Front. Earth Sci. 2013, 7(4): 508–521
DOI 10.1007/s11707-013-0399-2

RESEARCH ARTICLE

Geochemical and geochronological constrains on the Chiang Khong volcanic rocks (northwestern Thailand) and its tectonic implications

Xin QIAN[1], Qinglai FENG (✉)[1], Chongpan CHONGLAKMANI[2], Denchok MONJAI[2]

1 State Key Laboratory of Geological Process and Mineral Resources, China University of Geosciences, Wuhan 430074, China
2 School of Geotechnology, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

Abstract Volcanic rocks in northwestern Thailand exposed dominantly in the Chiang Khong area, are commonly considered to be genetically linked to the tectonic evolution of the Paleo-Tethyan Ocean. The volcanic rocks consist mainly of andesitic to rhyolitic rocks and are traditionally mapped as Permian-Triassic sequences. Our zircon U-Pb geochronological results show that two andesitic samples (TL-1-B and TL-31-B), are representative of the Doi Yao volcanic zone, and give a mean weighted age of 241.2±4.6 Ma and 241.7±2.9 Ma, respectively. The rhyolitic sample (TL-32-B1) from the Doi Khun Ta Khuan volcanic zone erupted at 238.3±3.8 Ma. Such ages indicate that Chiang Khong volcanic rocks erupted during the early Middle Triassic period. Seven samples from the Doi Yao and Doi Khun Ta Khuan zones exhibit an affinity to arc volcanics. Three rhyolitic samples from the Chiang Khong area have a geochemical affinity to both arc and syn-collisional volcanic rocks. The Chiang Khong arc volcanic rocks can be geochemically compared with those in the Lampang area in northern Thailand, also consistent with those in Jinghong area of southwestern Yunnan. This indicates that the Chiang Rai arc-volcanic zone might northwardly link to the Lancangjiang volcanic zone in southwestern China.

Keywords volcanic rocks, geochemistry, zircon U-Pb age, early Middle Triassic, Chiang Khong, northwestern Thailand

Received February 13, 2013; accepted May 31, 2013

E-mail: qinglaifeng@cug.edu.cn

1 Introduction

Southeast Asia and adjacent part of southwestern Yunnan preserve abundant signatures of the Paleo-Tethys evolution. They have tectonically been subdivided into numerous blocks/terranes including the Yangtze, Simao, Baoshan, Tengchong, Indochina, Sukhothai, Inthanon, etc. (Fig. 1). A series of geological investigations on tectonic evolution of these blocks have been carried out. However, there are still many debates, such as the comparison of the Paleo-Tethyan tectonic zones between northwestern (NW) Thailand and southwestern (SW) Yunnan. In northern Thailand, the Nan (or Nan–Uttaradit or Nan River) suture has been regarded by many scholars as the main oceanic basin of the Paleo-Tethyan Ocean and they thought this suture could be connected with the Langcangjiang zone (Metcalfe, 1988; Bunopas, 1994; Hada et al., 1999; Ueno and Hisada, 1999; Ferrari et al., 2008; Sone and Metcalfe, 2008). Other scholars have discovered that the Langcangjiang tectonic zone is the volcanic arc zone of the Changning–Menglian zone and can be linked with the Chiang Rai volcanic arc zone and the Chiang Mai suture, respectively (Wu et al., 1995; Zhong, 1998; Chonglakmani et al., 2001; Metcalfe, 2002; Feng et al., 2004, 2005, 2008; Shen et al., 2009, 2011). Other sutures also have been proposed in northern Thailand including the Loei suture in the east and Yuam suture in the west (Fig. 1) (Chutakositkanon et al., 1997; Chonglakmani and Helmcke, 2001; Charusiri et al., 2002; Hisada et al., 2004; Panjasawatwong et al., 2006; Udchachon et al., 2011).

These differing opinions are mainly a result of poor understanding of the geology of northern Thailand. For this reason, we carried out a geological survey and comparative study. The aim of this paper is to present petrochemical data and U-Pb ages of the volcanic rocks in NW Thailand and to discuss their connection.

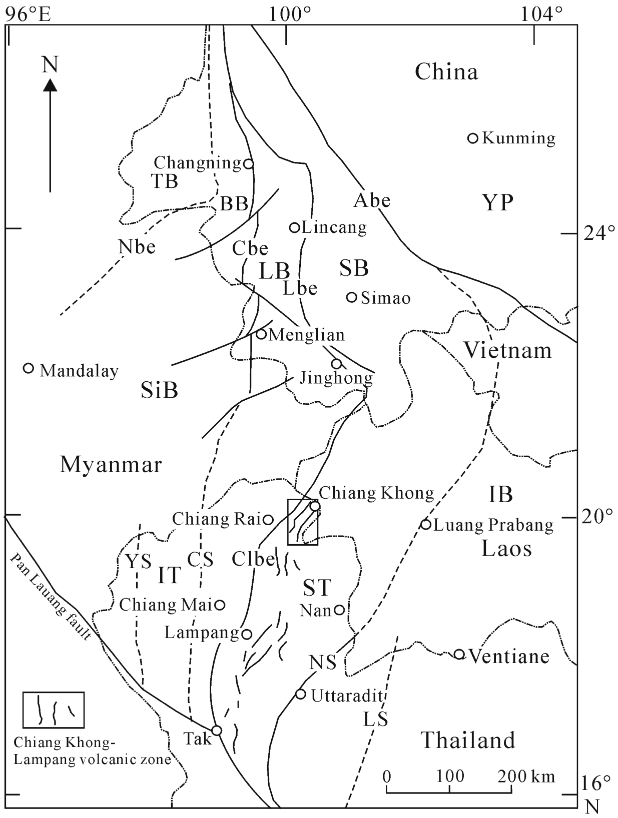

Fig. 1 Skeptically geological map of the Chiang Khong volcanic zone in NW Thailand (revised after Feng et al., 2005 and Barr et al., 2006). YP: Yangtze Plate; SB: Simao Block; LB: Lincang Block; BB: Baoshan Block; TB: Tengchong Block; Abe: Ailaoshan belt; Lbe: Lancangjiang belt; Cbe: Changning-Menglian belt; Nbe: Nujiang belt; IB: Indochina Block; ST: Sukhothai terrane; IT: Inthanon terrane; SiB: Sibumasu Block; LS: Loei suture; NS: Nan suture; Clbe: Chiang Kong –Lampang–Tak belt; CS: Chiang Mai suture; YS: Yuam suture.

2 Geological setting and petrography

Geological reconnaissance in the study area was first made by the German Geological Mission to Thailand and as a consequence, a geological map was published at a scale of 1 : 250,000 (von Braun and Hahn, 1976). In NW Thailand, the pre-Jurassic volcanic rocks can be subdivided into four zones from west to east: Chiang Rai–Chiang Mai, Chiang Khong–Lampang–Tak, Nan–Uttaradit and Loei–Phetchabun volcanic zones (Fig. 2(a)) (Panjasawatwong et al., 2003). The samples in this paper were taken from northern part of the Chiang Khong–Lampang–Tak volcanic zone, which is composed by the NE-trending Doi Yao and Doi Khun Ta Khuan volcanic zones separated by a Cenozoic basin (Fig. 2(b)). Previous workers (von Braun and Hahn, 1976; Panjasawatwong et al., 2003) considered that the volcanic rocks in the Doi Khun Ta Khuan and Doi Yao zones have erupted at Permian-Triassic period. Barr et al. (2006) further proposed that the volcanic rocks formed in a continental margin arc setting. The mafic-ultramafic rocks are Permian-Triassic and the granitic rocks are Triassic in age. The Permian-Triassic volcanic rocks are composed of rhyolite, andesite, tuff, and agglomerate that are interlayered with the Permian–Triassic sedimentary rocks. The Upper Triassic to Lower Jurassic volcanic rocks include rhyolite, rhyodacite, dacite, andesite, and tuff. The sedimentary sequences in the study area include the following units: the Devonian–Carboniferous sedimentary package consists of limestone, chert, shale, sandstone, and conglomerate; the Permian-Triassic sedimentary sequences comprise gray to dark greenish gray sandstone, siltstone and shale interlayers, with thickly to very thickly bedded, light gray conglomerate, mudstone, and tuff; the lower Jurassic sedimentary rocks comprise reddish brown, purple, and pale yellowish green sandstone, siltstone, shale, and volcanic conglomerate (von Braunand Hahn, 1976).

