Vietnam Journal of Earth Sciences Vol.38 (4) 372-392

(VAST)

Vietnam Academy of Science and Technology

Vietnam Journal of Earth Sciences

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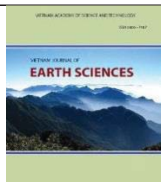

Petrography and geochemistry of Permian basalts of the Cam Thuy formation and their relation to Song Da and Emeishan magmatic rocks

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Received 20 November 2015. Accepted 15 November 2016

ABSTRACT

Cam Thuy Permian basalts consisting of thick lava flows and pyroclastic layers appear along both sides of the Song Ma fault zone in Thanh Hoa and in Son La and Ninh Binh provinces, NW Vietnam. The magmatism has been thought to have genetic relationship with Permian volcanism in the Song Da rift zone, which is believed to be part of the Emeishan large igneous province, having been extruded along the Red River shear zone following Paleogene India-Eurasian collision. A set of Cam Thuy volcanic samples including olivine and alkaline basalts was collected in the Lam Son area (Tho Xuan, Thanh Hoa province) to analyze for geochemical major, trace element and Sr-Nd-Pb isotopic composition. The Cam Thuy basalts are high-TiO_2, CaO, FeO*, moderate MgO and SiO_2 that plot between the Song Da and Emeishan high- and low-Ti basalt distribution fields and closely overlap that of Song Da's high-Ti field. The primitive mantle and chondrite normalized trace element patterns of Cam Thuy basalts are essentially enriched oceanic island basalt (OIB)-like; this feature, together with crustal contamination-free, chondritic Sr, Nd and Pb initial (255Ma) isotopic composition are certainly of asthenospheric origin. These geochemical and isotopic characteristics are closely analogous to those features observed for the Song Da high-Ti basalts, suggesting similarity in their source of origin. Nevertheless, while the Song Da (and Emeishan) magmatism is signified by the presence of both high- and low-Ti basalts, with the latter being derived from heterogeneous and partially crustal-material contaminated sources in the lithospheric mantle, this low-Ti volcanic rock type has yet to be discovered in the Cam Thuy formation.

Keywords: Northwest Vietnam, Song Ma fault zone, Song Da Rift zone, Cam Thuy Permian basalt, isotopic geochemistry.

1. Introduction

The Song Da structure, viewed as a typical intracontinental rift zone (Tran and Tran, 2008), is located between two large fault systems in northwestern Vietnam, including the Red River Shear zone (RRSZ) to the north and the Song Ma (Ma River) in the west

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(Figure 1a) The Song Da rift zone consists of a series of structural zones such as Son La, Song Da, Ninh Binh and part of Thanh Hoa in the Vietnam tectonic map of Dovjikov et al (1965). Late Permian mafic, ultramafic and felsic pluton-volcanic magmatic fields are widespread in the Song Da rift zone, including Cam Thuy, Vien Nam-Ba Vi, Kim Boi - Hoa Binh, Son La Pass, Bac Yen - Van Yen, Deo Chen, Nam Muoi, Nam So, Sin Ho and other areas (Polyakov et al., 1992, 1996; Balykin et al., 1996, 2010; Hoang et al., 2004, 2016a; Tran et al., 2011, 2015) (Figure 1a).

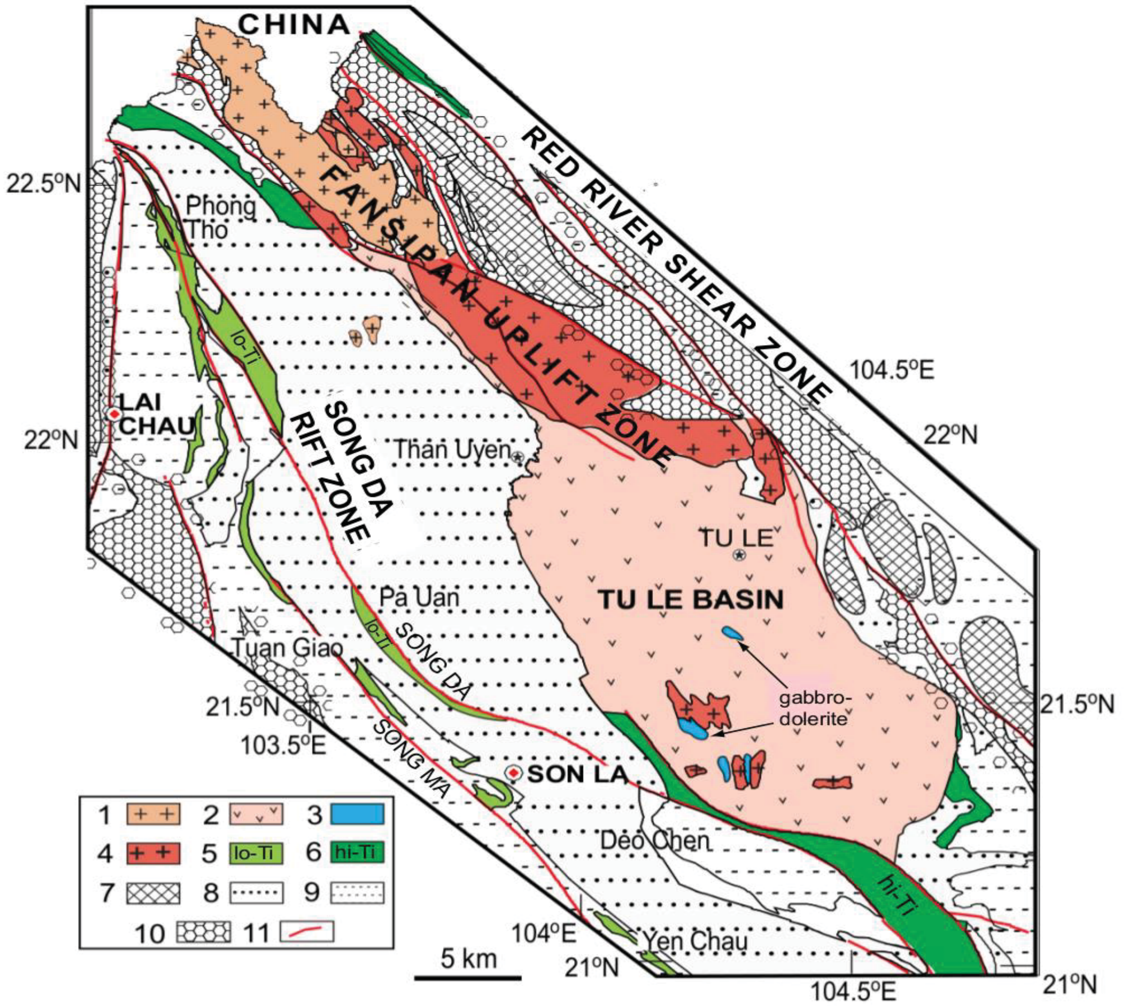


Figure 1a. Geological scheme of northwestern Viet Nam, simplified from Geological Map of Viet Nam at 1:1,500,000 (Tran and Nguyen, 1988) showing distribution areas of Song Da Permian magmatic rocks and major tectonic structures in NW Viet Nam. (1) Cenozoic granite; (2) Fan Si Pan Permian granite (Fan Si Pan uplift); (3) gabbro and dolerite; (4) Permian rhyolite and trachyte-dacite; (5) low-Ti basalt, picrite; (6) high-Ti basalt; (7) Neoproterozoic granite; (8) Mesozoic formations; (9) Paleozoic formations; (10) Pre-Cambrian metamorphic rocks (including Archean meta-granite); (11) faults

The Cam Thuy volcanic formation consists mainly of (high-Ti) basalt and andesitic - basalt (basalt-andesite association) that outcrops widely in southeastern Song Ma anticlinoria, in the Cam Thuy and Tho Xuan districts (Thanh Hoa province), and scattered small centers in and around the Son La area (Son La province). This magmatic formation has long been viewed as part of the Song Da late Permian mafic - ultramafic pluton-volcanic association and termed as Cam Thuy late Permian magmatic formation (Tong and Vu, 2005). The magmatic rocks of Cam Thuy formation, however, have not been studied. Several authors (e.g. Tran et al., 1995, 2002, 2011, 2015; Hanski et al., 2004; Balykin et al., 2010) have suggested that the Song Da volcanic rocks are geochemically comparable to magmatic rocks in the Emeishan large igneous province (LIP) in SW China, which was formed by melting of deep mantle sources under the influence of a hot, deep-rooted plume (Chung and Jahn, 1995; Chung et al., 1997). The Song Da and Cam Thuy magmatic rocks are thus considered as a portion of Emeishan (E)-LIP that was extruded southeastward between the Song Ma and Red River fault zones following the India-Eurasian collision in the late Paleogene (about 30 Ma) (Chung et al., 1997; Wang et al., 2007; after Gilder et al., 1996).

The objectives of this study are to (1) identify the petrography and determine the elemental and Sr, Nd and Pb isotopic compositions of Cam Thuy representative basalts to highlight their source region and formation parameters; (2) compare these characteristics with those of (a) Song Da and (b) Emeishan magmatic rocks that could provide evidence of their sharing a common source region.

2. Emeishan-LIP and Song Da volcanic magmas

2.1. Emeishan volcanic rocks

The Emeishan magmatic region is defined as a Large Igneous Province (LIP) for its thick magmatic layers (up to 5000 m) and large distribution area (about 250,000 km^2), occurring in Yunnan, Sichuan and Guizhou provinces, SW China. The Emeishan-LIP rests on an Early Permian limestone basement, about 1 km thick, possibly because of extension and subsidence tectonics in association with rifting activity of the south China plate (Xu et al., 2001). The basement was uplifted prior to the major eruption stages that formed Emeishan-LIP within a 3-million-year span, between 253 Ma and 250 Ma (Xu et al, 2001, 2004). Emeishan basalts are generally classified as low- and high-Ti basalt types. The low-Ti basalt is characterized by low Ti/Y (<500) ratio, low total FeO (<12 wt%), high SiO_2 (48-53 wt%) and high Mg# (52-64); whereas the high-Ti basalt type has high Ti/Y (>500) ratio, high FeO (>12.7-16.4 wt%), low SiO_2 (45-50 wt%) and high Mg# (51-61) (Xu et al., 2001).

2.2. Mafic, ultramafic magmatic rocks in the Song Da rift zone

Permian mafic and ultramafic magmatic rocks are distributed widely in the Song Da rift zone. On the basis of their geochemical characteristics, the mafic and ultramafic Song Da magmatic rocks may be classified into four associations belonging to high- and low-Ti magmatic types. The high-Ti andesite-basalt association outcrops in the Cam Thuy and Son La areas; the high-Ti picrite-basalt-andesite association occurs in the Nam So area, and the trachyandesite, trachydacite and trachybasalt association appears in the Doi Bu, Vien Nam and Nam Muoi areas. The low-Ti rock type, including mafic and ultramafic volcanic rocks belongs to the picrite (komatiite?)-basalt association in the Nam Muoi, Pa Uon and Deo Chen areas (Fig. 1a) (Polyakov et al, 1991; Balykin et al, 1996, 2010; Chung et al, 1997; Tran et al., 1998, 2004, 2008, 2015; Hanski et al, 2004; Hoang et al., 2004, 2016a).

