Vietnam Journal of Earth Sciences 38(3), 242-255

(VAST)

Vietnam Academy of Science and Technology

Vietnam Journal of Earth Sciences

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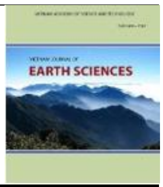

Magma source feature and eruption age of volcanic rocks in the Tram Tau district, Tu Le Basin

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Received 19 September 2015. Accepted 13 May 2016

ABSTRACT

A set of samples including porphyritic rhyolite, rhyo-trachyte, trachyte and basalt was collected in the Tram Tau district, Tu Le Mesozoic Basin, in NW Viet Nam for analysis for major, trace, elemental and Rb-Sr and Sm-Nd isotopic compositions. The volcanic rocks are alkaline and highly enriched in trace elements including rare earth elements (REEs). However, primitive mantle and chondrite trace element normalized patterns expose strong negative anomalies for Ba, Sr, Eu and Ti, possibly reflecting fractional crystallization of plagioclase (for Sr and Eu), pyroxene, and especially amphibole (for Ba and Ti). The measured $^{87}Sr/^{86}Sr$ isotopic ratios, varying between 0.8142 and 0.75283, are plotted against the corresponding $^{87}Rb/^{86}Sr$ forming an isochron that provides an age of 157± 2.9 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.708, corresponding to late Jurassic - early Cretaceous (J_3-K_1) in agreement with previously reported data. The corresponding Nd isotopic compositions expressed as $\varepsilon_{Nd\ (157Ma)}$ vary from -8,27 to -2.32 and the Nd model ages are Mesoproterozoic, ranging from 1 to 1.3 Ga. This highly enriched magma was postulated to have formed by mixing of a depleted mantle and Mesoproterozoic crustal rocks (for example, granite) following a continental extension event. Mixing between crustal rocks having strontium isotopic ratios of 0.715 and 0.730 and a depleted mantle with $^{87}Sr/^{86}Sr$ ratio of 0.703 would occur, respectively, at 3÷4% and 2÷5% to generate the observed strontium isotopic ratios in the Tram Tau volcanic rocks.

Keywords: Tram Tau, Tu Le Basin, NW Viet Nam, isotopic mixing, geochemistry.

1. Introduction

Intraplate rifting structures such as Song Da - Tu Le and Song Hien are important units in the tectonic framework of northern Viet Nam in the Late Permian - Early Mesozoic (Tran and Tran, 2009). The Tu Le Basin, termed as intraplate rift (Dovjikov et al., 1965; Tran and Nguyen, 1979, 1988; Vu and Bui, 1989; Dao and Huynh, 1995) located to the northeast of the Song Da rift (Figure 1) is a dependent trough-shaped basin, formed in the Mesozoic (Hutchison, 1989; Nguyen and Tran, 1992) with a total thickness reaching up to 5000 m (Phan, 1977; Nguyen, 1978). The lower section of the basin is filled with Jurassic - Cretaceous red sediments, while the upper section is comprised by volcanic rocks having contrasting compositions including rhyolite, trachyte and basalt, where alkaline

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rhyolite, rhyo-trachyte and trachyte are dominant. Plutonic magmatic rocks such as gabbro, syenite, granosyenite, sub-alkaline and alkaline granite are minor and found at Phu Sa Phin and elsewhere in the Tu Le Basin (Nguyen et al., 1995).