3 Sampling and analytical methods

Ten samples involving andesite, rhyolite, dacite and rhyolitic tuff were collected from the Doi Yao, Doi Khun Ta Khuan and Chiang Khong in the Chiang Khong volcanic zone (Fig. 2). Two andesitic samples (TL-1-B and TL-31-B) and one rhyolitic sample (TL-32-B1) were selected for zircon U-Pb dating and ten samples for major and elemental analyses.

Samples were powdered into 200 meshes for elemental analysis. Major elements were analyzed by the titrimetric method at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan. Elemental analyses were carried out at the Wuhan Supervision and Test Center for Mineral Resources of Ministry of Land and Resources 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 1.

Zircons were separated from rock samples 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 a LA-ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan. The detailed analytical procedure follows Yuan et al. (2004) and involved a 193 nm Geolas 2005M laser-ablation system coupled to an Agilent 7700a 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,

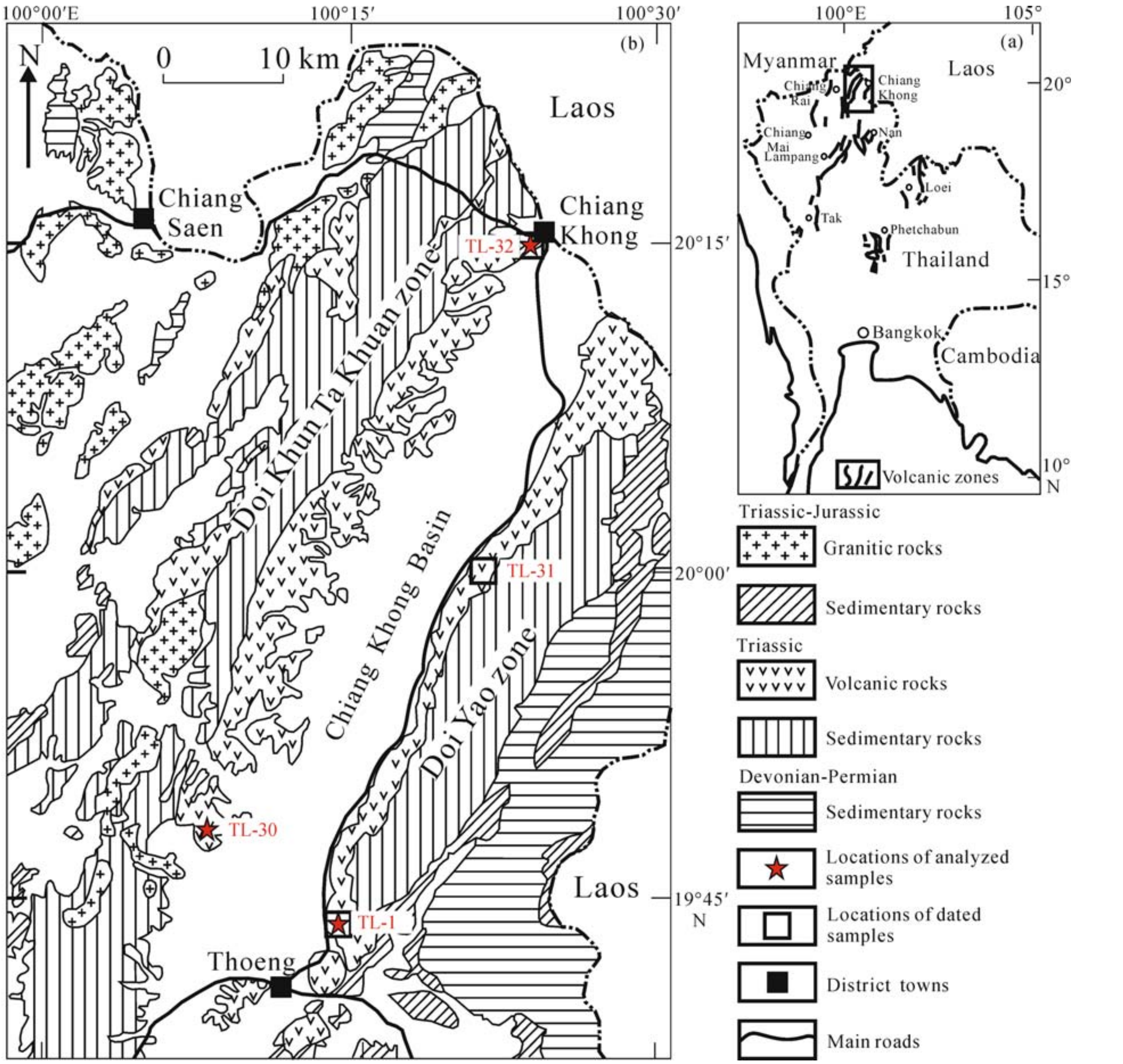

Fig. 2 Geographic map showing the Chiang Khong volcanic zone (a) and geological map of the Chiang Khong–Thoeng area (b) (revised after von Braun and Hahn, 1976; Panjasawatwong et al., 2003; Barr et al., 2006).

^{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 30s gas blank and 40s signal acquisition. Off-line selection and integration of background, analyte signals, time-drift correction, and quantitative calibration were conducted by ICPMSDataCal (Liu et al., 2010). 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).

4 Results

4.1 LA-ICP-MS zircon U-Pb geochronology

The LA-ICP-MS zircon U-Pb analytical results for the three volcanic samples are presented in Table 2. The ^{207}Pb/^{206}Pb ages were used for older (>1000 Ma) zircon grains, while ^{206}Pb/^{238}U ages were adopted for younger ones. Zircon grains from the samples are mostly euhedral

Table 1 Major and trace element analytical data for the Chiang Khong volcanic rocks in NW Thailand