Low MgO, high FeO, CaO and Na_2O (mafic components) contents in the high-Ti basalt in the Song Da rift zone, together with oceanic island basalt (OIB)-like trace elemental (and rare earth element) and Sr, Nd isotopic characteristics, suggest that the high-Ti basalt is derived from an enriched and fertile (asthenosphere) mantle source (Hofmann, 1997; Hoang et al., 2016a). The low-Ti basalt type, in contrast, shows high MgO, low in the mafic component, and various trace element compositions, which reflect various geochemical features including those of island arc, mid-oceanic ridge basalt (N-MORB) and oceanic island basalt (OIB)-like type. The initial (255 Ma) Sr and ε_{Nd} of the low-Ti volcanic rocks are highly variable, most certainly produced from highly heterogeneous lithospheric mantle source. In general, the Sr-Nd isotopic compositions of Song Da Permian magmatic rocks are anomalously enriched, suggesting the melt may have interacted with crustal materials (Hoang et al., 2016a).

2.3. Formation ages of Emeishan and Song Da magmatism

The radiometric age range of Song Da magmatism is controversial. Age dates obtained for Song Da magmas range from 257 ±24 Ma by Rb-Sr (Polyakov et al., 1996), of 258.5±1 by $^{40}Ar/^{39}Ar$ (Tran et al., 2008), and 270 ± 21 Ma by Re-Os (for 12 komatiite samples) (Hanski et al., 2004), closely matching those of Emeishan basalts (Lo et al., 2002; Zhou et al., 2002) which suggest the bulk of activity occurred between c. 251 and 259 Ma. Balykin et al. (1996) reported Rb-Sr ages of 257 ±7.2 Ma for Song Da komatiitic clinopyroxene separates from the northwestern side of the rift zone. More recently, Tang et al. (2015) reported U-Pb ages of 256.2 ±1.4 Ma for zircons from a volcanic sequence in Binchuan, southern part of Emeishan LIP, and of 258.5 ±3.5 Ma for a Baimazhai picrite, northwest of Jinping, immediate northern tip of the Song Da volcanic zone. Therefore, ages between 255 and 258 Ma (late Permian) are currently taken for mafic and ultramafic magmatic rocks in the Song Da rift zone and several other nearby regional magmatic formations (e.g., Tran et al., 2015; Usuki et al., 2015; Hoang et al., 2016b).

Until recently, no reliable age has been determined for the Cam Thuy volcanic formation. While expecting new radiometric ages, we temporarily adopt ages of 258-255 Ma for Cam Thuy formation for the following reasons: (1) its geological proximity to the Song Da magmatic rift zone, (2) high concentration of late Permian age (258 to 255 Ma) of magmatic formations in NW Vietnam (e.g. Tang et al., 2015; Tran et al., 2015; Usuki et al., 2015), and (3) the availability of stratigraphic correlation-based late Permian (P_3) age for Cam Thuy volcanic formation (Tong and Vu, 2005, and references therein).

3. Sampling and analytical procedures

Basalt sampling was conducted in the Lam Son area (Tho Xuan district, Thanh Hoa province), where massive basaltic lavas occur as large blocks along the Ho Chi Minh trail (Figs.1b-c; 2a-d), with thickness up to 600 m (Le and Tran, 1995). Layers of pyroclastic flows associated with the basaltic volcanism are exposed widely along the road connecting Lam Son and Sao Vang airport (Tho Xuan town) (Fig. 1b, 2c-d). The pyroclastic products include welded, medium-grained tuff, intercalated with layers of coarse- to fine grained volcanic ash (Fig. 2d). Individual thickness varies from a few centimeters to approximately 30 cm, making the total visible thickness of the pyroclastic flows reach about 50 m (Fig. 2c-d). Samples were processed for microscopic study (Figs. 3a-f) and selection for geochemical and isotopic composition analysis.

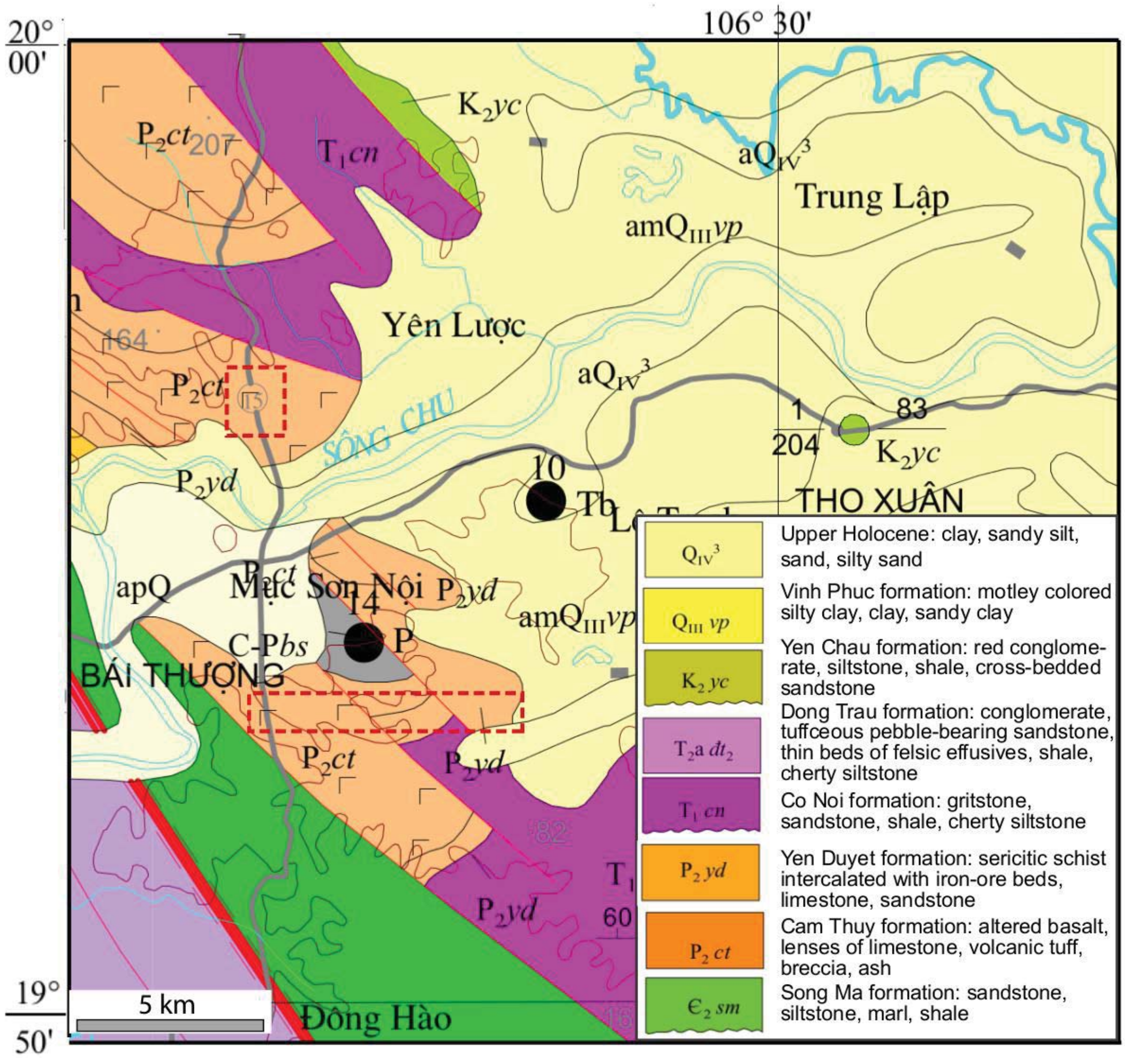


Figure 1. (b) Distribution scheme of Cam Thuy late Permian basalts in the Lam Son area (Tho Xuan, Thanh Hoa province), showing sampling sites (dashed rectangles). Simplified from 1:200,000 Geological Map of Viet Nam (after Le and Dang, 1995)

The major element compositions were acquired from fused glass beads made by mixture of sample and lithium tetraborate ($Li_2B_4O_7$) using a Bruker Pioneer X-Ray Fluorescence (XRF) analyzer at the Institute of Geological Sciences (VAST). Another set of samples was prepared for analysis using a Panalytical XRF at the Geological Survey of Japan (GSJ) for comparison. A set of 12 GSJ geological standards were used as external data calibration and accuracy evaluation.

The trace element and rare earth element compositions were acquired at the Geological Survey of Japan using an Agilent 8800 ICP-MS following procedures described in Ishizuka et al. (2003). The analytical accuracy as estimated from repeated measurements of GSJ standards is ±1% to ±6% (for Nd and Nb).

Figure 2. Outcrops Cam Thuy basalts in the Lam Son area, Tho Xuan, Thanh Hoa province: a- b: massive basaltic lava flows; c-d: volcanic pyroclastic layers

Sr, Nd and Pb isotopic ratios were measured at the GSJ using a VG-54 thermal ionization mass spectrometry (TIMS, GSJ) and at the University of the Ryukyus (Okinawa, Japan) using a Neptune multi-collector (MC)-ICP-MS. The element extraction chemistry was performed at the Geological Survey of Japan. The extraction procedures and TIMS Sr, Nd, Pb isotopic running parameters and analytical accuracy were described in Hoang and Uto (2006) and N. Hoang et al. (2013). The data are shown in Table 1.