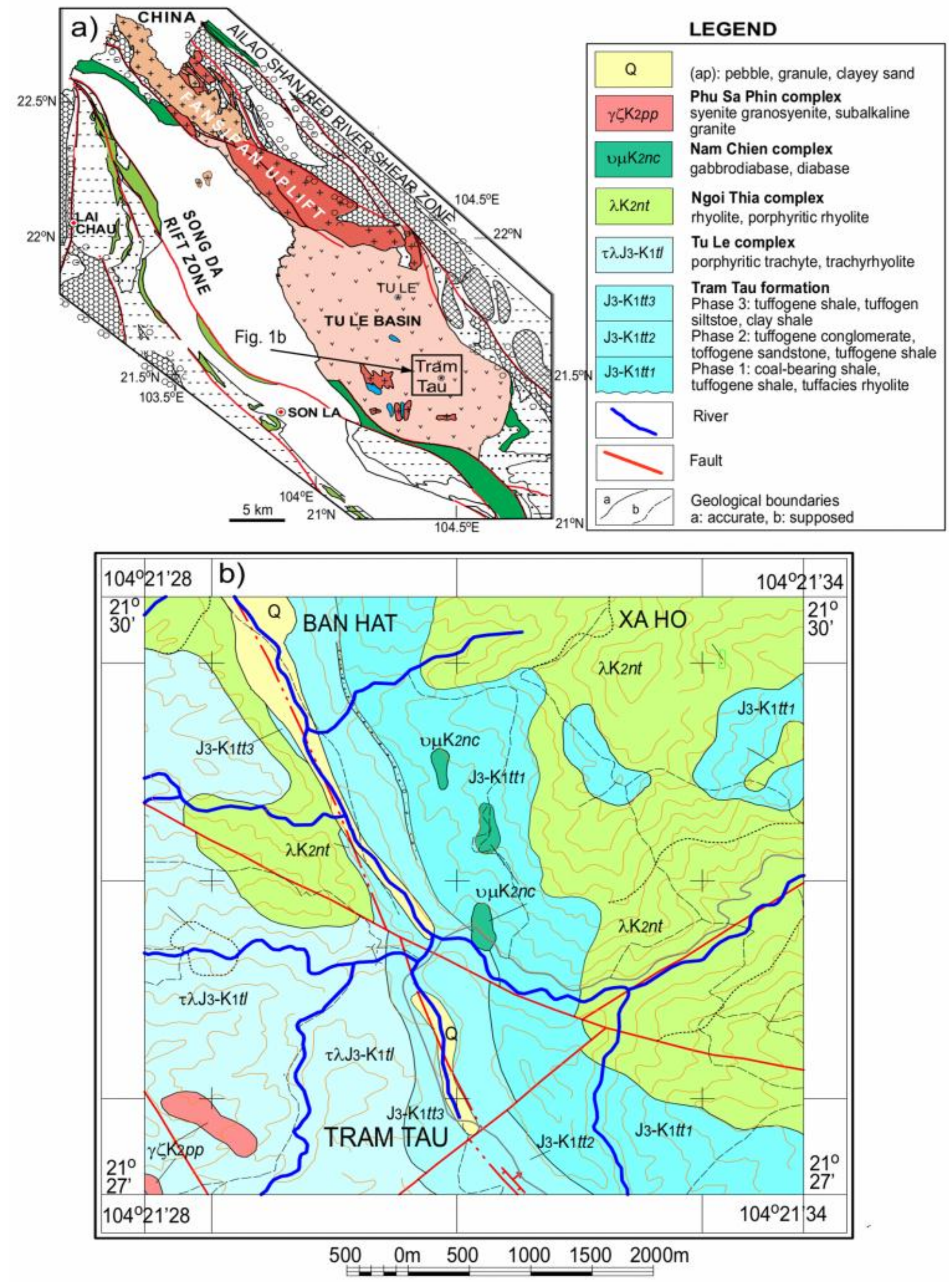


Figure 1. a) Schematic illustration of major tectonic units in NW Viet Nam, showing Ailao Shan Red River Tertiary Shear zone, Fan Si Pan Uplift terrain, Song Da Permian-Triassic plutonic-volcanic rift zone and Tu Le Mesozoic Volcanic Basin. Simplified from Tran et al. (2004); (b) geological scheme of Tram Tau district; sampling route started from Xa Ho to Ban Hat Liu to Tram Tau town, along the intervillage road. Simplified from Yen Bai geological sheet at 1:200,000 after Nguyen Vinh (2005)

The magmatic formations in the Tu Le Basin are divided into two sub-alkaline and alkaline pluton-volcanic mafic and felsic series. According to Nguyen et al. (1995, 1997) magmatism in the Tu Le Basin occurred at many successive stages, showing characteristic syn- pluton volcanic activity, on the one hand, and clearly contrasting compositions, on the other. Examples include alkaline mafic - silicic volcanic rocks in the Ban Hat village (Phan, 1977; Nguyen et al., 2000) and late Jurassic - Early Cretaceous sub-alkaline syn- pluton - volcanic mafic - silicic rocks of Nam Chien and Phu Sa Phin complexes (Tran, 1996; Vu and Tran, 2007), and alkaline volcanism of Ngoi Thia complex (Phan, 1977). The end of the Tu Le intraplate rifting was marked by the appearance of sole Al-oversaturated sub-alkaline granitoidic magmatism of Ye Yen Sun complex in early Paleogene (Nguyen and Tran, 1992; Tran et al., 2002, and references therein).

