	7.10	8.22	1.98	9.4
Na_2O	4.14	3.20	4.11	2.57	4.23
K_2O	1.44	1.41	0.91	0.79	0.26
P_2O_5	0.21	0.20	0.14	0.23	0.34
LOI	2.21	2.50	4.09	3.40	2.98
Mg#	56	55	59	47	60
Total	100.55	100.47	100.35	101.57	100.35
Trace element (ppm)					
Ba	245	221	64	128	50
Rb	25.4	27.6	12.5	12.2	1.1
Sr	883	899	717	423	808
Y	11.50	13.60	13.10	18.20	14.40
Zr	60.3	60.7	38.7	91.2	61.8
Nb	4.84	4.85	2.05	6.47	2.04
Th	1.08	1.12	0.39	1.13	2.53
Ni	24	16	35	62	51
V	105	110	232	215	235
Cr	20	18	34	178	178
Hf	1.54	1.55	1.18	2.31	1.63
Sc	14.40	13.90	36.10	24.80	30.70
Ta	0.31	0.32	0.12	0.43	0.12
U	0.48	0.54	0.11	2.65	1.02
La	7.38	9.57	4.12	8.89	12.90
Ce	15.00	14.90	10.20	19.60	27.40
Pr	2.11	2.07	1.53	2.73	3.61
Nd	9.48	9.19	7.67	11.60	16.00
Sm	2.20	2.15	2.14	2.90	3.74
Eu	0.82	0.82	0.81	1.02	1.07
Gd	2.31	2.24	2.38	3.14	3.33
Tb	0.37	0.36	0.38	0.50	0.47
Dy	2.11	2.07	2.44	3.18	2.67
Ho	0.41	0.40	0.47	0.67	0.50
Er	1.16	1.15	1.31	1.83	1.41
Tm	0.16	0.16	0.18	0.27	0.21
Yb	1.13	1.15	1.16	1.75	1.38
Lu	0.19	0.18	0.17	0.27	0.19
∑REE	44.83	46.41	34.96	58.35	74.88
Eu/Eu*	1.10	1.13	1.09	1.03	0.91
La_N/Yb_N	4.68	5.97	2.55	3.64	6.71
Gd_N/Yb_N	1.69	1.61	1.70	1.48	2.00
Nb_N/La_N	0.63	0.49	0.48	0.70	0.15

$Fe_2O_3^T$ represents total Fe-oxides; Mg#=molar Mg×100/(Mg+Fe); LOI. loss on ignition.

Loei sub-belt and 238±4 Ma for the andesite from the Phetchabun belt in NE Thailand. Our age is similar to the Middle Triassic ages of 247–238 Ma magmatic rocks from the Phetchabun belt and 246–241 Ma magmatic rocks from the western Loei sub-belt (Table 3, Fig. 1b) (Kamvong et al., 2014; Salam et al., 2014; Zaw et al., 2007). Ten older ages from 308 to 1 868 Ma are given in the sample, which can be interpreted as the ages of xenocryst zircons.