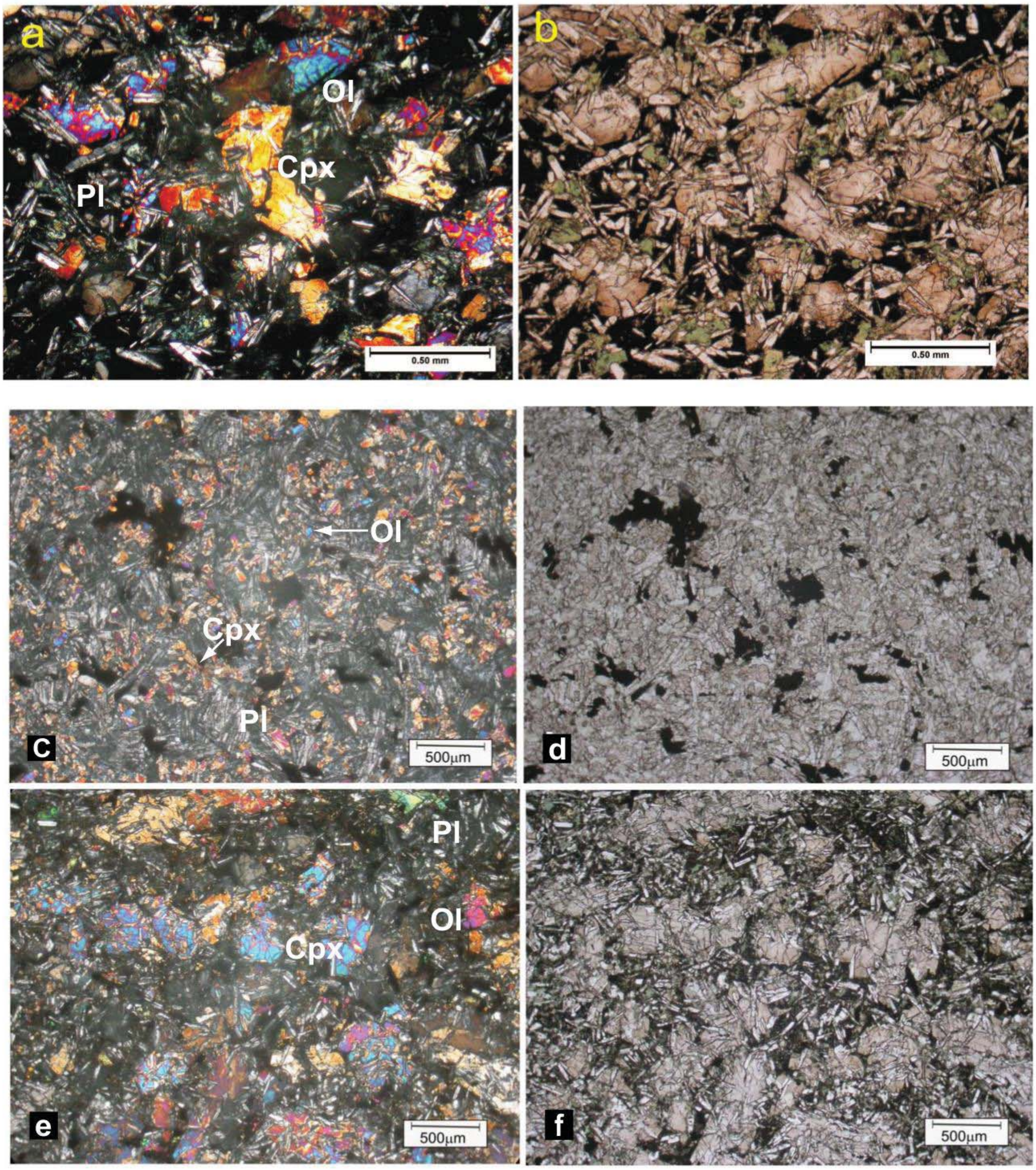


Figure 3. a, b: phyric olivine basalt (sample 040213/1) with subhedral olivine phenocrysts and needle-shaped plagioclase microlitic groundmass; c, d: aphyric alkaline basalt (sample 040213/6) containing microlites of olivine, clinopyroxene and plagioclase in the groundmass; e, f: phyric olivine basalt (sample 040213/8) with doleritic texture on the clinopyroxene and plagioclase microlitic groundmass; a, c, e: nichol (+); b, d, f: nichol (-); ruler is 0.5 mm

Table 1. Major, trace element and Sr-Nd-Pb isotopic compositions of the Cam Thuy late Permian basalts in the Lam Son area (Tho Xuan District, Thanh Hoa Province)

Sample	040213-1	040213-2	040213-3	040213-4	040213-5	040213-6	040213-7A	040213-7B	040213-8
Rock type	olivine basalt	olivine basalt	olivine basalt	olivine basalt	olivine basalt	alkaline basalt	olivine basalt	olivine basalt	tholeiitic basalt
SiO_2	47.70	47.92	48.84	48.33	48.58	47.99	48.64	49.89	50.33
TiO_2	2.81	2.68	2.74	2.70	2.70	2.67	2.69	2.61	2.66
Al_2O_3	15.92	15.31	14.91	14.76	15.04	15.36	15.31	14.92	15.16
FeO*	12.43	12.98	12.86	13.26	12.76	12.70	12.41	12.14	11.87
MnO	0.19	0.20	0.22	0.20	0.19	0.22	0.20	0.20	0.19
MgO	6.17	5.78	5.63	6.00	6.09	5.63	6.31	6.15	5.65
CaO	11.50	11.60	11.20	11.26	11.47	10.95	11.63	11.17	11.16
Na_2O	1.76	2.31	2.41	2.27	2.31	3.62	1.70	1.73	1.93
K_2O	1.12	0.83	0.79	0.82	0.49	0.48	0.72	0.81	0.65
P_2O_5	0.41	0.39	0.40	0.40	0.40	0.39	0.39	0.38	0.39
Mg#	52.5	49.8	49.4	50.2	51.5	49.7	53.1	53.0	51.5
Ti (ppm)	16830	16065	16419	16190	16178	16029	16137	15662	15949
K (ppm)	9306	6909	6555	6776	4029	3967	5947	6742	5361
Na_2O+K_2O	2.88	3.14	3.20	3.09	2.79	4.10	2.42	2.54	2.58
CIPW									
Quartz									2.05
Orthoclase	6.62	4.92	4.67	4.82	2.87	2.82	4.23	4.80	3.82
Albite	14.85	19.53	20.35	19.25	19.54	24.38	14.39	14.61	16.34
Anorthite	32.24	28.95	27.57	27.64	29.23	24.26	32.02	30.56	30.80
Nepheline						3.38			
Diopside	18.45	21.81	21.22	21.41	20.93	23.02	19.26	18.64	18.38
Hypersthene	12.60	5.99	11.90	10.31	13.91		21.96	24.38	22.67
Olivine	8.98	12.83	8.17	10.53	7.50	16.18	2.13		
Magnetite									
Ilmenite	5.33	5.09	5.20	5.13	5.12	5.08	5.11	4.96	5.05
Apatite	0.94	0.90	0.94	0.93	0.92	0.91	0.91	0.89	0.90

Table 1. (continued)

Sample	040213-1	040213-3	040213-5	040213-6	040213-7A	CT150616-C	CT150616-G	CT150616-J	CT150616-L
Rock type	olivine basalt	olivine basalt	olivine basalt	alkaline basalt	alkaline basalt	olivine basalt	tholeiite	alkaline basalt	olivine basalt
Rb	23.26	22.66	9.72	9.43	12.95	21.01	10.26	14.67	6.61
Sr	322.14	370.49	292.18	739.52	360.62	327.80	256.51	450.26	517.99
Y	33.23	31.26	32.61	30.99	32.54	27.29	29.16	28.91	33.58
Zr	177.22	161.86	176.63	167.93	172.07	155.53	164.68	185.71	191.21
Nb	22.94	20.84	21.76	21.32	22.18	18.95	19.10	27.98	28.38
Cs	0.57	0.86	1.17	0.57	0.53	0.50	0.08	0.26	0.11
Ba	261.04	302.32	130.16	149.33	153.96	285.94	124.37	601.53	530.67
La	25.09	25.26	27.15	23.88	26.52	20.80	25.04	31.95	34.49
Ce	58.15	54.61	57.73	53.57	58.42	48.15	53.99	76.70	82.07
Pr	7.10	6.64	6.88	6.65	7.09	5.81	6.75	9.75	10.18
Nd	31.54	29.58	31.07	29.51	31.82	25.28	30.13	43.50	45.50
Sm	7.01	6.70	6.83	6.55	7.02	5.73	6.66	8.72	9.32
Eu	2.40	2.25	2.22	2.31	2.33	2.11	2.44	3.43	3.74
Gd	6.94	6.55	6.55	6.42	6.90	5.60	6.45	7.78	8.66
Tb	1.11	1.04	1.06	1.04	1.09	0.89	1.00	1.12	1.24
Dy	6.26	5.73	6.01	5.86	6.19	5.11	5.68	6.17	6.55
Ho	1.21	1.15	1.19	1.16	1.23	1.00	1.08	1.12	1.25
Er	3.31	3.19	3.08	3.15	3.12	2.69	2.86	2.93	3.25
Tm	0.47	0.44	0.45	0.44	0.44	0.40	0.40	0.40	0.47
Yb	2.90	2.71	2.77	2.68	2.81	2.35	2.43	2.51	2.65

Lu	0.40	0.41	0.39	0.39	0.39	0.33	0.35	0.36	0.39
Hf	4.82	4.38	4.55	4.46	4.64	4.12	4.44	4.94	5.01
Ta	1.79	1.61	1.66	1.64	1.69	1.46	1.47	2.20	2.19
Pb	38.67	2.86	2.89	3.05	3.27	3.38	2.92	4.64	2.95
Th	3.64	3.35	3.39	3.38	3.45	2.80	2.79	3.47	3.54
U	0.90	0.74	0.80	0.70	0.90	0.55	0.63	0.25	0.87
V	324.98	326.07	330.74	336.07	357.86	337.43	321.15	406.91	401.09
Cr	150.18	148.35	161.59	152.94	157.01	261.50	208.18	95.69	102.91
Ni	95.44	92.71	95.19	91.88	92.33	147.54	110.99	75.38	80.74

Table 1. (continued)

Sample	040213-1	040213-3	040213-5	040213-6	040213-7A	CT150616-C	CT150616-G	CT150616-J	CT150616-L
Rock type	olivine basalt	olivine basalt	olivine basalt	alkaline basalt	alkaline basalt	olivine basalt	tholeiite	alkaline basalt	alkaline basalt
$^{87}Rb/^{86}Sr$	0.228	0.202	0.107	0.042	0.115	0.179	0.112	0.091	0.0356
$^{87}Sr/^{86}Sr_m$	0.706105	0.706269	0.705815	0.705986	0.705926	0.705989	0.706274	0.705655	0.705462
$^{87}Sr/^{86}Sr_{(255Ma)}$	0.705279	0.705536	0.705429	0.705836	0.705507	0.705340	0.705869	0.705325	0.7053327
$^{147}Sm/^{144}Nd_m$	0.142	0.140	0.136	0.137	0.136	0.140	0.137	0.124	0.126
$^{143}Nd/^{144}Nd_m$	0.512568	0.512578	0.512464	0.512570	0.512573	0.512615	0.512598	0.512572	0.512584
ε_{Nd}	-1.36	-1.17	-3.40	-1.32	-1.27	-0.45	-0.78	-1.29	-1.05
$\varepsilon_{Nd(255Ma)}$	0.43	0.67	-1.42	0.61	0.69	1.40	1.17	1.08	1.23
$^{143}Nd/^{144}Nd_{(255Ma)}$	0.512332	0.512345	0.512237	0.512341	0.512345	0.512382	0.512370	0.512365	0.512373
$T_{(DM)}$	1.23E+09	1.18E+09	1.34E+09	1.16E+09	1.14E+09	1.1E+09	1.1E+09	9.8E+08	9.9E+08
U (ppm)	0.90	0.74	0.80	0.70	0.90	0.548	0.627	0.247	0.865
Th (ppm)	3.65	3.35	3.39	3.38	3.45	2.802	2.794	3.470	3.542
Pb (ppm)	5.3	4.8	3.6	4	1.2	3.382	2.916	4.638	2.945
$^{238}U/^{204}Pb$	1.39	15.72	16.83	13.94	16.68	9.847	13.061	3.240	17.848
$^{235}U/^{204}Pb$	0.01	0.12	0.12	0.10	0.12	0.072	0.096	0.024	0.131
$^{232}Th/^{204}Pb$	5.84	73.70	73.56	69.56	66.26	52.027	60.165	46.976	75.520
$^{206}Pb/^{204}Pb_m$	18.309	19.291	19.439	19.348	19.436	19.189	19.271	18.674	19.282
$^{207}Pb/^{204}Pb_m$	15.606	15.647	15.638	15.626	15.647	15.632	15.631	15.594	15.622
$^{208}Pb/^{204}Pb_m$	38.357	39.725	39.813	39.787	39.791	39.583	39.625	39.424	39.681
$^{206}Pb/^{204}Pb_{(255Ma)}$	18.253	18.670	18.774	18.797	18.777	18.792	18.744	18.543	18.562
$^{207}Pb/^{204}Pb_{(255Ma)}$	15.603	15.615	15.604	15.597	15.613	15.611	15.604	15.587	15.585
$^{208}Pb/^{204}Pb_{(255Ma)}$	38.284	38.808	38.897	38.921	38.966	38.922	38.861	38.827	38.722