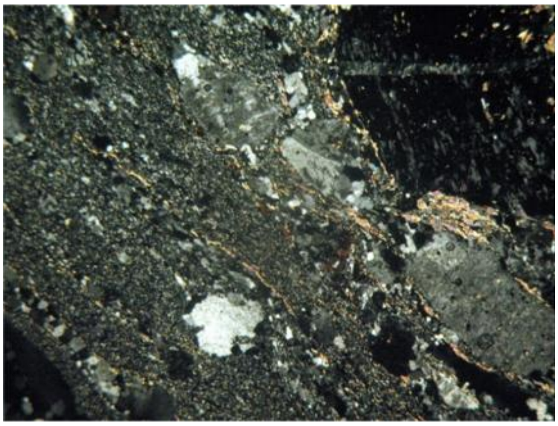
Alkaline and sub-alkaline pluton-volcanic felsic complexes classified as Jurassic-Cretaceous Ngoi Thia and Tu Le (τλJ-K *tl*) complexes (Dovjikov et al., 1965; Phan, 1977; Nguyen, 1978; Vu et al., 1989; Nguyen et al., 2000, 2003; Tran et al., 2004; Tran and Tran, 2009; Pham et al., 2000; Tran, 2011) are exposed in the Tram Tau district, Yen Bai province (Figure 1). A large set of rhyolite, rhyo-trachyte and trachyte samples was collected along two cross-sections along the stream near the Hat Liu Commune administration building to Xa Ho commune, Tram Tau district. Additional samples along with (rare) fresh basalts were collected at outcrops from Ban Hat communal headquarter toward the provincial route leading to Tram Tau town with a total length about 5 km. The samples were processed for petrographic study, and age, geochemical and isotope data acquisition and interpretation for magma source character and related mantle dynamic processes of the Tu Le pluton-volcanic complex.

2. Petrography

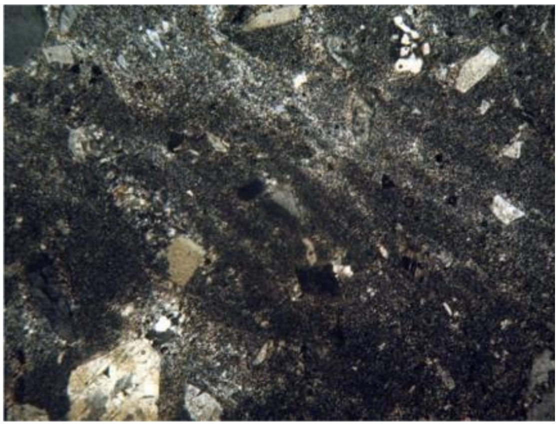
Rhyolite, rhyo-trachyte, trachyte samples were collected along two cross-sections, along the inter-village road from the Ban Hat bridge to Xa Ho village; additional samples, including basalts, were sampled at outcrops along Ban Hat village administrative building toward the intersection leading to Tram Tau town (Figure 1) in a total length of nearly 5 km. The rhyolite, rhyo-trachyte, trachyte and (rare) basalt are porphyritic. The rhyolite is grayish white, rosy white, relatively fresh. The phenocrysts including K-feldspar and quartz take up to 30% of the total rock volume. The feldspar is idiomorphic, with sizes up to 0.5 × 1 mm. Quartz phenocrysts, up to 15 vol.% (sample 120405-3), are mostly sub-idiomorphic, sometimes irregularly fragmented, with sizes up to 1 × 1 mm. The groundmass is trachytic, containing microlites of quartz, biotite, and small amounts of K-feldspar and volcanic glass (Figure 2a, b).

The trachyte is gray, murky white or rosy white, having lesser phenocrysts compared with the porphyritic rhyolite. K-feldspar is the only phenocryst, and up to 1 x 1.8 mm in dimension, occupying volumes ranging from 5% to 15%. The groundmass is trachytic, consisting of microlites of K-feldspar, hydrous mica (or biotite?), and a minor amount of quartz and secondary carbonate minerals.

The basalt (diabase?) (Figure 2c) is black, sometimes greenish black with plagioclase and clinopyroxene in the phenocryst phase (ca. 7 vol.%). The plagioclase phenocrysts are elongated up to 2 mm long, randomly distributed among the clinopyroxene phenocrysts, which are irregularly tabular-shaped, about 0.1 × 0.3 mm in dimension. Secondary minerals include epidote, chlorite, sericite and calcite, which appear as aggregates in the groundmass.



(a)



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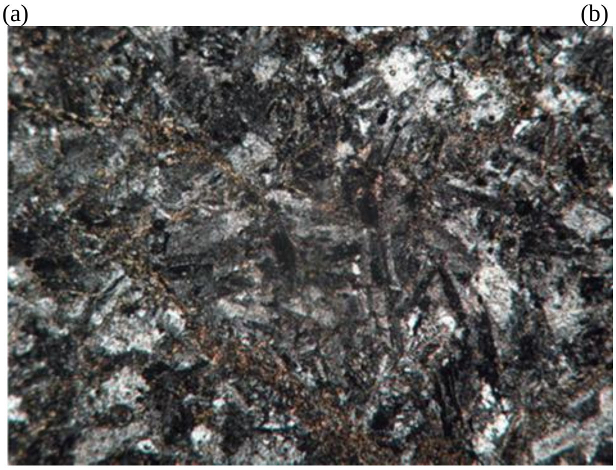

(c)

Figure 2. Photomicrographs from thin sections of Tram Tau volcanic rocks showing porphyritic rhyolite with K-feldspar and quartz phenocrysts (a, b); elongated plagioclase and small tabular clinopyroxene in doleritic texture of basalt (c)

3. Sample preparation and analytical procedures

3.1. Sample preparation

About 50 g of fresh sample was chosen for geochemical and isotopic analysis. The samples were crushed to <2 mm, then washed in an ultrasonic bath for about 30 minutes, followed by repeated rinsing with purified water before being dried overnight in an oven at about 100°C. Loss on ignition was calculated using about 2 g of powder, baked in an oven at 1050°C for about one hour.