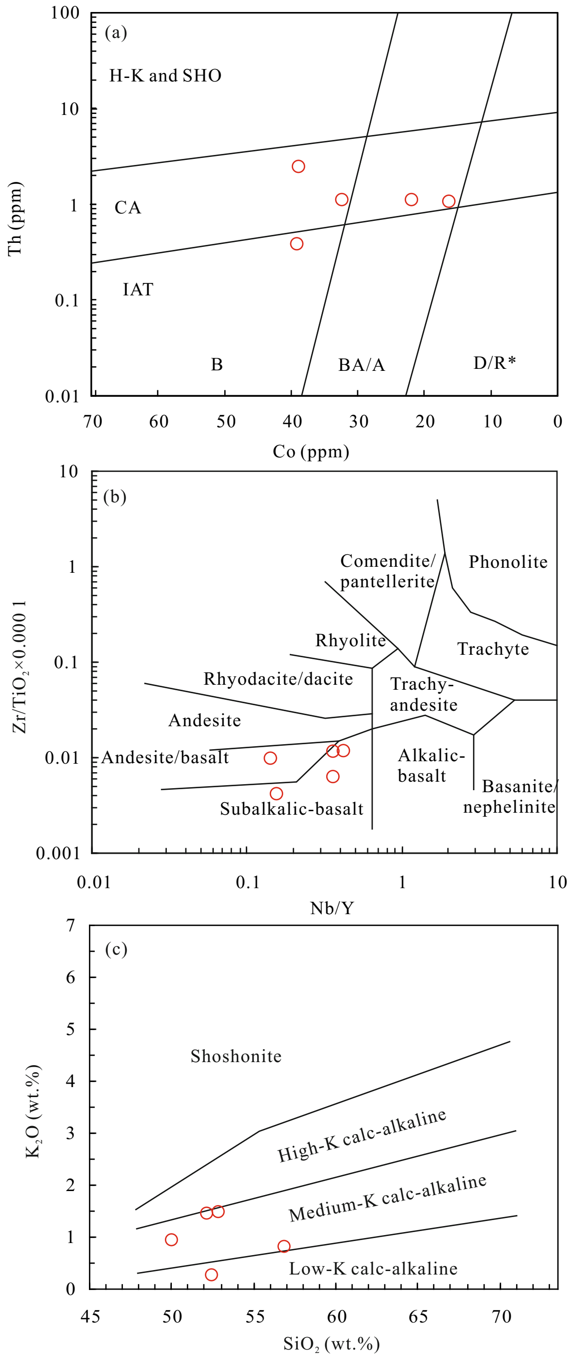

Figure 5. Co-Th (a) (Hastie et al., 2007), Nb/Y-Zr/TiO_2 (b) (Winchester and Floyd, 1977) and SiO_2-K_2O (c) (Le Maitre et al., 1989) diagrams for the Sayabouli volcanic rocks in NW Laos. CA. calc-alkaline; H-K. high-K calc-alcaline; SHO. shoshonite; IAT. island-arc tholeiite; B. basalt; BA/A. basaltic andesite and andesite; D/R*. dacite and rhyolite (* indicates that latites and trachytes also fall in the D/R fields).

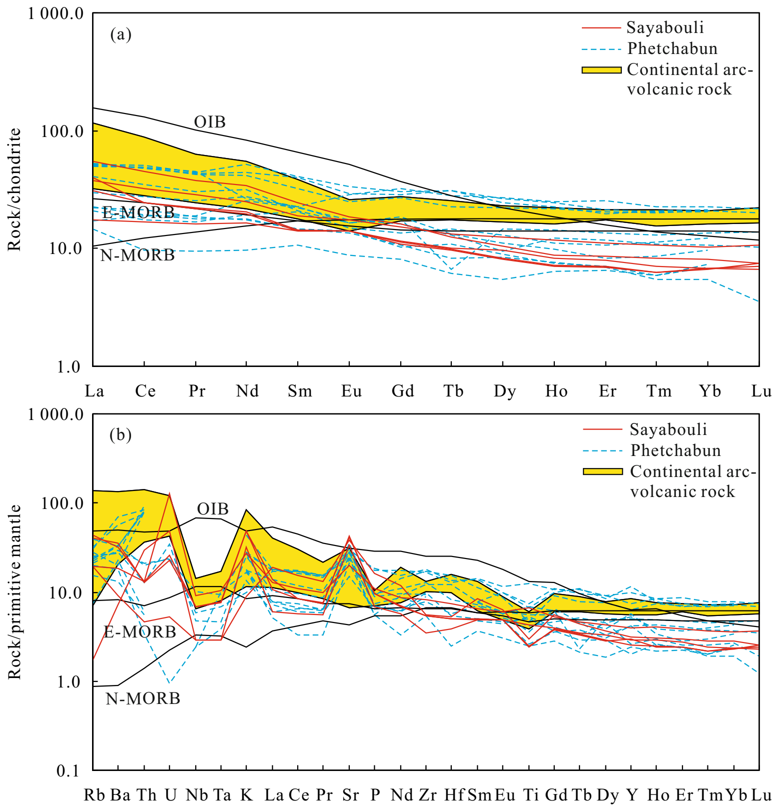

Figure 6. Chondrite-normalized REE patterns and primitive mantle normalized trace element spider diagram for the Sayabouli volcanic rocks in NW Laos. The N-MORB, E-MORB, OIB, normalized values for chondrite and primitive mantle are from Sun and McDonough (1989). Data of continental arc volcanic rocks are from Peng et al. (2008). Data of the Phetchabun volcanic rocks are from Boonsoong et al. (2011) and Intasopa (1993).