Sample	Doi Yao zone		Doi Khun Ta Khuan zone					Chiang Khong area		
Major oxide/(wt.%)	TL-1-B1	TL-1-B2	TL-30-B1	TL-30-B2	TL-30-B3	TL-30-B4	TL-30-B5	TL-32-1	TL-32-2	TL-32-3
SiO_2	59.01	60.04	67.08	71.77	73.18	68.67	79.07	74.65	79.95	83.20
TiO_2	1.04	1.02	0.64	0.57	0.52	0.74	0.53	0.43	0.14	0.14
Al_2O_3	15.40	15.20	15.83	13.01	13.16	15.04	10.26	13.55	10.18	8.59
$Fe_2O_3^T$	8.65	8.49	4.84	5.14	3.02	4.42	2.03	2.03	0.53	0.50
MgO	2.40	2.17	0.95	0.70	0.35	0.45	0.20	0.07	0.07	0.15
CaO	5.17	4.80	0.83	0.81	1.69	0.62	1.71	0.17	0.10	0.08
Na_2O	3.36	3.45	3.15	3.33	5.30	3.23	4.14	6.26	0.19	0.11
K_2O	2.52	2.46	4.41	2.71	0.86	3.59	0.21	1.90	7.50	5.86
MnO	0.14	0.13	0.07	0.07	0.04	0.02	0.02	0.02	0.01	0.01
P_2O_5	0.25	0.25	0.18	0.14	0.11	0.18	0.14	0.02	0.01	0.01
LOI	2.04	1.86	1.88	1.46	1.46	2.74	1.64	0.50	0.76	0.76
Total	99.98	99.87	99.86	99.71	99.69	99.70	99.95	99.59	99.44	99.41
Element/ppm										
Sc	22.68	22.83	14.21	12.00	10.46	14.63	9.02	10.30	3.06	2.59
Co	39.14	35.32	14.42	25.65	25.07	18.62	37.83	27.62	52.65	38.30
Rb	78.94	71.96	158.9	90.17	30.24	157.4	6.34	30.90	251.1	251.7
Sr	448	413	96	101	374	176	298	39.4	43.5	25.6
Zr	150	146	218	188	173	238	182	235	87	76
Nb	7.90	10.42	12.41	15.91	9.76	17.94	10.28	12.44	7.55	5.44
Hf	4.68	4.43	6.03	5.08	4.70	6.38	4.88	6.36	2.79	2.38
Ta	0.81	1.00	1.04	1.40	0.65	1.22	0.91	0.85	0.77	0.65
Th	7.41	6.91	11.07	13.08	10.41	16.67	9.78	8.75	11.96	11.02
Ba	531	523	1378	753	195	1460	50.2	309	1299	593
Cr	5.4	4.94	5.1	6.5	2.9	4.8	6.03	3.16	3.45	4.02
Ni	0.51	0.69	0.31	1.14	1.03	0.14	1.65	1.58	4.36	3.08
La	23.09	21.75	26.05	20.93	38.97	22.13	22.84	83.77	26.95	18.97
Ce	44.56	41.64	53.77	43.10	57.57	41.10	35.36	77.50	22.98	25.97
Pr	5.65	5.56	6.74	6.11	7.41	5.71	5.51	18.62	4.79	3.65
Nd	22.97	21.82	25.91	23.97	28.00	22.59	21.46	73.13	15.52	11.75
Sm	4.64	4.55	4.82	4.75	5.05	4.51	4.32	13.15	2.66	1.76
Eu	1.30	1.26	0.97	0.86	1.08	0.87	0.82	3.32	0.52	0.46
Gd	4.66	4.29	4.62	4.60	5.23	5.11	4.43	14.38	2.43	1.42
Tb	0.73	0.75	0.75	0.75	0.79	0.80	0.73	2.10	0.39	0.21
Dy	4.33	4.46	4.55	4.45	4.60	5.09	4.13	11.20	2.16	1.29
Ho	0.90	0.89	0.93	1.00	0.95	1.10	0.84	2.03	0.43	0.25
Er	2.39	2.43	2.82	2.81	2.65	3.32	2.48	5.26	1.25	0.78
Tm	0.36	0.37	0.47	0.47	0.42	0.56	0.39	0.79	0.22	0.14
Yb	2.29	2.27	3.04	3.11	2.76	3.71	2.52	4.95	1.40	1.02
Lu	0.37	0.35	0.50	0.49	0.44	0.63	0.41	0.74	0.23	0.18
Y	23.43	23.11	25.99	26.41	25.45	31.67	23.15	58.56	12.12	7.43
Eu/Eu*	0.85	0.86	0.62	0.55	0.64	0.56	0.56	0.74	0.61	0.87
La_N/Yb_N	7.24	6.89	6.14	4.83	10.11	4.28	6.49	12.13	13.81	13.34
Gd_N/Yb_N	1.69	1.57	1.25	1.23	1.57	1.14	1.45	2.40	1.43	1.15
Nb_N/La_N	0.33	0.46	0.46	0.73	0.24	0.78	0.43	0.14	0.27	0.28

Table 2 LA-ICP-MS zircon U–Pb data for the Chiang Khong volcanic rocks in NW Thailand

Spot no.	Concentration/ppm				Isotope ratio						Calculated apparent age/Ma					
	Pb	Th	U	Th/U	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$	
					Ratio	1σ	Ratio	1σ	Ratio	1σ	Age	1σ	Age	1σ	Age	1σ
TL-1-B-1	127	580	1384	0.42	0.05759	0.00343	0.30353	0.01901	0.03749	0.00055	514	112	269	15	237	3
TL-1-B-2	141	854	1534	0.56	0.05049	0.00305	0.2635	0.01584	0.03728	0.00065	218	106	237	13	236	4
TL-1-B-3	118	678	1184	0.57	0.05364	0.00393	0.2807	0.01956	0.03809	0.00062	356	129	251	16	241	4
TL-1-B-4	103	573	1023	0.56	0.05503	0.00429	0.2857	0.0226	0.03785	0.00063	413	149	255	18	239	4
TL-1-B-5	138	322	2426	0.13	0.05398	0.00227	0.33593	0.01498	0.04426	0.00071	370	72	294	11	279	4
TL-1-B-6	165	412	1808	0.23	0.05346	0.00249	0.4032	0.01892	0.05406	0.00108	348	70	344	14	339	7
TL-1-B-7	147	821	1299	0.63	0.05312	0.00349	0.29414	0.01929	0.03926	0.00065	334	119	262	15	248	4
TL-1-B-8	99.6	66.7	2608	0.03	0.05303	0.00304	0.2877	0.01541	0.03896	0.00063	330	92	257	12	246	4
TL-1-B-9	68.2	308	480	0.64	0.04977	0.00673	0.30337	0.04044	0.04421	0.00102	184	279	269	32	279	6
TL-1-B-10	129.8	125	1887	0.07	0.05601	0.0032	0.47809	0.0243	0.06191	0.0016	453	130	397	17	387	10
TL-1-B-11	250	1309	2548	0.51	0.05108	0.00417	0.27475	0.02176	0.03901	0.00078	244	187	246	17	247	5
TL-1-B-12	153	363	1900	0.19	0.06013	0.00328	0.36463	0.01832	0.04375	0.00073	608	79	316	14	276	5
TL-1-B-13	63.4	288	550	0.52	0.06269	0.00521	0.37939	0.02728	0.04637	0.00101	698	116	327	20	292	6
TL-31-B-1	87	408	530	0.77	0.0557	0.00398	0.30665	0.02121	0.04005	0.00067	440	125	272	16	253	4
TL-31-B-2	63	318	381	0.83	0.04605	0.00474	0.23233	0.02361	0.03659	0.00062	994	134	212	19	232	4
TL-31-B-3	79	383	434	0.88	0.05367	0.00786	0.27863	0.04033	0.03765	0.00085	357	321	250	32	238	5
TL-31-B-4	392	2186	3704	0.59	0.05093	0.0017	0.27147	0.00876	0.03839	0.00039	238	55	244	7	243	2
TL-31-B-5	407	2388	3664	0.65	0.0525	0.00191	0.28224	0.01029	0.03857	0.00042	307	63	252	8	244	3
TL-31-B-6	43	199	296	0.67	0.06007	0.01027	0.30073	0.05082	0.03631	0.00093	606	381	267	40	230	6
TL-31-B-7	36	200	312	0.64	0.05708	0.00396	0.29433	0.01998	0.0374	0.00083	495	110	262	16	237	5
TL-31-B-8	35	193	288	0.67	0.07285	0.00561	0.35124	0.02401	0.03668	0.00082	1010	102	306	18	232	5
TL-31-B-9	72	357	808	0.44	0.05526	0.00326	0.28718	0.01603	0.0385	0.00065	423	95	256	13	244	4
TL-31-B-10	72	355	678	0.52	0.06204	0.00341	0.33064	0.01689	0.03895	0.00062	676	82	290	13	246	4
TL-31-B-11	32	173	270	0.64	0.07711	0.00681	0.39024	0.03113	0.03816	0.00085	1124	124	335	23	241	5
TL-31-B-12	54	264	390	0.68	0.05003	0.00516	0.27841	0.02807	0.04036	0.00086	196	231	249	22	255	5
TL-31-B-13	218	1285	1675	0.77	0.05075	0.0024	0.26806	0.01148	0.03854	0.00058	230	71	241	9	244	4
TL-31-B-14	236	1277	1451	0.88	0.05683	0.00292	0.3098	0.01476	0.03994	0.00057	485	80	274	11	252	4
TL-31-B-15	77	365	828	0.44	0.05214	0.00274	0.26603	0.01402	0.03762	0.00081	292	81	240	11	238	5
TL-31-B-16	147	930	1027	0.91	0.05044	0.00262	0.259	0.01342	0.03708	0.00055	215	92	234	11	235	3
TL-31-B-17	52	261	341	0.77	0.05604	0.00879	0.28608	0.04342	0.03702	0.00148	454	348	255	34	234	9
TL-31-B-18	46	302	351	0.86	0.07178	0.00581	0.35837	0.03343	0.03608	0.00074	980	159	311	25	229	5