3.2. Analysis of major and trace elements

The analysis for major elements were obtained from fused glass beads using a XRF Bruker Pioneer analyzer at the Institute of Geological Sciences, Vietnam Academy of Science and Technology (VAST). Geological standards JP-1, JB-1a, JB-3, JA-1, JA-2, JG-1, JR-1 and JR-3 provided by the Geological Survey of Japan (GSJ) were employed for the analytical calibration, and the accuracy evaluation, which is better than ±5%. The trace elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) using an Agilent 8800 ICP-MS at GSJ. The trace element analytical procedures and running parameters were similar to those described in Ishizuka et al. (2003). Reproducibility of this method is better than ±4% for rare earth elements, Rb and Nb, and better than ±6% for other elements. Data are shown in Table 1.

Table 1. Major and trace element compositions, and Rb-Sr, Sm-Nd isotopic ratios of representative samples from Ban Hat Liu, Tram Tau (Tu Le Basin)

Sample ID	120405-1	120405-2	120405-3	120405-8	03032013-7	03032013-5
Longitude	E2378075	E2378193	E2378321	E2377766	E2374474	E2376010
Latitude	N0433692	N0433874	N0433875	N0434426	N0436073	N0435090
Rock type	Rhyolite	Rhyolite	Rhyolite	Rhyolite	Trachyte	Basalt
SiO_2	72.94	72.19	72.78	76.66	67.56	52.08
TiO_2	0.45	0.44	0.42	0.28	0.99	2.62
Al_2O_3	12.72	12.85	12.79	10.97	21.64	17.08
FeO*	3.09	2.98	3.11	2.73	2.52	8.14
MnO	0.01	0.04	0.04	0.07	0.01	0.11
MgO	0.51	0.24	0.24	0.26	0.65	8.12
CaO	0.08	0.78	0.58	0.26	0.02	1.80
Na_2O	1.60	2.30	2.11	1.25	0.16	3.19
K_2O	7.66	6.82	6.85	6.30	6.38	6.15
P_2O_5	0.04	0.06	0.06	0.02	0.08	0.71
LOI	0.88	1.28	1.03	1.21	1.10	0.65
Sum	100	100	100	100	100	100
Rb (ppm) (**)	174.576	147.227	169.898	208.442	195.024	
Sr (ppm) (†)	13.665	21.668	18.024	10.201	21.352	139.004
$^{87}Rb/^{86}Sr$	36.9666	19.6608	27.3117	59.1313	26.4283	51.682
$(^{87}Sr/^{86}Sr)_m$	0.788251	0.752829	0.768902	0.841203	0.767512	7.7824
2σ (±)	0.000008	0.000008	0.000010	0.000008	0.000008	0.725747
$(^{87}Sr/^{86}Sr)_i$	0.705837	0.708998	0.708014	0.709389	0.708586	
ε_{Sr} (t=157 Ma)	19.0	63.8	49.9	69.4	58.0	
Sm (ppm) (**)	8.117	19.028	12.680	21.214	27.991	7.597
Nd (ppm) (†)	39.958	114.495	50.640	106.223	141.148	41.795
$^{147}Sm/^{144}Nd$	0.12706	0.10395	0.15662	0.12491	0.12403	0.11369
$(^{143}Nd/^{144}Nd)_m$	0.512521	0.512334	0.512669	0.512574	0.512476	0.512269
2σ (±)	0.000010	0.000006	0.000006	0.000007	0.000006	0.000008
$(^{143}Nd/^{144}Nd)_i$	0.512238	0.512102	0.512320	0.512296	0.512200	
ε_{Nd} (157 Ma.)	-3.93	-6.57	-2.32	-2.79	-4.67	
$T_{(DM)}$ (Ga)	1.1	1.1	1.3	0.99	1.1	

Remarks: FeO* = 0.85×(FeO + Fe_2O_3); (**) analyzed by ICP-MS, (†) by isotope dilution; m: measured, i: initialized for t = 157 Ma; $\varepsilon_{Sr(t)} = [(^{87}Sr/^{86}Sr)_i /0.7045)-1] \times 10^4$, t =157 Ma; $\varepsilon_{Nd(t)} = [(^{143}Nd/^{144}Nd)_m /0.512439)-1] \times 10^4$; 0.512439 is CHUR's (Chondrite Uniform Reservoir) $^{143}Nd/^{144}Nd$ at t = 157 Ma (present value is 0.512638); T (depleted) model age = $1/\lambda \times \ln\{1+ [(^{143}Nd/^{144}Nd)_m) -0.51315]/[(^{147}Sm/^{144}Nd)_m- 0.2135]$, where 0.51315 and 0.2135 are $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ for present depleted mantle; λ: decay constant of ^{147}Sm to ^{143}Nd, = 6.54×10^{-12}; LOI: loss on ignition; The basalt (diabase) sample (03032013-5) of unknown origin is not used for isochron construction