4.2 Source Characteristics and Tectonic Setting

The samples analyzed in this study have LOI contents of 2.21 wt.%–4.09 wt.%, showing weak weather alteration. Discussion of their source characteristics herein focuses on the high field strength elements (e.g., Nb, Ta, Zr, Th, Ti, Y and REE).

As mentioned above, five samples from the Sayabouli area exhibit arc geochemical characteristics, e.g., low TiO_2, Ni, Cr and higher Al_2O_3 contents, and a marked enrichment in LILEs and LREEs and depletions in HFSEs, suggesting their formation being under an arc setting. In comparison with those of the typical continental arc volcanic rocks from the Lancangjiang tectonic zone (Peng et al., 2008), these volcanic samples from the Sayabouli area have lower Th/Nb, higher Th/Yb and higher La/Ta ratios. All samples both from the Sayabouli and Phetchabun areas have lower Sm/Th (0.20–11.66) and higher Th/Y (0.02–0.73) ratios than the normal mid-ocean ridge basalts (N-MORB) (Fig. 7a), suggesting an enriched mantle source. The enriched process of the mantle was probably associated with the interaction of a depleted mantle with fluid/melt released from the down-going slab or sediment. All samples from the Sayabouli and Phetchabun areas have variable Ba/Th (19.84–437.93), Ba/La (3.89–71.54) and Ba/Nb (19.78–116.90) ratios and constant $(La/Sm)_N$ (0.40–2.87) (Figs. 7b and 7c) (Su et al., 2012), suggesting significant enrichment of slab-derived fluid in the source and negligible involvement of sediments. Most samples from the Sayabouli and Phetchabun areas are plotted in the field of plate-margin basalt in the Zr/Y-Ti/Y diagram (Fig. 8a) (Pearce and Gale, 1977). In the Nb/Yb-Th/Yb discrimination diagram (Fig. 8b) (Pearce and Peate, 1995), most samples plot in the field of continental arcs. In the Nb×2-Zr/4-Y diagram (Fig. 8c) (Meschede, 1986), all samples fall in the field of volcanic arc basalt. In the Hf/3-Th-Nb/16 diagram (Fig. 8d) (Wood, 1980), samples from the Sayabouli area fall in the field of island-arc basalt. All these features suggest a continental arc setting for the generation of these volcanic rocks both in the Sayabouli and Phetchabun areas.

4.3 Tectonic Implications

In the western margin of Indochina Block, tectonic evolution was complex and it would be possibly more than a single suturing process, including Nan suture and Loei fold belt (Chonglakmani and Helmcke, 2001). In NE Thailand, volcanic rocks in the Loei fold belt can be separated into eastern, central, and western sub-belts (Fig. 1b) (Barr and Charusiri, 2011; Boonsoong et al., 2011; Panjasawatwong et al., 2006). The arc-related rhyolite samples of eastern sub-belt yielded a whole-rock Rb-Sr isochron age of 374±33 Ma (Late Devonian) (Intasopa and Dunn, 1994) and U-Pb zircon ages of 434±4 and 425±7 Ma (Table 3) (Late Silurian) (Khositanont et al., 2008). These arc-like rhyolites in the eastern sub-belt may have formed in an older volcanic arc, which led to the spread of the Loei ocean basin/back-arc basin (Boonsoong et al., 2011; Intasopa and Dunn, 1994; Intasopa, 1993). Panjasawatwong et al. (2006) reported that the mafic rocks from the central sub-belt are mid-ocean ridge basalts and island-arc mafic lava which have been built on an oceanic basement in a major ocean or in a mature back-arc basin (Boonsoong et al., 2011), and have a whole-rock Rb-Sr isochron age of 361±11 Ma (Late Devonian) (Table 3) (Intasopa and Dunn, 1994). In addition, the volcanic rocks in the western sub-belt and Phetchabun belt have been geochemically interpreted as the products of volcanism along an active continental margin (Zaw et al., 2014; Salam et al., 2014; Boonsoong et al., 2011; Marhotorn et al., 2008; Tangwattananukul et al., 2008). Kamvong et al. (2014) acquired 244 to 241 Ma zircon ages (Table 3) for the Puthep adakites in the western sub-belt and suggested that the Puthep adakites formed in the initial stage of subduction during the Early Triassic and corresponded to the eastward subduction of a slab beneath the western Indochina Block. Salam et al. (2014) acquired 259 to 246 Ma zircon ages (Table 3) of the volcanic rocks in the Phetchabun belt and suggested that these volcanic rocks can be divided into two suites, the Late Permian suite 1 units probably formed immediately after the beginning of subduction and at the creation of a new island arc. The Early Triassic suite 2 units were erupted during ongoing subduction. Zaw et al. (2014) and Shen et al. (2010) suggested that the Permian–Middle Triassic volcanic rocks both from the western Loei sub-belt and Phetchabun belt in Thailand may have formed in the subduction of the Nan ocean/back-arc basin. Moreover, Yang et al. (2016) acquired 311 to 316 Ma zircon ages for the MORB-like gabbro and meta-basalt in the Nan suture and thought that the closure of Nan ocean/back-arc basin may have occured after the Middle Triassic.