(Continued)

Spot no.	Concentration/ppm				Isotope ratio						Calculated apparent age/Ma					
	Pb	Th	U	Th/U	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$	
					Ratio	1σ	Ratio	1σ	Ratio	1σ	Age	1σ	Age	1σ	Age	1σ
TL-31-B-19	191	990	2020	0.49	0.05034	0.00189	0.27506	0.00989	0.03933	0.00046	211	62	247	8	249	3
TL-31-B-20	508	3194	2910	1.1	0.05269	0.00178	0.27647	0.00861	0.03787	0.00042	315	50	248	7	240	3
TL-31-B-21	183	905	1824	0.5	0.05035	0.00299	0.26063	0.01508	0.03755	0.00051	211	138	235	12	238	3
TL-32-B1-1	5035	626	963	0.65	0.10326	0.00231	4.44571	0.10715	0.31047	0.00368	1683	27	1721	20	1743	18
TL-32-B1-2	3850	1017	1387	0.73	0.10656	0.00235	4.43805	0.10117	0.30006	0.00281	1741	28	1719	19	1692	14
TL-32-B1-3	5551	240	707	0.34	0.11502	0.00261	5.58227	0.13105	0.3499	0.00374	1880	27	1913	20	1934	18
TL-32-B1-4	4679	487	715	0.68	0.09849	0.00416	3.78039	0.15149	0.27838	0.00375	1596	81	1589	32	1583	19
TL-32-B1-5	4142	373	548	0.68	0.11304	0.00304	4.75014	0.13315	0.3026	0.00345	1849	34	1776	24	1704	17
TL-32-B1-6	2203	510	1380	0.37	0.05647	0.00215	0.29093	0.01143	0.03715	0.00043	471	66	259	9	235	3
TL-32-B1-7	6512	301	484	0.62	0.04605	0.00441	0.24228	0.02296	0.03816	0.00051	2045	200	220	19	241	3
TL-32-B1-8	4221	588	811	0.73	0.04605	0.00296	0.23382	0.0147	0.03683	0.00051	455	141	213	12	233	3
TL-32-B1-9	4028	1818	1790	1.02	0.06689	0.00269	0.35178	0.01258	0.03855	0.00047	834	54	306	9	244	3
TL-32-B1-10	1949	964	955	1.01	0.05123	0.00277	0.26817	0.01347	0.03821	0.00058	251	88	241	11	242	4
TL-32-B1-11	5369	778	2306	0.34	0.08502	0.00235	3.02011	0.07978	0.25334	0.0026	1316	35	1413	20	1456	13
TL-32-B1-12	3651	972	806	1.21	0.05529	0.00282	0.28598	0.01403	0.03727	0.00052	424	84	255	11	236	3
TL-32-B1-13	3894	555	916	0.61	0.09471	0.0024	3.50416	0.08907	0.26441	0.00295	1522	31	1528	20	1512	15
TL-32-B1-14	4305	511	675	0.76	0.05445	0.00532	0.29075	0.0279	0.03872	0.00072	390	224	259	22	245	4
TL-32-B1-15	3611	261	524	0.50	0.04901	0.00286	0.24947	0.01389	0.03706	0.00053	148	100	226	11	235	3
TL-32-B1-16	6680	664	2392	0.28	0.08973	0.00201	2.84084	0.06567	0.22693	0.00285	1420	25	1366	17	1318	15

with elongation ratios varying from 1.5∶1 to 3∶1, colorless or light brown, and prismatic with concentric oscillatory zoning (Fig. 3).

4.1.1 Doi Yao andesite (TL-1-B)

Thirteen spots are analyzed and give a relatively wide range in U (480–2608 ppm) and Th (66–1309 ppm) concentration, with Th/U ratios ranging between 0.03 and 0.64. Considering their CL images, the zircons should be of an igneous origin (Wu and Zheng, 2004). Seven analyses of thirteen spots yield a weighted mean $^{206}Pb/^{238}U$ age of 241.2±4.6 Ma (MSWD = 1.6) (Fig. 4), representing the formation age of the andesite. The apparent $^{206}Pb/^{238}U$ ages of the remaining spots range from 387±10 Ma to 276±5 Ma, which can be interpreted as the ages of the xenocrysts.

4.1.2 Doi Yao andesite (TL-31-B)

Th/U ratios for twenty-one analytical zircons range from 0.44 to 1.10, similar to those of magmatic zircons (Wu and Zheng, 2004). These spots form a coherent cluster on the concordia plot and define a weighted $^{206}Pb/^{238}U$ mean age of 241.7±2.9 Ma (MSWD = 3.0) (Fig. 4), representing the formation age of the andesite.

4.1.3 Doi Khun Ta Khong rhyolite (TL-32-B1)

U and Th concentration of sixteen analysis on sixteen zircons range from 484–2392 ppm and 240–1818 ppm, respectively. Their Th/U ratios are in the range of 0.28–1.21, similar to those of magmatic zircons (Wu and Zheng, 2004). Eight spots yield a weighted $^{206}Pb/^{238}U$ mean age of 238.3±3.8 Ma (MSWD = 2.0) (Fig. 4), representing the formation age of the rhyolitic sample. The remaining spots (TL-32-B1-1, -2, -3, -4, -5, -11, -13) give the older ages from 1880±27 Ma to 1316±35 Ma, representative of the ages of the xenocrystic grains (Fig. 3).

4.2 Geochemical characteristics

Ten samples were selected for whole-rock major oxides and trace elemental analyses (Table 1). All major oxides are volatile-free normalized to 100%. The volcanic rocks have 60.25–84.34 wt.% of SiO_2. Two samples (TL-1-B1 and TL-1-B2) are andesite, with 60.25–61.26 wt.% of SiO_2. Al_2O_3, CaO, MgO, $Fe_2O_3^T$, and TiO_2 show the negative correlation with SiO_2. A scatter trend is shown in the plot of $Na_2O + K_2O$ and SiO_2 (Fig. 5). In the $SiO_2-(K_2O+Na_2O)$ (TAS) (Irvine and Baragar, 1971; Le Bas et al., 1986) and $Zr/TiO_2-Nb/Y$ diagram (Winchester and Floyd, 1977) (Fig. 6), these samples fall