3.3. Analysis of Sr and Nd isotopes

For Sr and Nd isotopic analysis, about 20 g of the cleaned chipped samples were washed in purified HCl 6N to eliminate secondary minerals (chlorite, carbonate, etc.). The samples were rinsed with clean water and dried in an oven at about 100°C. About 2 g of each processed sample were ground in an agate mill, then about 50 mg of the powder was weighed in a 15 ml Teflon beaker to be dissolved using concentrated HNO_3 and HF (ratio 1:2) on a hotplate for about 48 hours. After evaporation the samples were ready for anion exchange column chemistry.

Sr element was extracted using Sr-spec resin from Eichrom. Details of this procedure are described in Hoang and Uto (2006). Acids used for Sr extraction were HNO_3, having molarities varying between 0.05 and 7.5N. Solutions collected before Sr extraction were used for extraction of Nd and Sm using AG50W8X 200-400 resin followed by Ln-resin (Eichrom).

The isotopic ratios were measured on a 9-Faraday collector VG Sector 54 thermal ionization mass spectrometer (TIMS) at GSJ. Sr and Nd isotope running parameters were described in Hoang and Uto (2006). The reproducibility values of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are, respectively, ±0.000007 and ±0.00001 - ±0.000006. The isotopic compositions are shown in Table 1.

Table 1 (continued). Trace element compositions of representative volcanic samples from Ban Hat Liu, Tram Tau (Tu Le Basin)

Sample ID	120405-1	120405-2	120405-3	120405-8	03032013-7	03032013-5
Rock type	Rhyolite	Rhyolite	Rhyolite	Rhyolite	Trachyte	Basalt
(ppm)*						
Rb	174.58	147.23	169.90	208.44	195.50	148.89
Sr	8.47	22.54	14.53	11.12	20.35	47.56
Zr	86.06	83.12	153.59	598.97	1.499.28	36.58
Nb	161.27	144.50	110.43	202.14	305.94	54.25
Cs	0.48	0.53	0.52	0.76	3.405	6.964
Ba	218.34	452.19	537.84	138.56	1.005.23	629.57
Hf	2.34	2.22	4.13	15.72	36.27	0.92
Ta	9.95	9.01	7.99	14.84	22.02	3.87
Pb	3.63	4.87	4.70	3.33	25.49	2.89
Th	31.71	24.81	20.49	29.30	53.52	4.20
U	8.74	5.07	3.88	6.61	10.96	0.74
V	13.48	10.92	7.13	0.27	26.85	196.04
Cr	41.62	75.02	125.46	62.13	13.38	121.34
Ni	18.58	32.67	55.35	33.16	11.38	86.39
La	30.61	151.00	58.19	116.42	165.02	45.91
Ce	69.94	300.32	165.12	244.30	330.09	92.42
Pr	8.41	30.91	12.29	26.00	40.61	10.36
Nd	39.96	114.49	50.64	106.22	141.15	41.79
Sm	12.12	19.03	12.68	21.21	27.99	7.60
Eu	1.07	1.37	1.15	1.40	2.38	2.41
Gd	11.68	13.99	13.62	20.46	23.24	7.00
Tb	2.15	2.18	2.37	3.41	4.07	0.88
Dy	13.77	11.57	13.32	19.48	23.85	3.82
Ho	2.93	2.40	2.77	4.00	5.01	0.63
Er	8.56	7.05	8.12	11.38	15.02	1.40
Tm	1.18	1.00	1.15	1.80	2.40	0.18
Yb	6.99	5.76	6.92	9.94	14.79	0.96
Lu	0.75	0.74	0.90	1.33	2.11	0.15
Y	68.91	60.27	78.16	107.24	121.33	15.91

Remark: (*) Analyzed by Agilent 8800 ICP-MS at the Geological Survey of Japan. Error (%) from ±2 to ±6 for rare earth and LIL elements, for Nb and Ta is ± 5%

3.3. Analysis of Sr and Nd isotopes

For Sr and Nd isotopic analysis, about 20 g of the cleaned chipped samples were washed in purified HCl 6N to eliminate secondary minerals (chlorite, carbonate, etc.). The samples were rinsed with clean water and dried in an oven at about 100°C. About 2 g of each processed sample were ground in an agate mill, then about 50 mg of the powder was weighed in a 15 ml Teflon beaker to be dissolved using concentrated HNO_3 and HF (ratio 1:2) on a hotplate for about 48 hours. After evaporation the samples were ready for anion exchange column chemistry.