In NW Laos, the volcanic rocks have been barely explored and were traditionally mapped as Permian–Early Triassic sequences. The study area is also concentrated in the Pak Lay area, which was named as the Pak Lay fold belt (Stokes et al., 1996). Stokes et al. (1996) suggested that the volcanic rocks from the Pak Lay area are arc-related, they also acquired 167 to 152 and 227 to 210 Ma ages with whole-rock K-Ar analyses, and suggested that the arc-related volcanism continued from the Triassic into the Late Jurassic and the suturing between the

Table 3 Dating results for the Silurian to Middle Triassic magmatic rocks in the Loei fold belt and Nan suture

Location	Lithology	Age±1σ	Method	Reference
Eastern sub-belt	Rhyolite	374±33 Ma	Rb-Sr whole rock	Intasop and Dunn, 1994
Eastern sub-belt	Tuff	428±7 Ma	LA-ICP-MS	Khositanont et al., 2008
Eastern sub-belt	Tuff	434±4 Ma	LA-ICP-MS	Khositanont et al., 2008
Central sub-belt	Basalt	361±11 Ma	Rb-Sr whole rock	Intasopa and Dunn, 1994
Western sub-belt	Andesite	237±12 Ma	Ar-Ar	Intasopa, 1993
Western sub-belt	Adakites	241±1.9 Ma	LA-ICP-MS	Kamvong et al., 2014
Western sub-belt	Adakites	244.6±1.8 Ma	LA-ICP-MS	Kamvong et al., 2014
Western sub-belt	Adakites	245.9±0.9 Ma	Re-Os	Kamvong et al., 2014
Phetchabun belt	Andesite	238±4 Ma	Ar-Ar	Intasopa, 1993
Phetchabun belt	Diorite porphyry	238±5 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Basalt	238±6 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Rhyolitic breccia	240±6 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Diorite	243±5 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Basaltic andesite	244±7 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Diorite	245.9±5.6 Ma	LA-ICP-MS	Salam et al., 2014
Phetchabun belt	Basalt	246±2 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Basalt	247±3.4 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Andesite	247.1±5.1 Ma	LA-ICP-MS	Salam et al., 2014
Phetchabun belt	Biotite granite	249.2±2.8 Ma	LA-ICP-MS	Salam et al., 2014
Phetchabun belt	Granodiorite	249.2±4.4 Ma	LA-ICP-MS	Salam et al., 2014
Phetchabun belt	Andesite	250±6 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Rhyolitic sandstone	258.6±2.3 Ma	LA-ICP-MS	Salam et al., 2014
Phetchabun belt	Granite	310±8 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Rhyolite	321±5 Ma	LA-ICP-MS	Zaw et al., 2007
Phetchabun belt	Rhyolitic breccia	323±4 Ma	LA-ICP-MS	Zaw et al., 2007
Sayabouli	Basaltic andesite	237.7±1.7 Ma	LA-ICP-MS	This study
Pak Lay area	Basalt	314.6±2.7 Ma	LA-ICP-MS	Qian et al., 2015
Pak Lay area	Basaltic andesite	315.4±3.8 Ma	LA-ICP-MS	Qian et al., 2015
Muang Feuang area	Andesite	330.4±2.2 Ma	LA-ICP-MS	Qian et al., 2015
Muang Feuang area	Rhyolite	334.9±1.7 Ma	LA-ICP-MS	Qian et al., 2015
Muang Feuang area	Tuff	349.6±1.7 Ma	LA-ICP-MS	Qian et al., 2015
Nan suture	Gabbro	311±10 Ma	LA-ICP-MS	Yang et al., 2016
Nan suture	Basalt	315.8±2.5 Ma	LA-ICP-MS	Yang et al., 2016