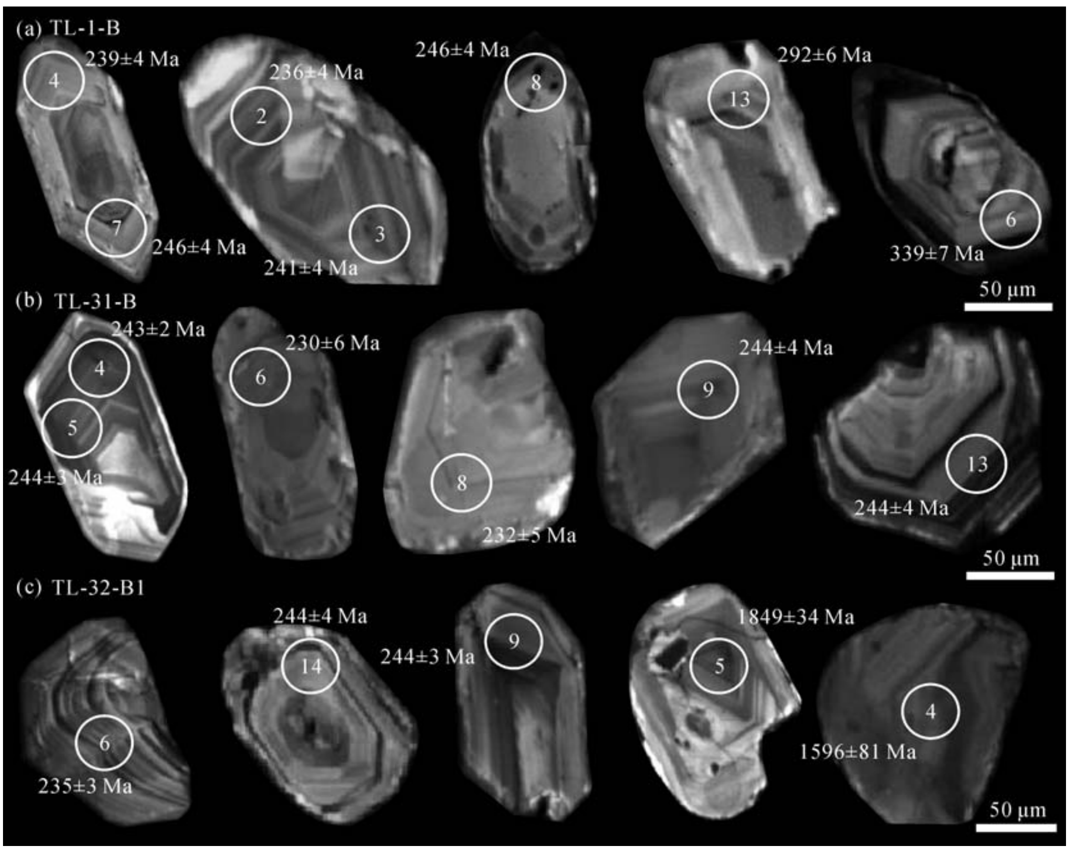

Fig. 3 Cathodoluminescence images (CL) of the representative gains for the Chiang Khong volcanic rocks in NW Thailand.

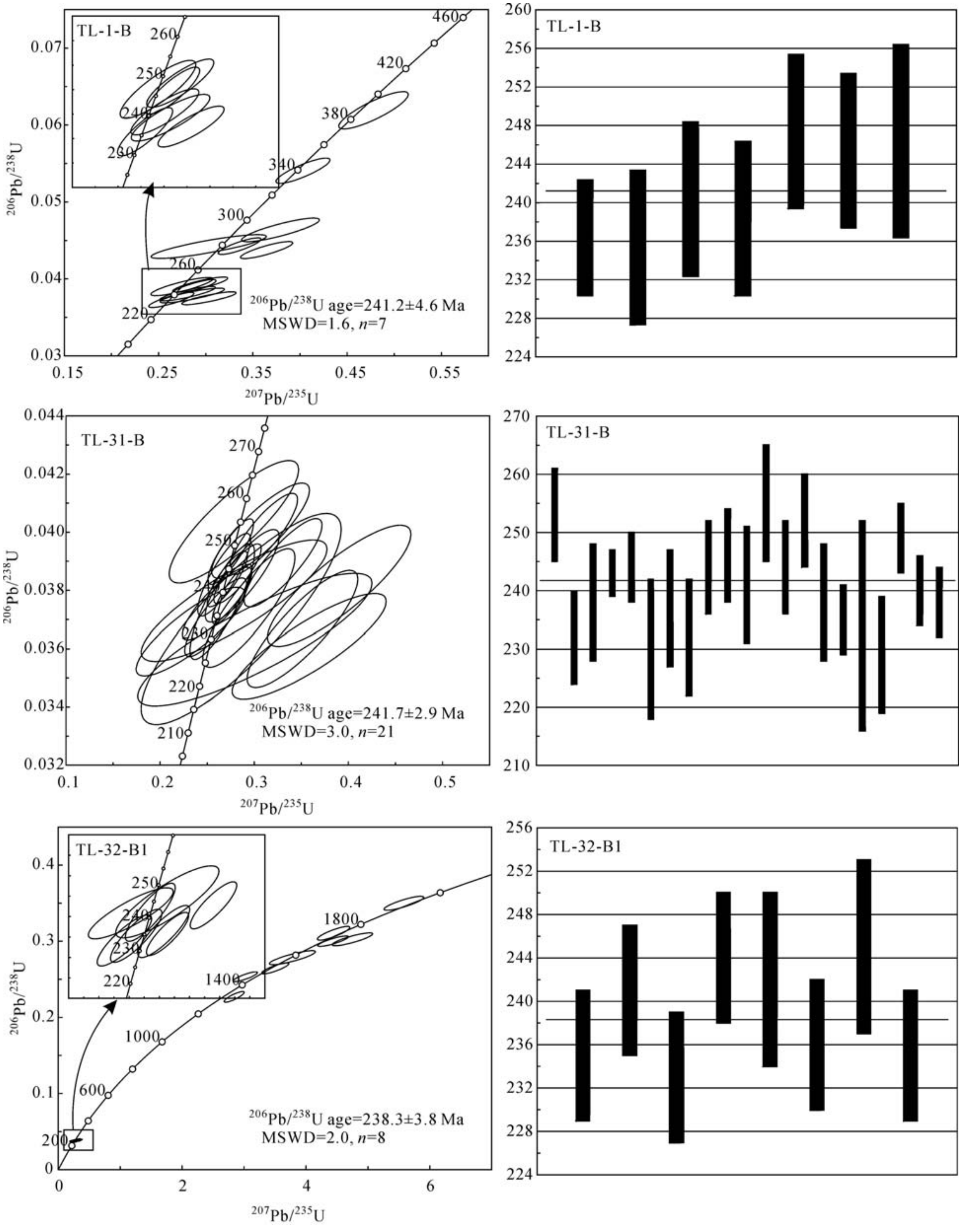

Fig. 4 LA-ICP-MS zircon U-Pb concordia diagrams for representative samples from the Chiang Khong volcanic zone in NW Thailand.