4. Analytical results

4.1. Petrographic characteristics

The analyzed samples are mostly phyric olivine basalts and subsidiary alkaline basalts with major phenocrysts of olivine constituting about 3 to 5 vol.% (Figs. 3a-f). The groundmass is intersertal, micro-doleritic, containing microlites of clinopyroxene, plagioclase, ore minerals, (rare) olivine and volcanic glass (Figs. 3c-d). Olivine phenocrysts are euhedral or subhedral, tablet- or irregular shaped, with sizes ranging from 0.1 by 0.3 mm to 0.3 by 0.5 mm (Fig. 2a-c). Some alkaline basalts contain iddingsite, a product of altered olivine. Some basalts are aphyric with the groundmass comprising microlites of clinopyroxene and plagioclase (Fig. 3c-d, e-f). The welded tuff contains fragments of altered lavas cemented by volcanic ash (Figs. 4c-d). The volcanic ash is coarse- or fine grained (Fig. 2d), disoriented (Fig. 5a) or layered and oriented (Fig. 5b).

4.2. Major element compositions

Cam Thuy basalts (in the Lam Son area) with SiO_2, varying from 47.70 to 50.33 wt.% and total alkaline oxides (Na_2O+K_2O) from 2.42 to 4.10 wt.%, are distributed in the subalkaline field, while only a few samples plot in the alkaline field (Fig. 6). This features are expressed in terms of CIPW normative mineralogical compositions showing that only one sample (040213/6) contains nepheline (Ne)-normative of 3.38 wt.% (Table 1), and all remaining samples are subakaline rock type (containing olivine (Ol)-normative) or tholeiitic basalt, containing quartz (Q)- and hypersthene (Hy)-normative (Table 1).

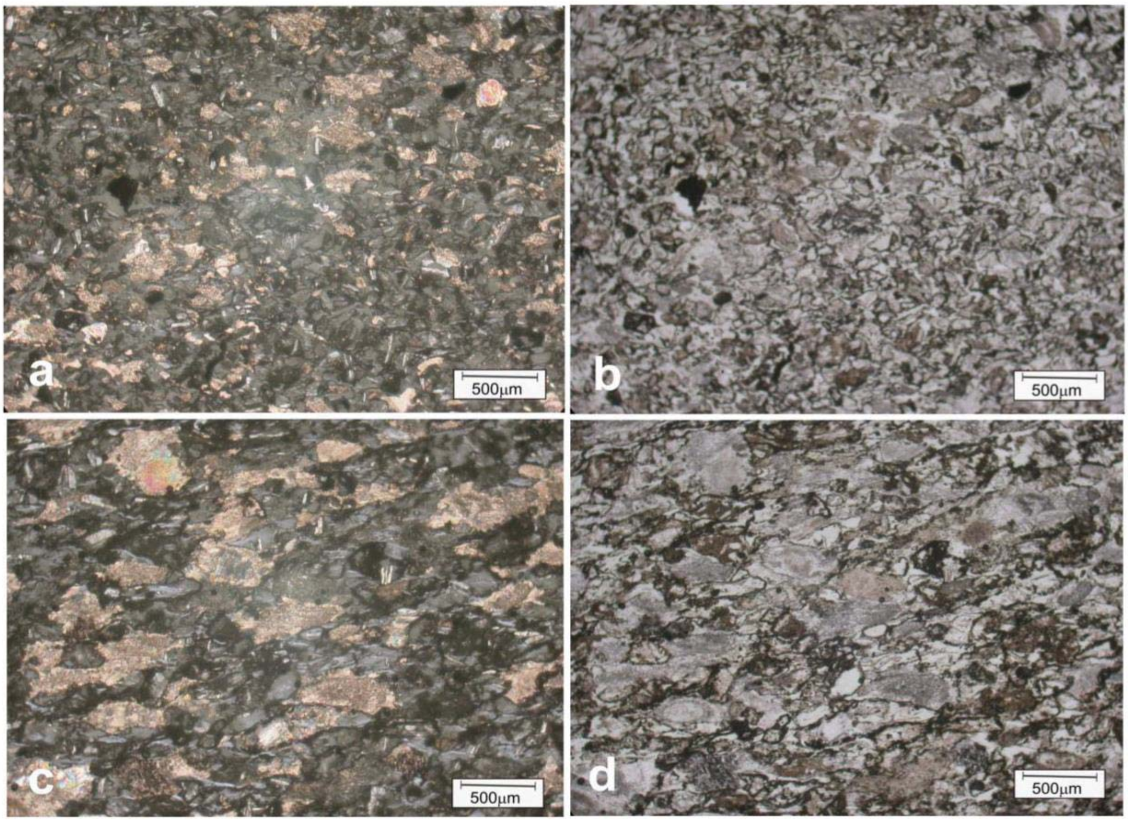


Figure 4. a-b (sample CT150616-E) and c-d (samplCT150616-F) tuff composed of basaltic fragments of variable sizes, cemented by volcanic ash; layered and oriented; fragments are partially chloritized, carbonatized and albitized lava

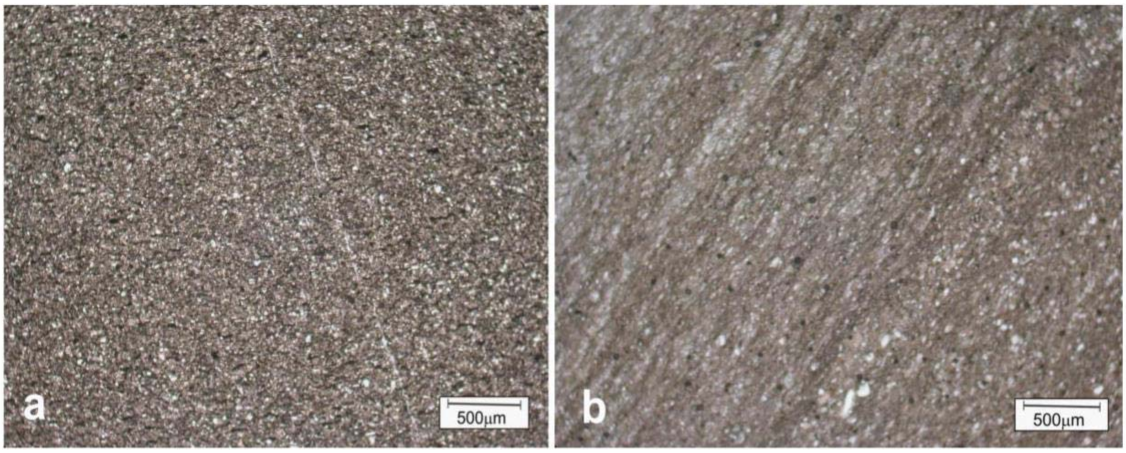


Figure 5. a: (sample CT150616-G); b: (CT150616-H) volcanic ash, coarse- or fine-grained, with or without orientation and zonation

MgO contents of the Cam Thuy basalts vary from 5.8 wt.% to 7.2 wt.%, plotted between MgO values of the Song Da and Emeishan basalts (Fig. 7). In a similar way, except for having much higher CaO contents than those of the Song Da and Emeishan basalts, the other oxides such as SiO_2, TiO_2, FeOt, Na_2O and K_2O of the Cam Thuy basalts plot between fields of the Song Da and Emeishan magmatic rocks and almost overlap those of high-Ti basalt type (Fig. 7).

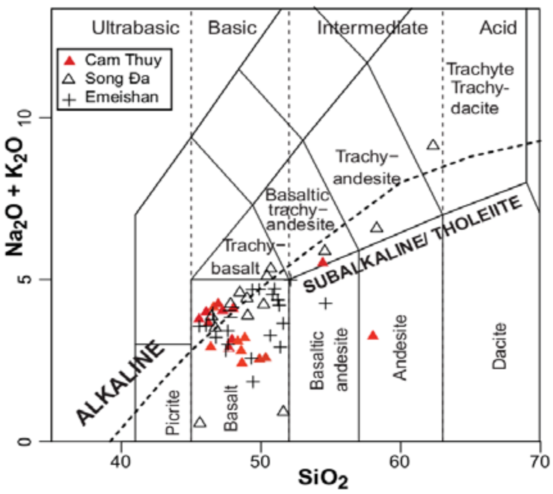


Figure 6. Basaltic TAS (total alkalis vs. SiO_2) classification (after Le Bas et al., 1986) showing samples of Cam Thuy basalt (this study); Song Da basalts (Hoang et al., 2016) and Emeishan samples (Xu et al., 2001, 2004). Cam Thuy basalts mostly overlap those of Song Da high-Ti basalt series and plot between high- and low-Ti of Emeishan magmas

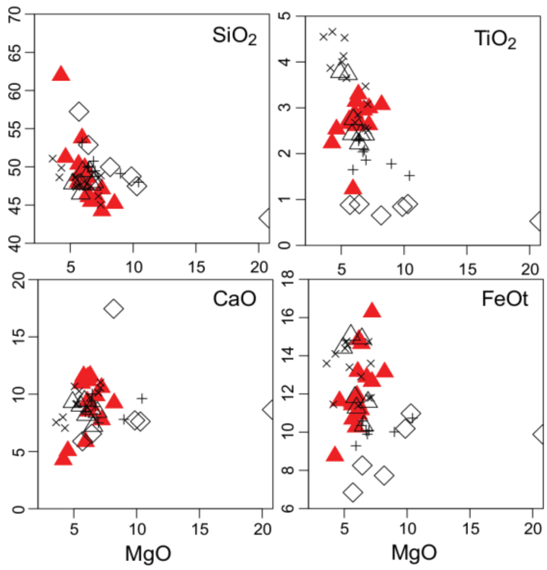


Figure 7. Correlation between MgO (wt.%) and major silicate oxides showing Emeishan and Song Da basalts with CaO values being lower compared with the Cam Thuy basalts, while TiO_2 contents of Cam Thuy basalts being comparable to Song Da high-Ti basalts (empty triangle) but lower than Emeishan high-Ti basalts (cross); symbols for Song Da low-Ti: empty diamond, Emeishan low-Ti magma: x

4.3. Trace element compositions

Primitive mantle normalized trace element (Hofmann, 1988) and chondrite normalized rare earth element (Anders and Grevesse, 1989) distribution patterns of the Cam Thuy basalts are shown (Figs. 8a, 9a, respectively) along with Song Da high-Ti basalts (Son La Pass and nearby areas) (Figs. 8b, 9b) and geological standards made from volcanic rocks of various tectonic settings (Figs. 8c, 9c) for comparison (N. Hoang et al., 2016a).