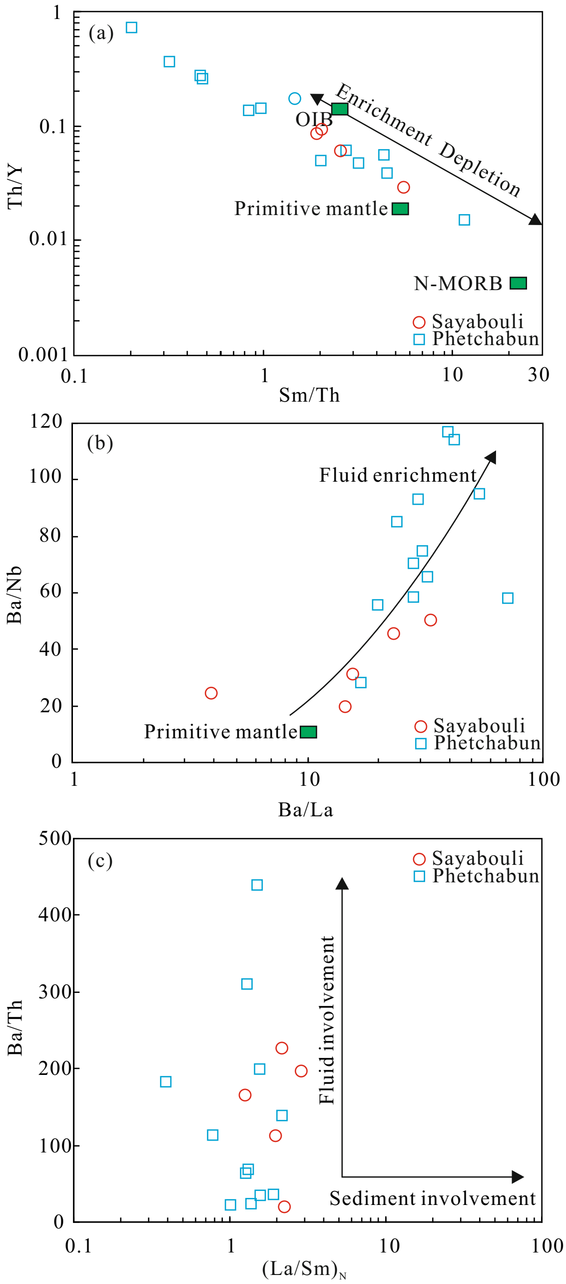

Figure 7. Plots of Sm/Th-Th/Y (a), Ba/La-Ba/Nb (b) and $(La/Sm)_N$-Ba/Th (c) (Su et al., 2012) for the Sayabouli volcanic rocks in NW Laos. The N-MORB, primitive mantle, OIB and normalized values are from Sun and McDonough (1989). Data of the Phetchabun volcanic rocks are from Boonsoong et al. (2011) and Intasopa (1993).