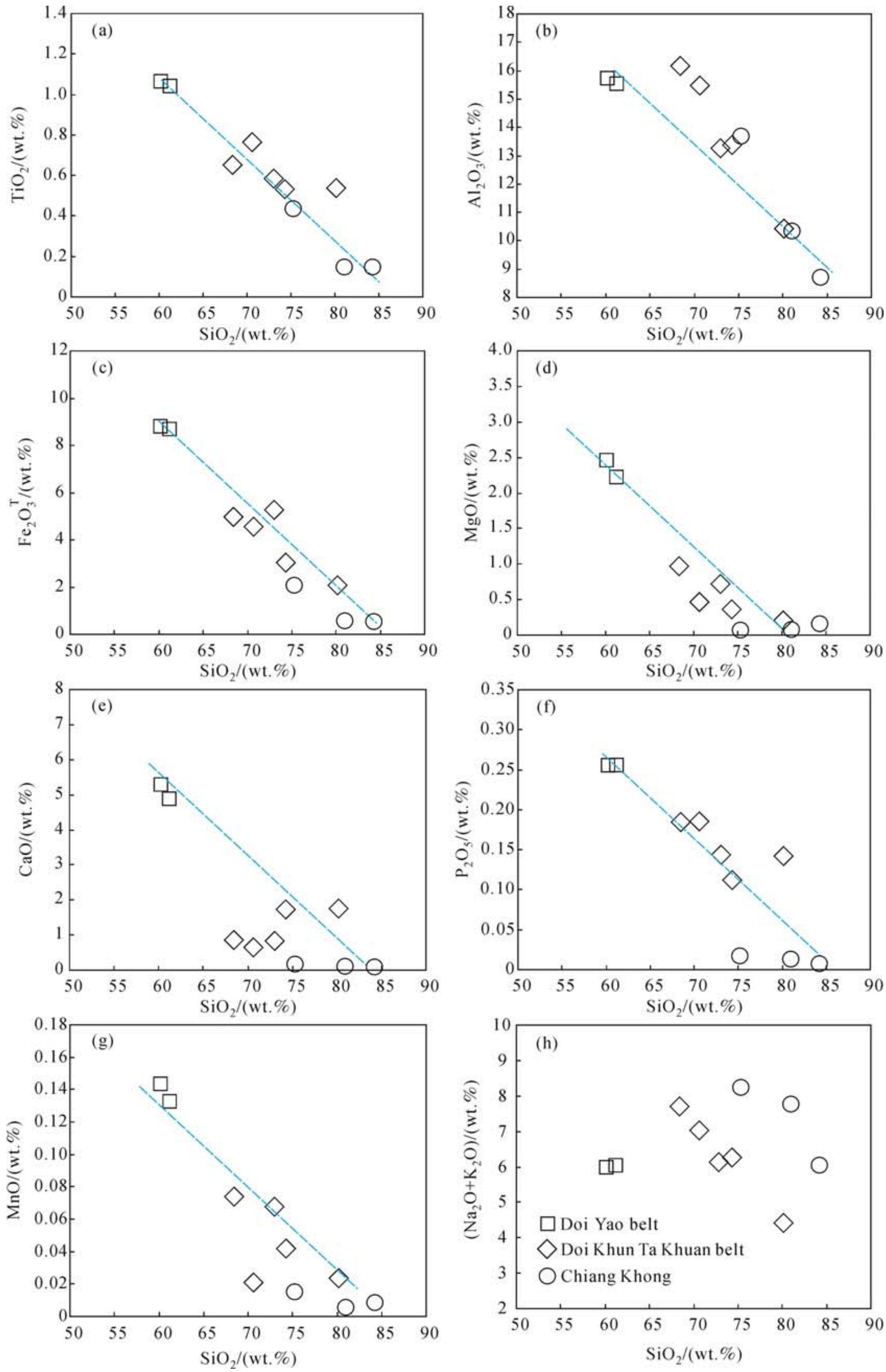

Fig. 5 SiO_2 versus TiO_2 (a), Al_2O_3 (b), $Fe_2O_3^T$ (c), MgO (d), CaO (e), P_2O_5 (f), MnO (g) and $Na_2O + K_2O$ (h) for the Chiang Khong volcanic zone in NW Thailand.

in the field of sub-alkaline rhyodacite/dacite with two samples being falling in the field of andesite. In the AFM diagram (Fig. 6) (Irvine and Baragar, 1971), the samples fall in the field of calc-alkaline.

All samples show similar chondrite-normalized REE patterns with light REE (LREE) enrichment and significant Eu/Eu* anomalies (0.55–0.87, Fig. 7(a)). La_N/Yb_N ratios range from 4.28 to 13.81 and Gd_N/Yb_N ratios from 1.14 to 2.40. All samples have lower Nb and Ta contents and higher Th/Nb, Th/Yb, and La/Yb ratios than those of average MORB (Fig. 7(a)). In the primitive mantle-normalized multielement spidergram (Fig. 7(b)), seven samples from Doi Yao and Doi Khun Ta Khuan zones show depletions in Nb, P, 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 0.28–0.78, indicative of a geochemical affinity to arc volcanic rocks. Three samples from the Chiang Khong area exhibit strong depletions in Sr, P, and Ti (Fig. 7(b)) with Nb_N/La_N ratios ranging from 0.14 to 0.28. All samples have lower Nb and Ta contents and higher Th/Nb, Th/Yb, and La/Yb ratios than those of average MORB (Fig. 7).

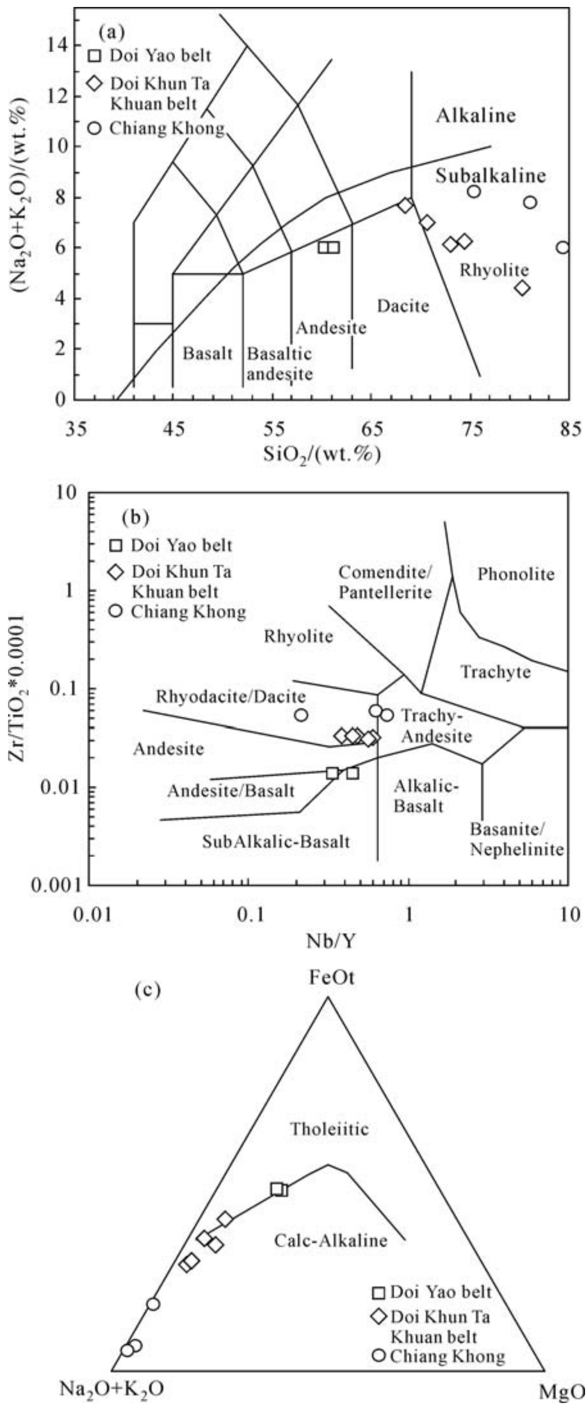

Fig. 6 TAS (a), Zr/TiO_2–Nb/Y (b) and AFM (c) diagrams for the Chiang Khong volcanic rocks in NW Thailand, original map are from Irvine and Baragar (1971), Winchester and Floyd (1977) and Le Bas et al., (1986), respectively.

5 Discussion

5.1 Ages of the Chiang Khong volcanic zone in NW Thailand

The new LA-ICP-MS zircon U-Pb dating of the three samples from Doi Yao zone (TL-1-B and TL-31-B) and Doi Khun Ta Khuan zone in Chiang Khong area (TL-32-B1) indicate the formation age ranging from 238 Ma to 241 Ma in the early Middle Triassic period. Barr et al. (2000, 2006) also reported the similar formation ages of 232.9±0.4 Ma for rhyolitic tuff from Doi Yao zone and 240±1 Ma for the rhyolite of Doi Luang zone in Lampang area. This result indicates that Doi Yao and Doi Khun Ta Khuan volcanic rocks were synchronously erupted. In the sample (TL-32-B1), eight older ages from 1880±27 Ma to 1316±35 Ma are given, which can be interpreted as the ages of inherited zircons. Such Mesoproterozoic and Paleoproterozoic ages are firstly reported from the Sukhothai terrane. Bodet and Schärer (2000) also reported abundant Precambrian ages, including 2.3–2.2 Ga, 2.0–1.9 Ga and 1.2–1.1 Ga from detrital zircons and baddeleyites from the sands of Nujiang, Langcangjiang (Mekong) and Red rivers, respectively. They also suggested the existence of the Precambrian basement in the Southeast Asia area that is similar to the Yangtze basement.