The trace and rare earth element distribution patterns of Cam Thuy basalts show smooth decrease from left to right (Figs.8b, 7b), almost overlapping trace and rare earth element distribution curve of the Song Da high-Ti basalts (Figs. 8b, 9b) (data from Hoang et al., 2016a). The basalt samples both of Song Da and Cam Thuy show patterns, which are closely analogous to oceanic island basalts (e.g. JB-1a and BHVO-2 in Figures 8c and 9c).

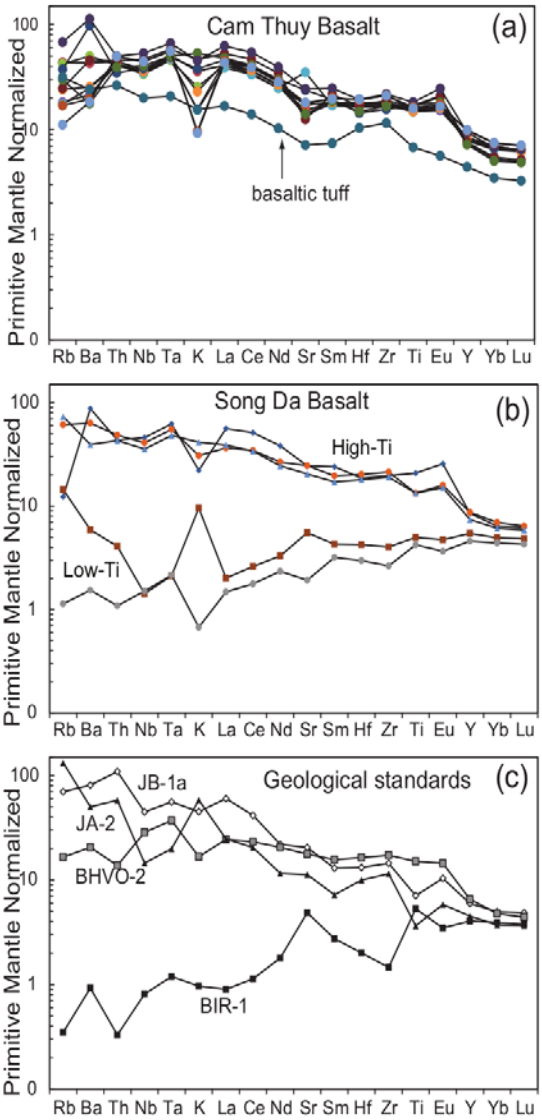
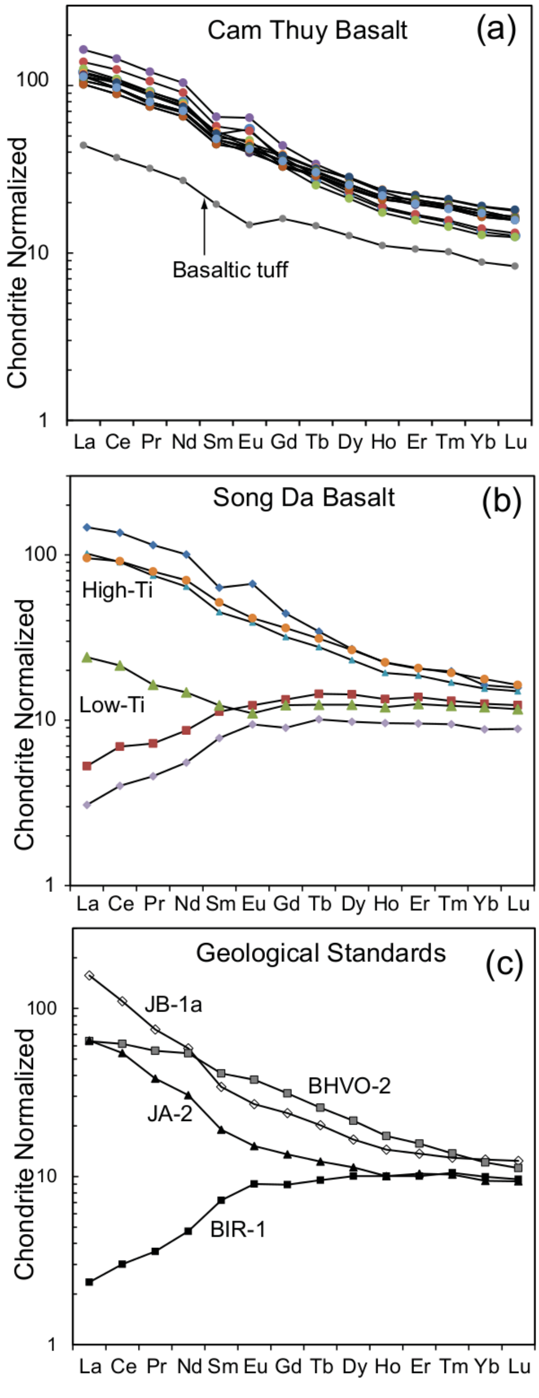


Figure 8. Primitive mantle normalized trace element patterns of Cam Thuy basalts (a) as compared to Song Da high-Ti basalts (b); geological standards (BIR-1: Indian MORB; BHVO-2: Hawaiian OIB; JB-1a: continental intraplate basalt; JA-2: arc andesite) are shown for comparison (c). Normalizing data are after Hofmann (1988). Note that the trace element distribution patterns of Cam Thuy basalts being closely analogous to Song Da high-Ti basalts are essentially oceanic island basalt-like



→ **Figure 9.** Chondrite normalized rare earth element (after Anders and Grevesse, 1989) distribution patterns of Cam Thuy basalts (a); shown are Song Da high-Ti basalts (b) and geological standards (c) for comparison (see Figure 8 caption). The rare earth element configuration curves of Cam Thuy basalts are comparable to Song Da high-Ti basalts while vastly different from the low-Ti basalt type, having a N-MORB shape (BIR-1)

4.4. Isotopic compositions

The initial $^{87}Sr/^{86}Sr$ ratios of the Cam Thuy basalts calculated for 255 Ma after Song Da basaltic eruption age (e.g. Balykin et al., 1996; Tran et al., 2008, after Tang et al., 2015) range from 0.70528 to 0.70584. These initial isotopic ratios accompanied by $\varepsilon_{Nd(255Ma)}$ varying from 0.69 to -1.41, are plotted between two fields of depleted mantle (DM) and enriched continental crust (Fig. 10), overlapping the field of the Song Da high-Ti basalt and covering partially that of Emeishan high-Ti basalt. The initial $^{87}Sr/^{86}Sr$ ratios of the Cam Thuy basalts are lower as compared with Emeishan basalts and much lower compared with Song Da low-Ti basalts having 255 Ma initial $^{87}Sr/^{86}Sr$ ratios from 0.7055 to 0.7115 accompanied by $\varepsilon_{Nd(255Ma)}$ changing between 7.5 and -9 (Xu et al., 2001; Hoang et al., 2004, 2016a).

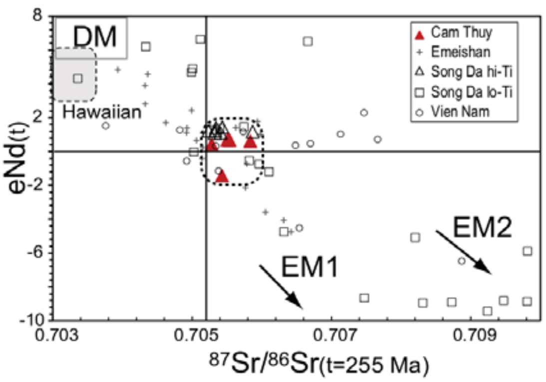


Figure 10. Plots of initial (255 Ma) $^{87}Sr/^{86}Sr$ isotopic ratios versus $\varepsilon_{Nd(t)}$ of Cam Thuy magmatic rocks. Emeishan and Song Da basalts are shown for comparison. Fields of depleted mantle (DM) and enriched mantle type 1 and 2 (EM1, EM2) and Hawaiian OIB (data from Norman and Garcia, 1999) are shown for reference. Note Cam Thuy basaltic distribution field includes that of Song Da high-Ti basalts away from Song Da low-Ti and Emeishan magmatic rocks

The initial $^{206}Pb/^{204}Pb$ ratios (255 Ma) of the Cam Thuy basalts plotted against $^{207}Pb/^{204}Pb_i$ and $^{208}Pb/^{204}Pb_i$ ratios are shown in Fig. 11a-b. The lead isotopic ratios plot close to the depleted mantle (DM) field (represented by Pacific MORB), overlapping the field of the Song Da high-Ti basalt and separating from the field of the low-Ti basalt. The latter, with higher $^{206}Pb/^{204}Pb_i$, $^{207}Pb/^{204}Pb_i$ and $^{208}Pb/^{204}Pb_i$, trend toward enriched fields.

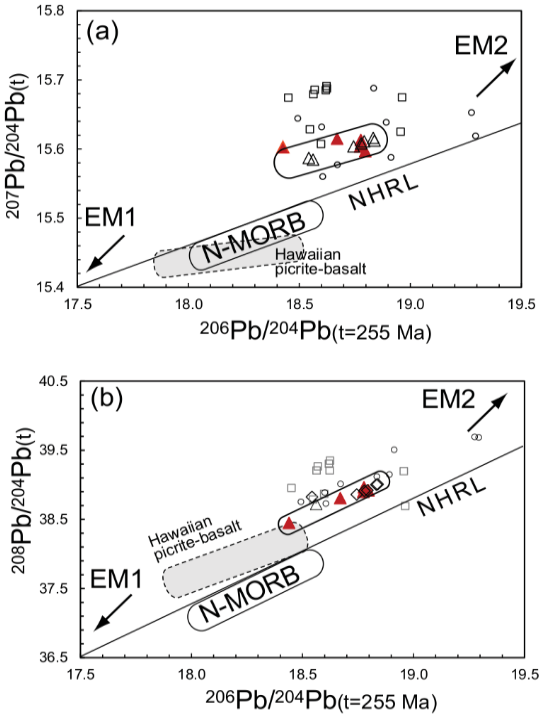


Figure 11. Plots of initial (255Ma) $^{206}Pb/^{204}Pb$ isotopic ratios versus (a) $^{207}Pb/^{204}Pb$ and (b) $^{208}Pb/^{204}Pb$ of Cam Thuy basalts as compared to Song Da basalts; EM2, EM1 (enriched mantle type 1 and 2), Hawaiian OIB (Norman and Garcia, 1999) and (depleted) Mid-Ocean Ridge Basalt (N-MORB) are shown for reference. Symbols as in Figure 10. Northern Hemisphere Reference Line (NHRL) illustrates enriched (above) and depleted mantle domains

5. Discussion

5.1. Tectonic setting of Cam Thuy basalts

Igneous rocks formed in different tectonic settings may be affected by in situ materials at different levels. For example, at a subduction zone, magmatic melts may be affected by oceanic crustal material, brought to the mantle by the subducting slab, in the form of hydrous fluid, which appears to be one of the causes of lowering melting temperature of the mantle wedge. Using Zr/Y plotted against Zr in the tectonic setting discrimination diagram (after Pearce and Norry, 1979), the Cam Thuy basalts, Emeishan and most of Song Da magmatic rocks plot in the field of intraplate magmas (Fig. 12). Some Song Da low-Ti basalts plot in the subduction field, making them different from the Cam Thuy lavas.