Sibumasu Block and the Indochina Block occurred in the Late Jurassic. However, these ages should be used more carefully since they were derived from K-Ar dating technique which could be disturbed by subsequent geological events. Manaka et al. (2008) suggested that the Late Carboniferous–Early Permian volcanic rocks from the Loei and Truong Son fold belts are geochemically characterized to have calc-alkaline affinity and are similar to those erupted in a volcanic-arc to syn-collisional tectonic setting. Some granodiorites from the Pak Lay volcanic rocks in Laos are the northern extension of the Loei fold belt, are Triassic in age (Sone and Metcalfe, 2008). The recent study comes from Qian et al. (2015), they acquired 315 to 350 Ma zircon ages (Table 3) from the Muang Feuang and Pak Lay areas and suggested that the main body of the Loei fold belt is the central sub-belt and the main subduction of the Loei Ocean occurred during the Early Carboniferous.

As mentioned above, the Loei fold belt may extend across western Cambodia up through Central Thailand and into Central Laos (Kamvong et al., 2014; Zaw et al., 2014), because of the lack of geochronology and geochemical data, the northern extension of the Permian–Middle Triassic volcanic rocks in the western Loei sub-belt and Phetchabun belt is undefined. Qian et al. (2015) suggested that the Loei fold belt can extend to the NW Laos and present a Carboniferous continental margin in NW Laos and the 321 to 323 Ma volcanic rocks and a 310 Ma granitic rock in the Phetchabun belt are possibly the southern extension of the Carboniferous volcanic rocks in NW Laos. The high precision age and geochemical data in this study have significance for the extension of the western Loei sub-belt and Phetchabun belt. The 237.7±1.7 Ma zircon age from NW Laos indicates the formation age of the Sayabouli volcanic rocks is the Middle Triassic. This age is also older than the Late Triassic–Jurassic ages which were acquired by Stokes et al. (1996). The characteristics of geochemistry and comparison study also suggest that the volcanic rocks formed under an arc setting and present a Late Permian–Middle Triassic continental margin in NW Laos and NE Thailand, which is different from the Carboniferous continental margin in NW Laos (Qian et al., 2015). The continental arc volcanic rocks in the Phetchabun belt, through the western sub-belt can be linked to the Sayabouli area in NW Laos. Considering other geological and geochronological data (Fig. 9, Table 3) (Yang et al., 2016; Qian et al., 2015; Kamvong et al., 2014; Zaw et al., 2014, 2007; Salam et al., 2014; Boonsoong et al., 2011; Khositanont et al., 2008; Charusiri et al., 2002; Intasopa and Dunn, 1994; Jungyusuk and Khositanont, 1992), we propose the following preliminary tectonic scenario for the Early Carboniferous to Middle Triassic of NW Laos (Fig. 10).

During the Early Carboniferous to Late Carboniferous (314–350 Ma), the Loei ocean basin was closed by subduction between the Sukhothai terrane and the Indochina Block, which formed a series of arc-volcanic rocks in the western margin of the Indochina Block (Qian et al., 2015). And then the Nan back-arc basin might have been opened by subduction roll-back of the main Paleotethys Ocean (ca. 311–316 Ma) (Fig. 10a) (Yang et al., 2016; Metcalfe, 2013; Ferrari et al., 2008); in the Late Permian, the initial subduction of the Nan ocean basin/ back-arc basin between the Sukhothai terrane and the Indochina Block started (ca. 259 Ma) (Fig. 10b) (Salam et al., 2014); in the Early–Middle Triassic, the subduction became mature and formed a series of arc-volcanic rocks (ca. 237–250 Ma) (Fig. 10c).

5 CONCLUSIONS

(1) The basaltic-andesite sample (LS-22-1) from the Sayabouli area yields zircon age of 237.7±1.7 Ma, suggesting a Middle Triassic origin.

(2) Basalt and basaltic-andesite samples both from the Sayabouli and Phechabun areas show depletions in Nb, Ta, P, Ti