5.2 Tectonic setting and implications

As mentioned above, seven samples from Doi Yao and Doi Khun Ta Khuan zones exhibit typical arc geochemical characteristics, e.g., low TiO_2 (0.53–1.04 wt.%), Ni, Cr and higher Al_2O_3 contents, and a marked enrichment in LILE and LREE and a depletion in HFSEs. These characteristics suggest their formation being under an arc setting. Three samples from the Chiang Khong area exhibit higher SiO_2 (75.34–84.34 wt.%) and lower TiO_2 (0.14–

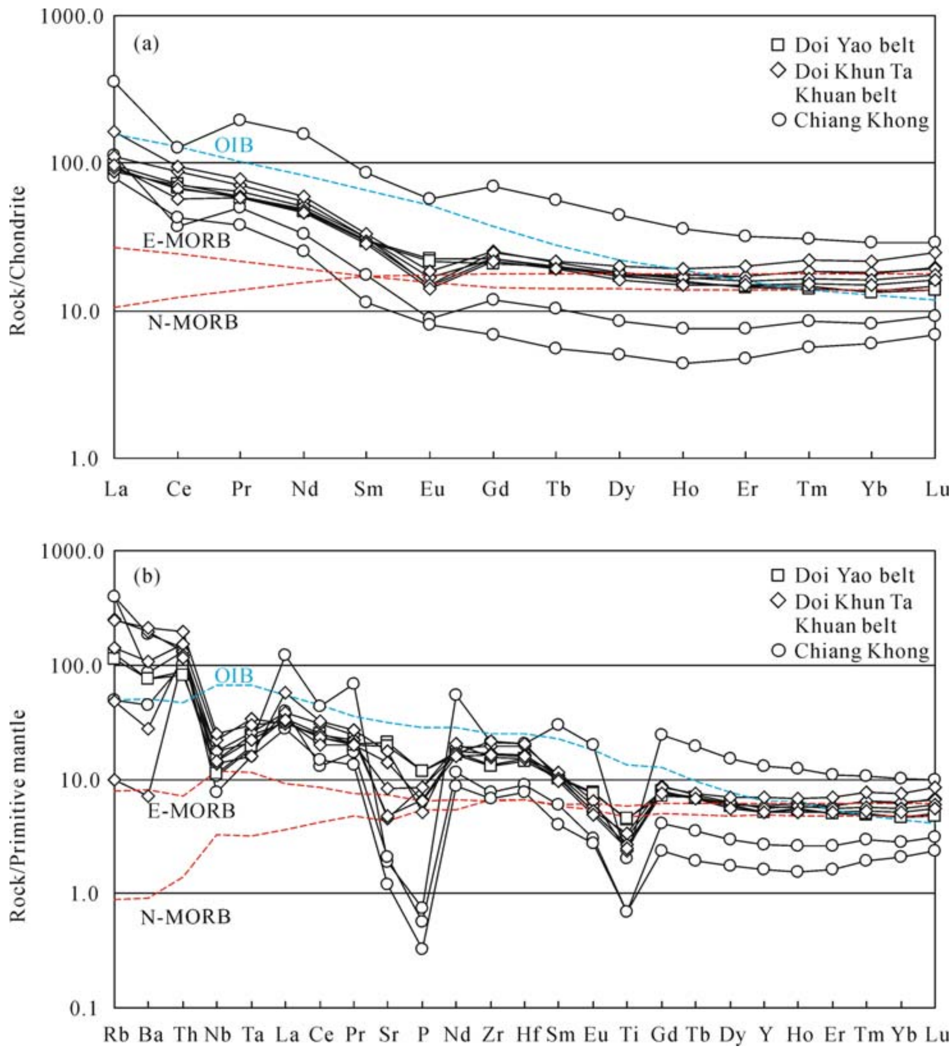

Fig. 7 Chondrite-normalized REE patterns (a) and primitive mantle-normalized multielement spider diagram (b) for the Chiang Khong volcanic rocks in NW Thailand. N-MORB, E-MORB, OIB, chondrite and primitive mantle are from Sun and McDonough (1989).

0.43 wt.%) contents, and strong depletion in Sr, P and Ti. In the Th/Ta–Yb discrimination diagram (Gorton and Schandl, 2000), all sample plots in the field are of active continental margin (Fig. 8(a)). In the Th/Yb–Nb/Yb discrimination diagram (Pearce and Peate, 1995), the majority of these samples fall into the field of continental arcs (Fig. 8(b)). Similar result is given in the Rb–(Y+Nb) and Nb–Y diagrams (Figs. 8(c) and 8(d)) (Pearce et al., 1984). The synthesis of these data points to the petrogenesis for andesitic samples being related to the continental margin volcanic arc setting, rhyolitic samples from the Chiang Khong area may formed in a transition setting from continental margin arc to syncollision. Barr et al. (2000, 2006) also proposed that the Lampang and Chiang Khong volcanic rocks were formed in an island-arc setting at middle Triassic period.

In the past twenty years, ophiolites, melanges, middle ocean-ridge basalts, oceanic island basalts, and arc volcanic rocks have been discovered in NW Thailand. These rocks are considered to be the products of the Paleo-Tethys evolution in Southest Asia. Chiang Khong and Lampang volcanic zones located between the Chiang Mai and Nan sutures in the Sukhothai terrane (Shen et al., 2009). Previous studies considered that these volcanic rocks in Chiang Khong and Lampang volcanic zones were formed in the Late Permian to Early Triassic period, and can be compared to the Langcangjiang arc volcanic zone in SW Yunnan (Yang et al., 1994; Wu et al., 1995; Barr et al., 2000, 2006; Chonglakmani et al., 2001; Metcalfe, 2002; Feng et al., 2005). Our results further verify the viewpoint of Barr et al. (2000, 2006).

The domestic research focused on the Yunxian and Jinghong arc volcanic rocks which are located in the southern Langcangjiang zone (Yang et al., 1994; Zhong, 1998; Peng et al., 2008; Wang et al., 2012). Yang et al. (1994) first suggested the correlation between the Lampang volcanic zone could compare to Lincang–Jinghong volcanic zone, but the volcanic rocks in that area were reported to