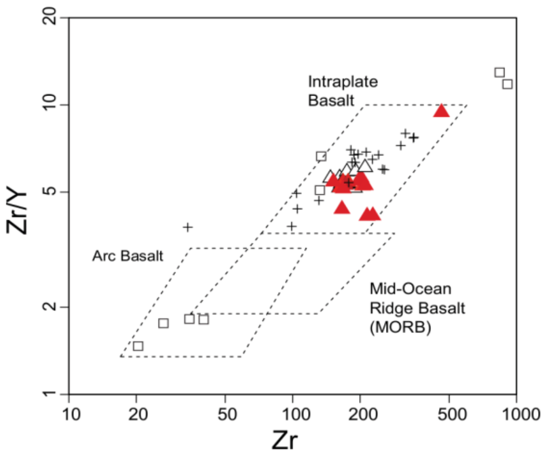


Figure 12. Tectonic discrimination diagram (after Pearce and Norry, 1979) showing Cam Thuy basalts plotting in intraplate basalt field comparable to Emeishan basalts and many of the Song Da magmatic rocks; some Song Da low-Ti basalts plot in field of island arc. Symbols as in Figure 10

Basaltic melts on the way to the surface may interact with crustal rocks. Crustal material interaction may result in increasing Ba, Rb, Th, etc., contents relative to Nb, Ta, Zr,… in basaltic melts, forming positive correlation between (for example) Ba/Nb against SiO_2 and negative correlation with MgO (or Mg#). Cam Thuy basalts have low SiO_2 and K_2O contents and show oceanic island basalt-like trace element distribution patterns (Figs. 8, 9), indicating minimal crustal involvement. Besides, correlation between Ti/Zr against Ba/Zr and Rb/Zr shows that most of the Cam Thuy basalts plot along the mantle array separating the mantle source and continental crust fields (Figs. 13a, b, 14) (after Hoang and Uto, 2003). Note that some of the Song Da low-Ti basalts plot in the crustal field, suggesting, to some extent, crustal contamination. Taken together with the Sr and Nd chondritic isotopic compositions (Fig. 10) and OIB-like trace element distribution patterns (Figs. 8 and 9), the Cam Thuy basalts reported here are certainly free from crustal contamination. These geochemical features are also observed for Song Da high-Ti basalts reported elsewhere (e.g. Hoang et al., 2016a), suggesting close similarity in source of origin and melt generation parameters between these two basaltic magmas.

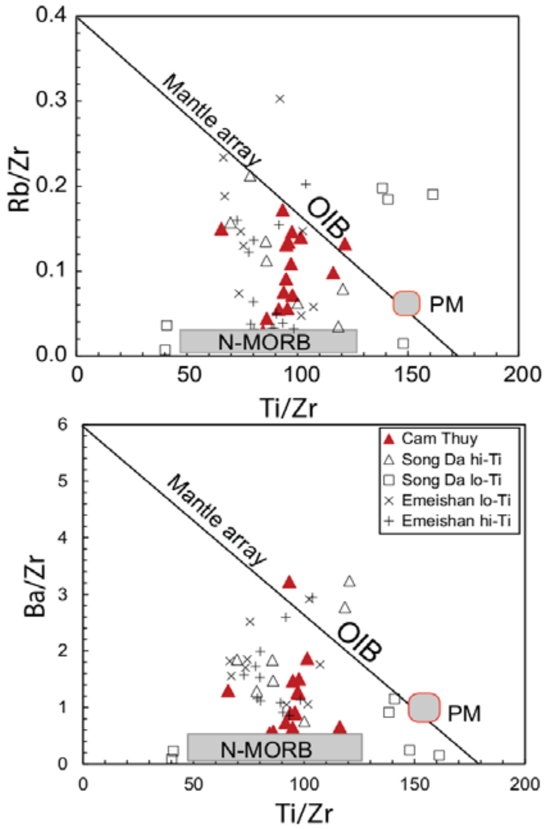


Figure 13. Correlation between (a) Ti/Zr and Ba/Zr and (b) Ti/Zr and Rb/Zr for Cam Thuy basalts as compared to Song Da basalts relative to depleted mid-ocean ridge basalt mantle (N-MORB), the mantle array (representing by oceanic island basalt: OIB, after Kogiso et al. (1997) and Frey et al. (2000), and primitive mantle after Hofmann (1988). Modified after Hoang and Uto (2003). See text for explanations

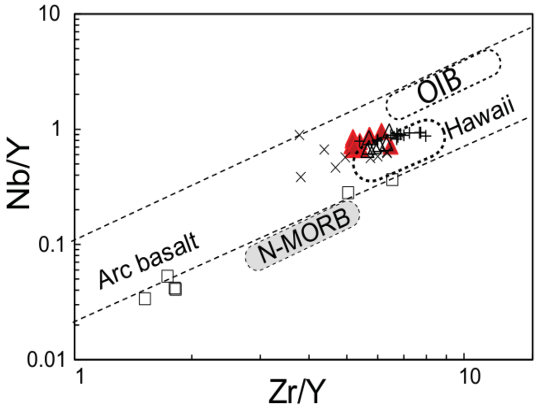


Figure 14. Plots of Zr/Y against Nb/Y of Cam Thuy basalt along with Song Da and Emeishan magmatic rocks; fields of OIB (North Arch, data from Frey et al., 2000), Hawaiian OIB (after Norman and Garcia, 1999), N-MORB and Arc magmas are shown for reference. Dashed lines signifying ranges of mantle-derived magmas are compiled from world literature

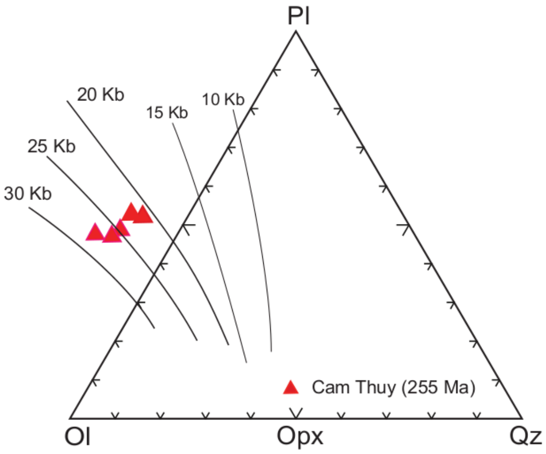


Figure 15. Plots of Olivine (Ol) – Plagioclase (Pl) – Quartz (Qz) for representative computed Cam Thuy primitive melt compositions (after Walker et al., 1979) compared with experimental isobaric liquidi from Hirose and Kushiro (1993) and Kushiro (1996). Accordingly, Cam Thuy basalts segregated from their magma sources between 22.5 and 28 Kb with potential temperatures of about 1400ºC to 1450ºC (after Hoang and Flower, 1998)

5.2. Mantle sources and melt forming conditions

Geochemical compositions of lithospheric mantle-derived rocks commonly have high MgO and SiO_2 contents but especially low FeO, CaO, Na_2O and K_2O (termed as mafic component), as a result of previous partial melting events (Turner and Hawkesworth, 1995). Generally, the lithospheric mantle-derived mafic melts are low in trace element compositions, especially highly incompatible elements such as Rb, Ba, K and light rare earth elements such as La, Ce and Nd. However, depending on the timing of melting events (long enough for radioactive decay to form sizable daughter products), cumulating melts from deeper mantle or extracting melts due to local melting could lead to enrichment or depletion of trace element or isotopic composition that may be different (Menzies et al., 1987; Carlson and Irving, 1994; Ionov and Hofmann, 2007). Several studies have suggested that lithospheric mantle is refractory in mafic component and “dry”, therefore it is difficult for partial melting to occur. However, Gallagher and Hawkesworth (1994) showed that water liberation from water-rich minerals (such as amphibole) (Ionov and Hofmann, 2007) along with hot mantle upwelling following a lithospheric extension event may facilitate melting processes to occur easily (Turner and Hawkesworth, 1995; Hoang and Flower, 1998).

Cam Thuy basalt are relatively low in MgO and SiO_2 contents, high FeO, CaO and Al_2O_3 although moderate in Na_2O and K_2O (Figs. 6, 7; Table 1). As mentioned above the trace element and rare earth element distribution patterns of Cam Thuy basalts are essentially oceanic island basalt (OIB)-like (Figs. 8, 9) in terms of BHVO-2, a Hawaiian OIB standard and JB-1a, a continental intraplate basalt, whose melts are viewed as asthenosphere- derived.

There are several approaches to estimating magma segregation depths. These include: (1) mathematical inversion of melt compositions of specified source and its sub-solidus residua, assuming fractional or batch melting within a polybaric melt column (e.g. McKenzie and O'Nions, 1991; Scarrow and Cox, 1995; Turner and Hawkesworth, 1995), (2) interpolation from H_2O-saturated and unsaturated experimental studies of fertile and refractory peridotite (e.g. Hoang and Flower, 1998). Assuming mantle H_2O contents beneath NW Vietnam to be minimal we have made best estimates of pressure, temperature and melt fraction by comparing primitive melt compositions with anhydrous or near-anhydrous experimental studies (e.g. Hirose and Kushiro, 1993; Kushiro, 1990, 1996), the approach adopted by Hoang and Flower (1998). The *primitive* melt compositions used were interpolated from high MgO basalts, with possible effects of olivine fractionation minimized. Assuming that realistic Mg/(Mg + Fe^{2+}) ratios of olivine in mantle residua approximate 0.70, having equilibrated with segregated partial melts. This was achieved by adding small (0.1%) increments of olivine to eruptive composition with MgO> 6wt%, assuming olivine being the sole liquidus phase observed (Yamashita et al., 1996; after Walker et al., 1979). It was likewise assumed that magmas with mafic phenocrysts of around $Fo_{89–90}$, match residual mantle olivine, according to an olivine-melt K_d (FeO/MgO) value of 0.30 and Fe_2O_3 to be 0.15 of FeO* (Roeder and Emslie, 1970). Plotted in the pseudo-ternary (normative) Ol-Pl-Qz system (Fig. 15; after Walker et al., 1979) estimated primitive Cam Thuy melt compositions are shown for comparison with experimental isobaric, partial melts of spinel/garnet lherzolite (Hirose and Kushiro, 1993; Kushiro, 1996). In the case of Cam Thuy, the calculated melts may reflect a decrease in melt fraction with increasing pressure (22.5 → 28 Kbar) suggesting a polybaric partial melting column between depths of 65 and 85 km. According to the approach adopted, comparison of primitive magmas to experimental studies of primitive basalts (Kushiro, 1996) and relatively fertile peridotites (HK-66 in Hirose and Kushiro, 1993), potential temperatures of about 1400ºC →1450ºC appear to be reasonable with primitive melts segregating at pressures between 22.5 and 28 Kbar (after Hoang and Flower, 1998), and the most plausible melting mechanism being adiabatic decompression of ductile asthenosphere.