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The isotopic ratios were measured on a 9 Faraday collector VG Sector 54 thermal ionization mass spectrometer (TIMS) at GSJ. Sr and Nd isotope running parameters were described in Hoang and Uto (2006). The reproducibility values of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are, respectively, ±0.000007 and ±0.00001- ±0.000006. The isotopic compositions are shown in Table 1.

4. Analytical results

4.1. Major and trace element compositions

The Tram Tau SiO_2 contents vary from 49 wt.% to 75 wt.% with the total alkaline oxides (e.g. $Na_2O + K_2O$) from 3.2 to 9 wt.%. The samples, with rhyolite as dominant rock type, plot mainly in the alkaline field in SiO_2 vs. ($Na_2O + K_2O$) diagram (Figure 3, after Le Bas et al., 1986). Chondrite normalized rare earth element (e.g. Anders and Grevesse, 1989) and primitive mantle (e.g. Sun and McDonough, 1989) trace element normalized patterns of the Tram Tau volcanic rocks are shown in Figures 4a and 4b, respectively. The rhyolite and trachyte contain high trace element concentrations relative to chondritic and primitive mantle values, although showing strong negative anomalies for Ba, Sr, Eu and Ti. The negative anomalies may reflect fractional crystallization of plagioclase and feldspar (for Sr and Eu), olivine, pyroxene and, especially amphibole (for Ba and Ti) (e.g. Ionov and Hofmann, 1995). These geochemical features have been described in detail elsewhere in the literature (e.g. Nguyen et al., 1995; 1996; Tran, 1996; Tran et al., 2004, 2009, 2011). The basalt, on the other hand, is relatively depleted, showing low trace element abundances (Table 1) and having flat distribution pattern.

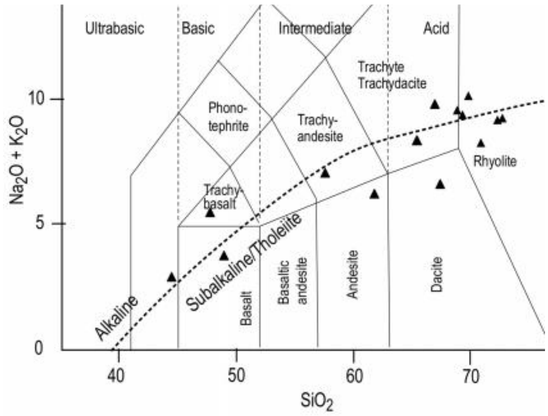

Figure 3. SiO_2 vs. ($Na_2O + K_2O$) classification diagram (after Le Bas et al., 1986) showing the majority of Tram Tau (Tu Le Basin, in general) samples are alkaline felsic type

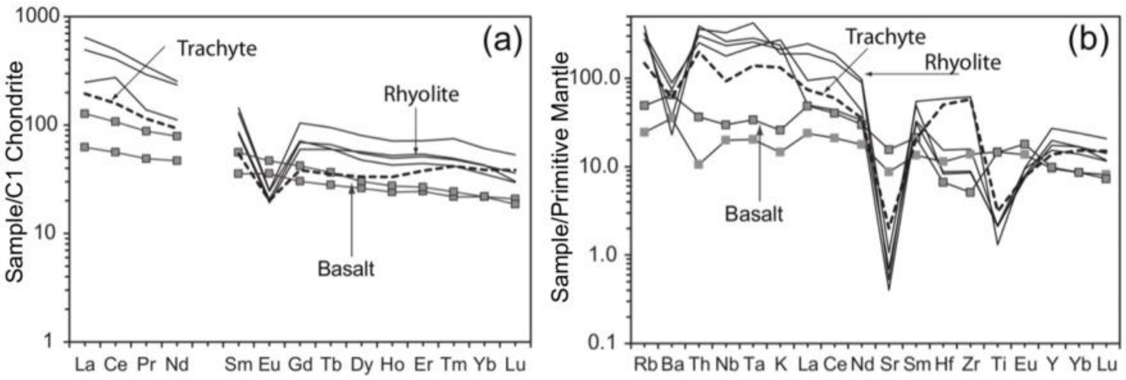

Figure 4. (a) Chondrite normalized rare earth element distribution patterns (after Anders and Grevesse, 1989) and (b) Primitive mantle normalized trace element (after Sun and McDonough, 1989) showing relative depletion of Ba, Eu, and Ti (b) and overall enrichment of all other elements

4.2. $^{87}Rb/^{86}Sr$ vs. $^{87}Sr/^{86}Sr$ isochron

A set of five samples including rhyolite, rhyo-trachyte and trachyte, and a basalt (120405-1, 120405-2, 120405-3, 120405-8, 03032013-7, and 03032013-5) were collected in the same outcrop near the Ban Hat bridge (Figure 1) for Rb/Sr age dating analysis. The Rb and Sr element contents were obtained both by isotope dilution and ICP-MS for comparison. The $^{87}Sr/^{86}Sr$ isotopic ratios of the samples were repeatedly run and the accuracy and precision were monitored by reference to measurements of NBS987 Sr isotopic standard. The $^{87}Rb/^{86}Sr$ were calculated based on the Rb and Sr concentrations by the following equation:

$^{87}Rb/^{86}Sr$ = Rb/Sr (ppm) x (A*b*^{87}Rb x *W*Sr)/(A*b*^{86}Sr x *W*Rb)

Where

A*b*^{87}Rb = % isotope ^{87}Rb in total Rb = 27.835%

A*b*^{86}Sr = % isotope ^{86}Sr in total Sr = 9.8615%

*W*Rb = atomic weight of ^{87}Rb = 85.468

*W*Sr = atomic weight of ^{86}Sr = 87.617.

The results are shown in Table 1. The $^{87}Rb/^{86}Sr$ isotopic ratios vary from 7.782 to 59.131 corresponding to $^{87}Sr/^{86}Sr$ varying from 0.7257 to 0.8412. Using Isoplot v. 4.1 by Ludwig (2012) for Excel 2010, plots of $^{87}Rb/^{86}Sr$ vs. $^{87}Sr/^{86}Sr$ form an isochron corresponding to 157 ±2.9 Ma (late Jurassic - early Cretaceous) and an initial $^{87}Sr/^{86}Sr$ ratio of 0.708 (Figure 5).

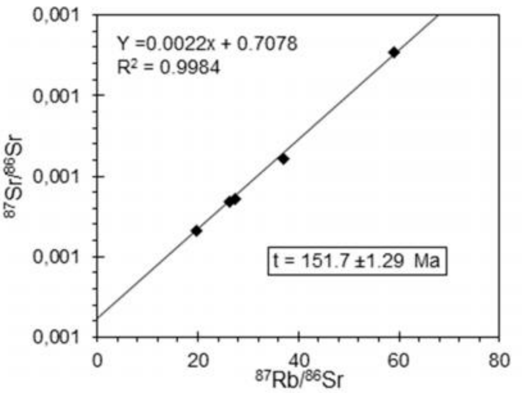

Figure 5. Plots of $^{87}Rb/^{86}Sr$ vs. $^{87}Sr/^{86}Sr$ (after Ludwig, 2012) of a set of samples (Table 2) collected in the Ban Hat Liu village forming an isochron of 157 ±2.9 Ma and an initial $^{87}Sr/^{86}Sr$ isotopic ratio of 0.708

5. Discussion

5.1. Regional tectonic - magma evolution

Tapponnier et al. (1982, 1990, 2001) suggested that Indochina was rotated clockwise while being extruded eastward along the Ailao Shan - Red River Shear zone (ASRRSZ) following the Indo - Eurasian collision in early Tertiary leading to the opening of (Viet Nam) East Sea (South China Sea) between 30 and 17 Ma (Tapponnier and Molnar, 1977; Tapponnier et al., 1982, 1990, 2001). Therefore, the ASRRSZ has been viewed as a suture zone between south China and Indochina (Leloup et al., 1995). With the aim of studying paleogeography in southern Chinese regions Gilder et al. (1996) conducted paleomagnetic, Rb-Sr and Sm-Nd isotopic measurements on samples collected from 23 Mesozoic granite outcrops in western Yunnan, China. They discovered that Mesozoic regional faults in southern China were mostly left lateral strike slips that activated simultaneously with intraplate extension as continental blocks having similar crustal structure moving northward (Gilder et al., 1996). These Mesozoic intraplate extension-induced granites are anomalously rich in Nd (>45 ppm) and Sm (>8 ppm), which reflect the difference between blocks extruded southeastward and those that remained stable in the north (Gilder et al., 1996). Following Gilder et al. (1996), while studying the relationship between geological and magmatic formations in northwest Yunnan and northwest Viet Nam, Chung et al. (1997) suggested that since the ASRRSZ is located in the South China continent, therefore the shear zone should not be viewed as a suture zone separating south China and Indochina as previously thought. These authors suggested that the boundary between the two blocks must be further south, possibly along the Song Ma ophiolite belt (Chung et al., 1997). According to these authors, following the India - Eurasian collision, a number of geological formations were extruded about 600 - 700 km from northwest Yunnan southeastward, to northwest Viet Nam, along this suture zone; also, the plate collision and collision-induced intraplate extension and spreading of (Viet Nam) East Sea about 30 million years ago could serve as the principal cause of the ASRRSZ formation.