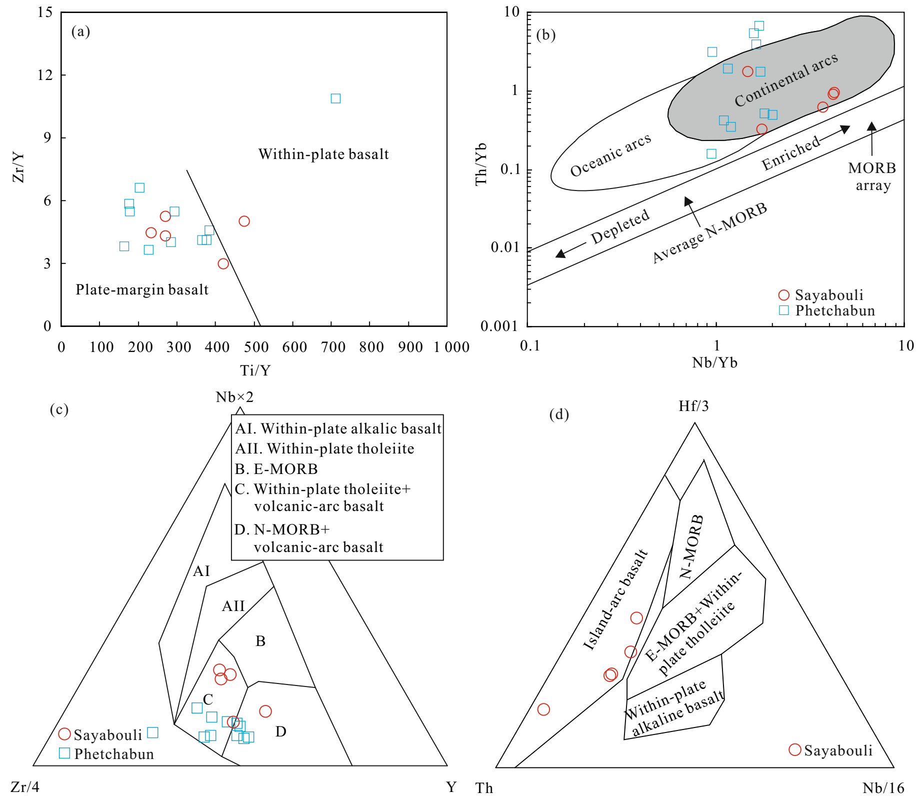

Figure 8. Geochemical discrimination diagrams for the Sayabouli volcanic rocks in NW Laos. Ti/Y-Zr/Y (a) (Pearce and Gale, 1977); Nb/Yb-Th/Yb (b) (Pearce and Peate, 1995); Nb×2-Zr/4-Y (c) (Meschede, 1986); Hf/3-Th-Nb/16 (d) (Wood, 1980). Data of the Phetchabun volcanic rocks are from Boonsoong et al. (2011) and Intasopa (1993).