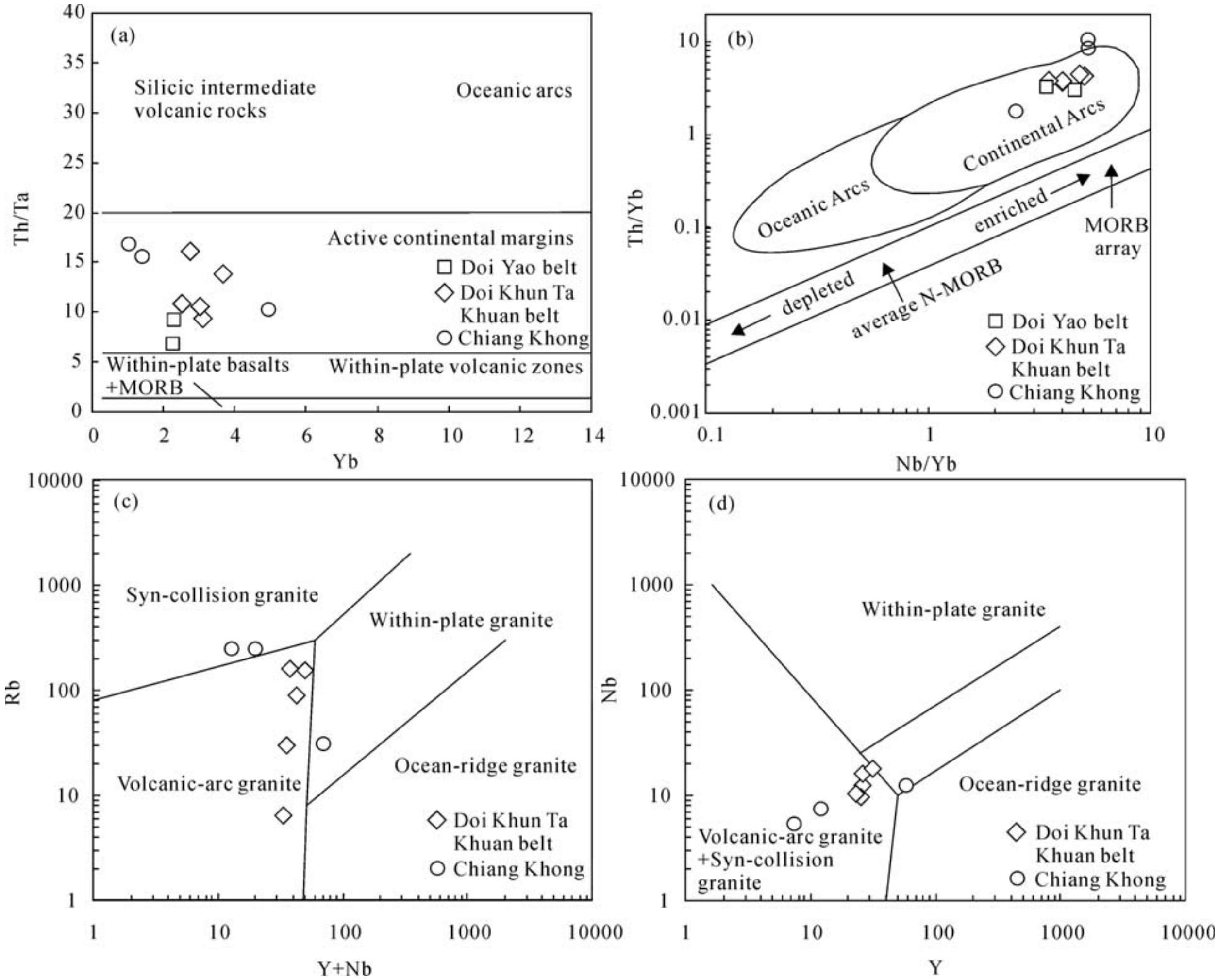

Fig. 8 Geochemical discrimination diagrams for the Chiang Khong volcanic rocks in NW Thailand. Th/Ta–Yb (a) (Gorton and Schandl, 2000); Nb/Yb–Th/Yb (b) (Pearce and Peate, 1995); Rb–(Y+Nb) (c) and Nb–Y (d) (Pearce et al., 1984).

range in age from Carboniferous to Late Triassic. Feng et al. (2005) suggested that volcanic rocks in both the Lampang and Chiang Khong areas can correlate with the volcanic rocks in the Simao Basin of Yunnan, who proposed the correlation based on sedimentary units. According to the geochemical and geochronological data of andesitic samples collected from the Manghuai Formation of the Langcangjiang tectonic zone, Peng et al. (2008) also proposed the part of the Manghuai Formation volcanic suite rocks in the southern Langcangjiang zone might be compared with subduction-related arc volcanic rocks and formed in a continental margin volcanic arc setting. Barr et al. (2000, 2006) also thought these rocks in both Lampang and Chiang Khong areas were similar to the Middle Triassic Manghuai Formation volcanic rocks in the southern Lancangjiang zone. Wang et al. (2012) suggested that the Triassic volcanic rocks from southern Lancangjiang tectonic zone formed in a transition-type continental margin orogenic belts and got an age of 236.7±2.2 Ma from a quartz andesitic sample in the Manghuai Formation by the Ar-Ar dating. With the dating results, Wang et al. (2012) suggested the main collision stage of Lancangjiang zone is inferred in Early Triassic. Our data indicate a presence of an early Middle Triassic continental margin in Chiang Khong and Lampang of NW Thailand. The arc volcanic zone in Lampang, through Chiang Khong, Laos, and can link to the Jinghong volcanic zone in SW Yunnan (SW China) (Fig. 9).

6 Conclusions

(i) Three andesitic and rhyolitic samples from the Chiang Khong volcanic zone give the zircon U-Pb ages of 241.2±4.6 Ma, 241.7±2.9 Ma, and 238.3±3.8 Ma, respectively, suggesting an early Middle Triassic origin.

(ii) Andesitic, dacitic, and rhyolitic samples from Doi Yao and Doi Khun Ta Khuan zones exhibit the geochemical affinity to arc volcanics, suggesting a presence of the an early middle Triassic continental margin in NW Thailand. Rhyolitic samples from the Chiang Khong area might be the product of the tectonic transition from arc to syncollisional stages.

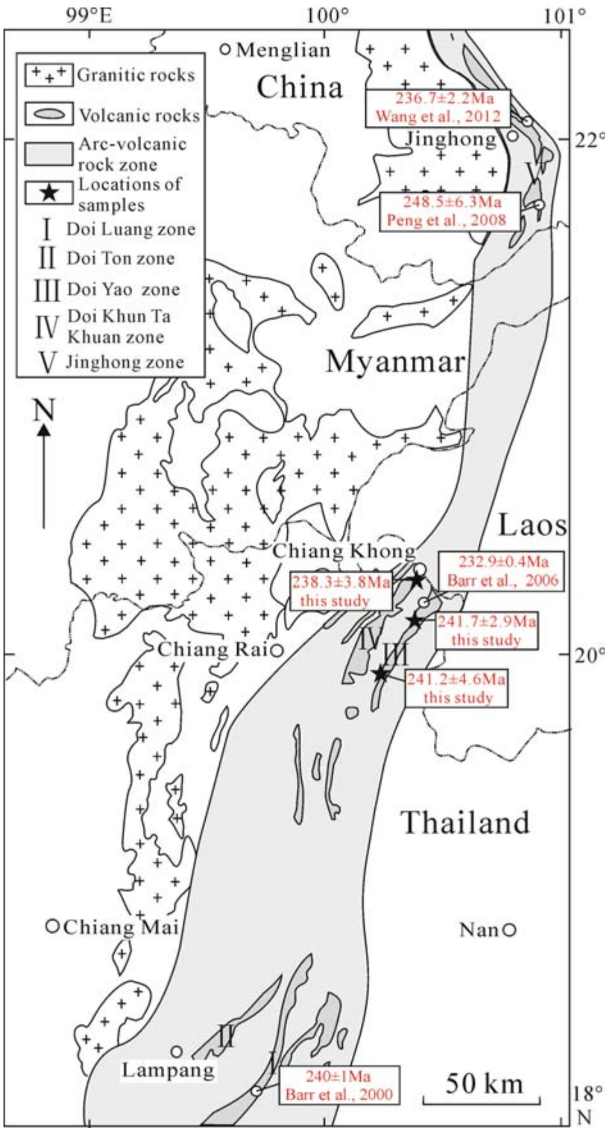

Fig. 9 Geological map of the arc-volcanic zones in NW Thailand and SW China.

(iii) Our data indicate the Chiang Khong arc volcanic zone in northern Thailand can link to the Jinghong volcanic zone in SW Yunnan (SW China).

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 41172202 and 41190073), China Geological Survey (1212011121256), Ministry of Education of China (20110145130001), and State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan (Project No. MSFGPMR201202).

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