5.3. Geochemical - petrographic comparison between Cam Thuy, Song Da and Emeishan magmatic rocks

Song Da magmatic rocks are categorized into high-Ti and low-Ti types. Low-Ti rock type is lower in Nb, Ta, lighter rare earth elements and higher in MgO and SiO_2 relative to the high-Ti magma type (Balykin et al., 2010; Xu et al., 2001, 2004). Trace element and isotopic characteristics of the Cam Thuy basalts are essentially oceanic island basalt (OIB)-like, approximated to Song Da high-Ti basalts (Figs. 8-9). Their initial (255 Ma) Pb, and especially Sr and Nd isotopic ratios are chondritic (Figs. 10, 11). The above geochemical and isotopic characteristics along with the computed melting pressures and temperatures Fig. 15), for Cam Thuy basalts and Song Da (in the Son La area) high-Ti basalt indicate that they are most likely derived from an enriched and possibly fertile mantle source (Fig. 14). These features also differentiate the above magmatic rocks from the Song Da low-Ti rock type, which has been considered as heterogeneous lithospheric mantle- derived melts (Figs. 10-14). An analogous type has yet to be discovered among the Cam Thuy volcanic rocks.

The Emeishan high- and low-Ti magmatic types are geochemically heterogeneous, showing highly variable major and trace element contents, covering both Cam Thuy and Song Da magmatic distribution fields (this study; Xu et al., 2001; Hoang et al., 2016a). Their Sr-Nd isotopic compositions are also highly variable (Figs. 10, 12-14), trending from depleted to enriched field; although the enrichment, is not comparable to Song Da low-Ti magmatic type, leaving the latter most enriched magma type among the three basaltic regions (Figs. 10-11). A study of picrites in the Emeishan large igneous province suggests a secular change from melting of a peridotite to a garnet pyroxenite mantle source produced, respectively, from the low- and high-Ti magma end-members. Moreover, the similarity in Sr and Nd isotopic compositions ($^{87}Sr/^{86}Sr_i$~ 0.7045 and $\varepsilon_{Nd(t)}$~ 1.7) of the two magma types may reflect a source in the sub-continental lithospheric mantle rather than the convective asthenosphere or a deep mantle plume (Kamenetsky et al., 2012).

It has been long believed that Song Da (and Cam Thuy) magmatic association is part of the Emeishan LIP having been extruded southeastward about 700 km from its SW Chinese site along the Red River Shear zone or an extruding channel between the Red River and Song Ma Fault zone (Fig. 1a) following the India - Asia collision about 30 Ma (Chung et al., 1997; Wang et al., 1997; Lan et al., 2000; Tran et al., 2008; after Tapponnier et al., 1982, 1986; Le Loup et al., 1995; Gilder et al., 1996). While there is not much physical evidence supporting the extrusion mechanism (see Flower et al., 1998; Cung and Geissman, 2013); the fact that the Song Da high- and low-Ti magma types may not be genetically related (Hoang et al., 2016a; after Kamenetsky et al., 2012), and that the distribution of Cam Thuy magmatic formation on both sides of the Song Ma fault zone needs further investigation.

6. Concluding remarks

Cam Thuy Permian volcanic rocks exposed in the Lam Son area (Tho Xuan, Thanh Hoa province) comprise thick basaltic lava flows and pyroclastic layers, with a total thickness exceeding a few hundred meters. The rock types are mostly olivine-phyric basalt and a minor amount of alkaline basalt and *(quartz-normative)* tholeiitic basalt.

The *computed* melt compositions of the Cam Thuy basalts compared with experimental partial melting of a relatively fertile and enriched spinel lherzolite (HK-66, Hirose and Kushiro, 1993) show their melt segregation pressures from 22.5 to 28 Kb (ca. 65 to 85 km) and corresponding temperatures from 1400ºC to 1450ºC. Their trace element characteristics are enriched oceanic island basalt (OIB)-like. The major and trace element features along with their chondritic Sr-Nd (and Pb) isotopic compositions match those of the Song Da (and some of Emeishan) high-Ti magma type, and in conjunction with their geographical proximity, suggesting that they may share a same fertile and thermally anomalous mantle source.

Various low-Ti basaltic and picritic rock types, viewed as melts generated from heterogeneously depleted and refractory sources in the sub-continental lithospheric mantle, appear popular in the Song Da and Emeishan magmatic associations (e.g. Chung and Jahn, 1995; Xu et al., 2001, 2004; Kamenetsky et al., 2012; Tran et al., 2015) but have yet to be discovered in the Cam Thuy magmatic formation. This difference may reflect discrete source heterogeneity and melting mechanism among the three Permian volcanic fields.

Acknowledgments

This study is supported by (Vietnam) National Foundation for Science and Technology Development (NAFOSTED) under grant number 105.05-2012-22 (NH). The Institute of Geological Sciences, VAST, is thanked for financing the major and trace element analysis. Tran Thanh Hai, Hanoi University of Mining and Geology, and Phan

Van Hung (IGS) are thanked for providing information on the outcrops. Critical comments by two anonymous reviewers help improve the manuscript significantly from an earlier version. Proof reading and suggestions by Rolando Peña (University of the Philippines, Quezon) are gratefully acknowledged.

References

Anders, E., Grevesse, N., 1989. Abundances of the elements: meteorite and solar. Geochimica et Cosmochimica Acta 53, 197-214.

Balykin, P.A, Polykov G.V., Petrova T.E., Hoang, H.T., Tran, T.H., Ngo, T.P., Tran, Q.H., 1996. Petrology and evolution of the formation of Permian-Triassic mafic-ultramafic associations in North Vietnam. J. Geology B/7-8, 59-64, Hanoi.

Balykin, P.A, Polykov, G.V., Izokh, A.E., Tran, T.H., Ngo, T.P., Tran, Q.H., Petrova, T.E, 2010. Geochemistry and petrogenesis of Permian ultramafic- mafic complexes of the Jin-ping-Song Da rift (Southeastern Asia), Russian Geology and Geophysics, 51, 6, 611-624.

Carlson, R.W., Irving, A.J., 1994. Depletion and enrichment history of subcontinental lithospheric mantle: An Os, Sr, Nd, and Pb isotopic study of ultramafic xenoliths from northern Wyoming Craton. Earth and Planetary Science Letters 126, 457-472.

Chung S.L, Jahn, B.M., 1995. Plume-lithosphere interaction in generation of the Emeishan flood basalts at the Permian-Triassic boundary, Geology, 23, 10, 889-892.

Chung, S.L., Lee, T.Y., Lo, C.H., Wang, P.-L., Chen, C.-Y., Nguyen, T.Y., Tran, T.H., Wu, G.-Y., 1997.Intraplate extension prior to continental extrusion along the Alao Shan-Red River shear zone. Geology, 25, 311-314.

Cung, T.C., Geissman, J., 2013. A review of the paleomagnetic data from Cretaceous to lower Tertiary rocks from Vietnam, Indochina and South China, and their implications for Cenozoic tectonism in Vietnam and adjacent areas. Journal of Geodynamics 69, 54-64.

Dovjikov, A.E. (Editor), 1965. Geology of Northern Viet Nam. General Dept. Geology of Viet Nam. Science and Technique Publishing, Hanoi, 668p (in Russian).

Gallagher, K., Hawkesworth, C.J., 1994. Mantle plumes, continental magmatism and symmetry in the South Atlantic. Earth and Planetary Science Letters, 123, 105-117.

Gilder, S.A, Gill, J., Coe, R.S., Zhao, X.X., Liu, Z.W., Yuan, K.R., Liu, W.L., Kuang, G.D, Wu, H.R., 1996. Isotopic and paleomagnetic constrains n the Mesozoic tectonic evolution of south China. Jourral of Geophysical Research 101, 16,137-16, 154.

Flower, M.F.J., Tamaki, K., Hoang, N., 1998. Mantle extrusion: a model for dispersed volcanism and DUPAL-like asthenosphere in East Asia and the WPAC. In: Flower, M.F.J., Chung, S.L., Lo, C.H. (Eds.), Mantle Dynamics and Plate Interactions in east Asia, Geodynamics Series, vol. 27. American Geophysical Union, pp. 67-88.

Frey, F.A., Clague, D., Mahoney, J.J., Sinton, J.M., 2000. Volcanism at the edge of the Hawaiian plume: petrogenesis of submarine alkalic lavas from the North Arch volcanic field. Journal of Petrology 41, 667-691.

Hanski, E., Walker, R.J., Huhma, H., Polyakov, G.V., Balykin, P.A., Tran, T. Hoa, Ngo, T. Phuong, 2004. Origin of the Permian-Triassic komatiites, northwestern Vietnam: Contributions to Mineralogy and Petrology 147, 453-469.

Hirose, K., Kushiro, I., 1993. Partial melting of dry peridotites at high pressures: determination of composition of melts segregated from peridotite using aggregate of diamond. Earth and Planetary Science Letters 114, 477-489.

Hofmann, A.W, 1997. Mantle geochemistry: the message from oceanic volcanism. Nature 385, 219-229.

Hofmann, A.W., 1988. Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust. Earth and Planetary Science Letters 90, 297-314.

Ionov, D., Hofmann, A.W., 2007. Depth of formation of subcontinental off-craton peridotites. Earth and Planetary Science Letters 261, 620-634.

Ishizuka, O., Taylor, R.N., Milton, J.A., Nesbitt, R.W., 2003. Fluid-mantle interaction in an intra-oceanic arc: constraints from high-precision Pb isotopes. Earth Planet. Sci. Lett. 211, 221-236.

Izokh, A.E., Polyakov, V.G., Tran, T. Hoa, Balykin, P.A., Ngo, T. Phuong, 2005. Permian-Triassic ultramafic-mafic magmatism of northern Viet Nam and southern China as expression of plume magmatism. Russian Geology and Geophysics (Geologiya I Geofizika) 46 (9), 922-932 (942-951).

Kamenetsky, V., Chung, S-L., Kamenetsky, M.B., Kuzmin, D.V., 2012. Picrites from the Emeishan large igneous province, SW China: a compositional continuum in primitive magmas and their respective mantle sources. Journal of Petrology 53 (10), 2095-2113.

Kogiso, T., Tatsumi, Y., Shimoda, G., Barsczus, H., 1997. High μ (HIMU) ocean island basalts in southern Polynesia: New evidence for whole mantle scale recycling of subducted oceanic crust. J. Geophys. Res. 102, 8085-8103.

Kushiro, I., 1990. Partial melting of mantle wedge and evolution of island arc crust. Journal of Geophysical Research 95, 15929-15939.