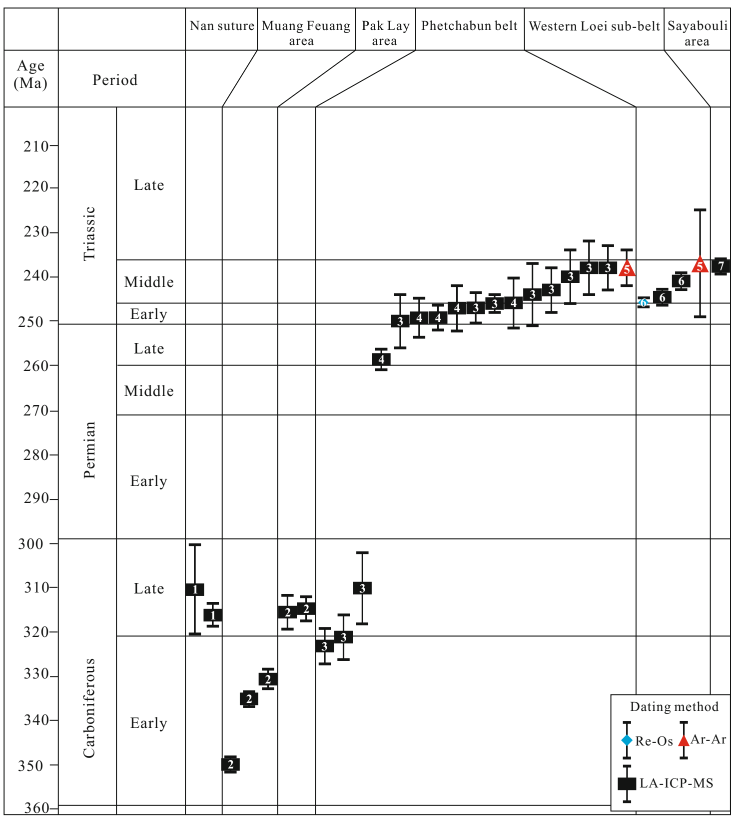

Figure 9. Summary of the Late Devonian to Middle Triassic ages from the Loei fold belt and Nan suture. Numbers on data points refer to the following sources: 1. Yang et al. (2016); 2. Qian et al. (2015); 3. Zaw et al. (2014, 2007); 4. Salam et al. (2014); 5. Intasopa (1993); 6. Kamvong et al. (2014); 7. this study.

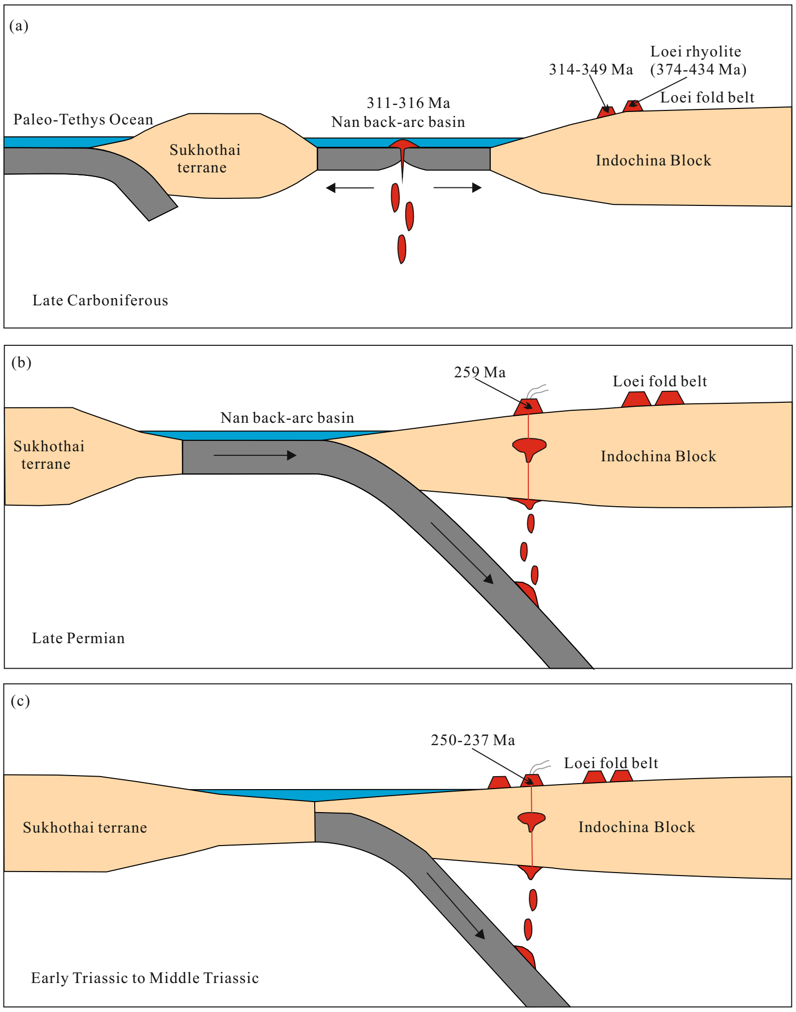

Figure 10. Tectonic evolution for the Early Carboniferous to Middle Triassic of NW Laos. (a) In the Late Carboniferous, the Nan back-arc basin may open, (b) in the Late Permian, the initial subduction of Nan back-arc basin has occured, (c) in the Early Triassic to Middle Triassic, the Nan back-arc basin continued to subduct.

and have high LILE/HFSE ratios, and exhibit the geochemical affinity to continental arc volcanic rocks, suggesting a Late Permian–Middle Triassic continental margin in the Sayabouli area of NW Laos and Phetchabun area of NE Thailand.

(3) Our data indicate that the Permian–Middle Triassic volcanic rocks in the Phetchabun belt through the western Loei sub-belt can northerly extend to the Sayabouli area in NW Laos.

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