Kushiro, I., 1996. Partial melting of a fertile mantle peridotite at high pressure: An experimental study using aggregates of diamond; in: Basu, A., Hart, S.R. (Eds.), Earth Processes: Reading the Isotopic Code. Geophys. Monogr. 95, American Geophysical Union, pp. 109-122.

Lan, C-Y., Chung, S-L., Shen, J.J-S., Lo, C-H., Wang, P-L., Hoa, T.T., Thanh, H.H., Martzman, S.A., 2000. Geochemical and Sr-Nd isotopic characteristics of granitic rocks from northern Vietnam. Journal of Asian Earth Sciences 18, 267-280.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27, 745-750.

Le, D. Bach, Dang, T. Quan., 1995.Geological and mineral resources map of Viet Nam 1:200.000. Thanh Hoa Sheet, with Explanatory note. General Dept. Geology of Vietnam, Hanoi.

Leloup H. Ph., R. Lacassin, P. Tapponnier, U. Scharer, Zhong Dalai, Liu Xaohan, Zhangshan, Ji Shaocheng and Phan Trong Trinh, 1995. The Ailao Shan-Red River shear zone (Yuunan, China), Tertiary transform boundary of Indochina. Tectonophysics, 251, 3-84.

Lo, C.H, Chung, S.L., Lee, T.Y., Wu, G., 2002. Age of the Emeishan flood magmatism and relations to Permian-Triassic boundary events. Earth and Planetary Science Letters 198, 449-458.

Menzies, M.A., Rogers, N.W., Tindle, A., Hawkesworth, C.J., 1987. Metasomatic and enrichment processes in lithospheric peridotites, an effect of asthenosphere-lithosphere interaction. In Menzies, M.A., Hawkesworth, C.J. (Eds.) Mantle Metasomatism, 313-359. Academic Press

Nguyen Hoang, Flower, M.F.J., 1998. Petrogenesis of Cenozoic basalts from Vietnam: Implications for the origin of a 'diffuse igneous province'. Journal of Petrology 39, No 3, 369-395.

Nguyen Hoang, Nguyen, D. Lu, Nguyen, V. Can, 2004. Paleozoic volcanic rocks in the Song Da region: mantle sources and dynamics. J. Geology 282(7-8, Series A), 10-18 (in Vietnamese with English abstract).

Nguyen Hoang, Shinjo, R., Ogasawara, M., Tran, T. Huong, Phan, V. Hung, Flower, M. F.J., 2016a. Sources of Permian magmas in the Song Da rift zone and their relation to the Emeishan-LIP volcanic rocks (SW China). Lithos (under review).

Nguyen Hoang, Tran T. Huong, Dao, T. Bac, Nguyen, V. Vu, Nguyen, T. Thu, Cu, S. Thang, Pham, T. Dang, 2016b. Magma source feature and eruption age of volcanic rocks in the Tram Tau district, Tu Le Basin. Vietnam Journal of Earth Sciences 38 (No 3), 242-255.

Nguyen Hoang, Uto, K., 2003. Geochemistry of Cenozoic basalts in the Fukuoka district (northern Kyushu, Japan): implications for asthenosphere and lithospheric mantle interaction. Chemical Geology 198, 249-268.

Nguyen Hoang, Uto, K., 2006. Upper mantle isotopic components beneath the Ryukyu arc system: Evidence for 'back-arc' entrapment of Pacific MORB mantle. Earth and Planetary Science Letters 249, 229-240.

Nguyen Hoang, Uto, K., Matsumoto, A., Itoh, J., 2013. Pleistocene intraplate magmatism in the Goto Islands, SW Japan: implications for mantle source evolution and regional geodynamics. J. Geodynamics 68, 1–17.

Norman, M.D., Garcia, M.O., 1999. Primitive magmas and source characteristics of the Hawaiian plume: petrology and geochemistry of shield picrites. Earth and Planetary Science Letters 168, 27-44.

Pearce, J.A., Norry, M.J., 1979. Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. Contributions to Mineralogy and Petrology 69, 33-37.

Polyakov, G.V., Balykin, P.A., Glotov, A.I., Tran, Q.H., Ngo, T.P., Hoang, H.T., Bui, A.N., 1991. Permo-Triassic association of high-magnesian volcanites of the Song Da Zone (North-Western Vietnam). Geologiyai Geofizika (Russian Geology and Geophysic) 32(9), 3-15 (1-11).

Polyakov, G.V., Nguyen, T.Y., Balykin, P.A., Tran, T. Hoa, Hoang, H. Thanh, Tran, Q. Hung, Ngo, T. Phuong, Petrova, T.E., Vu, V. Van, 1996. Permian - Triassic mafic and ultramafic formations in northern Viet Nam. Science and Technology Publ., Hanoi, 172 p (in Vietnamese).

Roeder, P.L., Emslie, R.F., 1970. Olivine-liquid equilibria. Contributions to Mineralogy and Petrology 29, 275-289.

Scarrow, J.H., Cox, K.G., 1995. Basalts generated by decompressive adiabatic melting of a mantle plume: a case study from the Isle of Skye, NW Scotland. Journal of Petrology 36, 3-22.

Tang, Q., Li, C., Zhang, M., Lin, Y., 2015.U–Pb age and Hf isotopes of zircon from basaltic andesite and geochemical fingerprinting of the associated picrites in the Emeishan large igneous province, SW China. Miner Petrol.109, 103-114.

Tapponnier, P., Peltzer, G., Armijo, R., 1986. On the mechanics of the collision between India and Asia. In: M.P. Coward and A.C. Ries (Editors), Collision Tectonics. Geological Society of London, special publication, pp. 115-157.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., Cobbold, P., 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. Geology, 7, 611-616.

Tong, D. Thanh, Vu Khuc, 2005.Stratigraphic units of Viet Nam. Vietnam national university publisher, Hanoi, 504pp (in Vietnamese).

Tran, D. Luong, Nguyen, X. Bao, 1988. Geological map of Viet Nam at 1:500,000. Geological Survey of Viet Nam.

Tran, T. Hoa, 2002. Subdivision and correlation of Permian-Triassic basaltoid association in the Song Da structure (NW Vietnam). Journal of Geology, 19-20.

Tran, T. Hoa (editor), 2011. Intraplate magmatism and metallogeny of North Vietnam. Science and Technology Published, Hanoi.

Tran, T. Hoa, Hoang, H. Thanh, Tran, T. Anh, Ngo, T. Phuong, Hoang, T. Hang, 1998. High-Ti basaltoid associations in the Song Da rift zone: chemical compositions and formation geodynamics. Journal of Geology, Series A, 244 7-15 (in Vietnamese with English abstract).

Tran, T. Hoa, Izokh, A.E., Polyakov, G.V., Borisenko, A.S., Tran, T. Anh, Balykin, P.A., Ngo, T. Phuong, Rudnev, S.N., Vu, V. Van, Bui, A. Nien, 2008. Permo-Triassic magmatism and metallogeny of Northern Viet Nam in relation to the Emeishan plume. Russian Geology and Geophysics (Geologiya i Geofizika) 49 (7), 480-491 (637-651).

Tran, T. Hoa, Lan, Ch-Y., Usuki, T., Shellnutt, J.G., Pham, Thi Dung, Tran, T. Anh, Pham, Ng. Can, Ngo, T. Ph., Izokh, A.E., Borishenko, A.S., 2015. Petrogenesis of Late Permian silicic rocks of Tu Le basin and Phan Si Pan uplift (NW Vietnam) and their association with the Emeishan large igneous province. Journal of Asian Earth Sciences, 109, 1-19.

Tran, T. Hoa, Nguyen Hoang, 2013. Guide to the field trip. International symposium "Large igneous provinces of Asia: mantle plumes and metallogeny", Hanoi, November 7-11, 2013, 20p.

Tran, T. Hoa, Nguyen, T. Yem, Ngo, T. Phuong, Hoang, H. Thanh, Tran, Q. Hung, Bui, A. Nien, Hoang, T. Hang, Polyakov, G., Balykin, P.A., Tran, T. Anh, 1995. Magnesia-ultrapotassic magmatic rocks and lamproite problems in northwestern Viet Nam. Journal of Geology 5, 412-419 (in Vietnamese with English abstract).

Tran, T. Hoa, Polyakov, G.V., Tran, T. A., Borisenko, A.S., Izokh, A.E., Balykin, P.A., Ngo, T. Phuong, Pham, T. Dung, 2015. Intraplate Magmatism and Metallogeny of North Vietnam. Modern Approaches in Solid Earth Sciences, Springer International Publishing house, Switzerland, 372p.

Tran, T. Hoa, Tran, T. Anh, Ngo T. Phuong., Izokh, A.E., Polyakov, V.G., Balykin, P.A., Lan C.Y., Hoang, H. Thanh, Bui, A. Nien, Pham, T. Dung, 2004. Gabbro-syenite associations of East Bac Bo structures: evidences of intra-plate magmatism? J. Geology, Ser. B 23 pp. 12-25.

Tran, V. Tri., Tran, T. Hoa, 2011. Late Paleozoic-Mesozoic Song Da - Tu Le intracontinental rift system. Geology and Natural Resources, Science and Technology Publisher, Hanoi, 425-431.

Turner, S., Hawkesworth, C., 1995. The nature of the sub-continental mantle: constraints from the major element composition of continental flood basalts. Chemical Geology 120, 295-314.

Usuki, T. Lan, Ch-Y., Tran, T. Hoa, Pham, T. Dung, Wang, K-L., Shellnut, G.L., Chung, S-l/., 2015. Zircon U-Pb ages and Hf isotopic compositions of alkaline silicic magmatic rocks in the Phan Si Pan - Tu Le region, northern Vietnam: Identification of a displaced western extension of the Emeishan Large Igneous Province. Journal of Asian Earth Sciences 97, 102-124.

Walker, D., Shibata, T., DeLong, D.E., 1979. Abyssal tholeiites from the Oceanographer Fracture Zone III. Phase equilibria and mixing. Contributions to Mineralogy and Petrology 70, 111-125.

Wang, C.Y., Zhou, M.F., Qi, L., 2007. Permian flood basalts and mafic intrusions in the Jinping (SW China - Song Da (northern Vietnam) district: Mantle sources, crustal contamination and sulfide segregation. Chemical Geology 243, 317-343.

Xu, Y., Bin, H., Chung, S.L., Menzies, M.A., Frey, F.A., 2004. Geologic, geochemical, and geophysical consequences of plume involvement in the Emeishan flood-basalt province. Geology 32, 10, 917-920.

Xu, Y., Chung, S.L, Jahn, B., Wud, G., 2001. Petrologic and geochemical constraints on the petrogenesis of Permian-Triassic Emeishan flood basalts in southwestern China. Lithos 58, 3-4, 145-168.

Yamashita, S., Tatsumi, Y., Nohda, S., 1996. Temporal variation in primary magma compositions in the northeast Japan Arc. The Island Arc 5, 276-288.

Zhou, M.F., Malpas, J., Song, X.Y., Robinson, P.T., Sun, M., Kennedy, K., Lesher, C.M., Keays, R.R., 2002a. A temporal link between the Emeishan large igneous province (SW China) and the end-Guadalupian mass extinction. Earth Planet. Sci. Lett.196, 113-122.