Accordingly, Lan et al. (2000 and references therein), on the basis of Sr and Nd isotopic characteristics, suggested that the Po Sen (Middle Proterozoic), Dien Bien (Permian - Triassic), Tu Le rhyolite and Phu Sa Phin granite complex (J_3 - K), south of Tu Le Basin, may belong to the same plutonic-volcanic association. Because the Phu Sa Phin granite and Tu Le rhyolite show $\varepsilon_{Nd(t=145Ma)}$ between -2.8 and +0.6, and the neodymium model ages (T_{DM}) between 0.6 and 1.1 Ga, with the Sm varying from 17 to 30 ppm and corresponding Nd varying between 120 and 240 ppm; this plutonic-volcanic association may be produced by intraplate extension in south China (Yunnan) having been transported to the present location by lithospheric extrusion along the ASRRSZ following the collision between India and Eurasia (e.g. Leloup et al., 1995; Chung et al., 1997; Lan et al., 2000; after Tapponnier et al., 1990 and Gilder et al., 1996).

In contrast to Lan et al. (2000) and previously reported late Jurassic - early Cretaceous ages (see above), Ngoi Thia and Tu Le magmatic rocks have recently been determined as Permian by U-Pb isotopic age dating in zircons from a Ngoi Thia rhyolite (256 ±4 Ma, Nguyen et al., 2003), a Phu Sa Phin granite (261±2.8 Ma, Tran et al., 2009).

5.2. Mantle source and magma genesis in the Tu Le basin

Model ages of the Tu Le rhyolites reported by Lan et al. (2000) vary between 0.6 and 1.1 Ga, corresponding to Mesoproterozoic - Neoproterozoic. This age indicates that the magma was generated by mixing between Emeishan-type mantle source and crustal material having ages from 600 to 1100 million years by intraplate extension following South China and Indochina plate amalgamation dynamics in early Mesozoic (e.g. Chung and Jahn, 1995; Chung et al., 1998; Tran and Tran, 2011). The initial strontium isotopic ratios (for 157 Ma) for the Tram Tau samples vary between 0.70584 and 0.70942 ($\varepsilon_{Sr(t)}$ varies from 19 to 70); and accompanying $\varepsilon_{Nd(t)}$ varying from -2.32 to -8.27 and the $T_{(DM)}$ varies from 1 to 1.3 Ga, but most about 1.1 ±0.03 Ga (Table 1). These isotopic compositions are too enriched for a mantle source; therefore, there must be some crustal material involved in the Tram Tau magma generation (Figure 6). Assuming the initial $^{87}Sr/^{86}Sr$ of Proterozoic crust underneath Tu Le basin is in the range of that beneath Mesozoic basins in western Yunnan (China) (Gilder et al., 1996) and southeast China (Jahn et al., 1976) between 0.715 and 0.730, and a depleted mantle being 0.70315 (average of Pacific-MORB, e.g. White et al., 1987); to generate magmatic melts having $^{87}Sr/^{86}Sr$ from 0.7058 to 0.7094, the percentage of the crustal rocks involved in the mixing with the mantle source would be ca. 3÷4% and 2÷5%, respectively, (Figure 6). The mixing process could involve mantle upwelling following a lithospheric extension event, triggering decompression melts that interacted with crustal rocks that subsided in gravitational response to the lithospheric extension and mantle upwelling. Under the impact of hot mantle melts, the crustal rocks may be partially melted and incorporated into the mantle melts forming geochemically enriched melts (e.g. Sun and McDonough, 1989) (Figure 4a, b), which underwent fractional crystallization processes on the way to the surface.

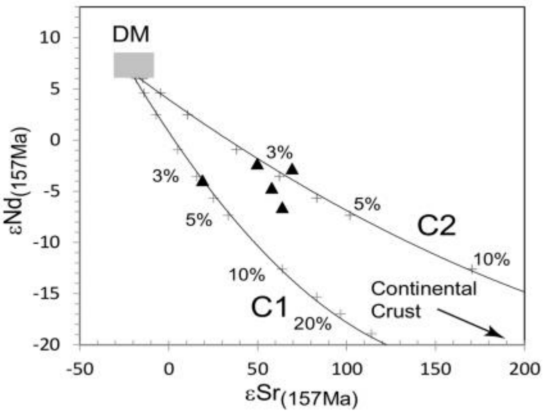

Figure 6. Plots of $\varepsilon_{Nd(t)}$ vs. $\varepsilon_{Sr(t)}$ of the Tram Tau volcanic rocks (ca. 157 Ma). Mixing curves were hypothesized assuming a mantle melt having $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios and Sr and Nd elemental contents, respectively, 0.703, 0.51315, 20 and 1.354 ppm to mix with 2 different crustal melts, having $^{143}Nd/^{144}Nd$, Sr and Nd contents (ppm), respectively, 0.5115 (ε_{Nd}= -22), 180 and 25; and $^{87}Sr/^{86}Sr$ isotopic ratios for curve (1) and (2), respectively, 0.715 (ε_{Sr}= 150), 0.730 (ε_{Sr}= 360). See explanations in the text.

Eruption age of the Tram Tau samples in this study is 157 ± 2.9 Ma, corresponding to late Jurassic - early Cretaceous. This age is in good agreement with many reported radiometric and fossil-base ages (e.g. Nguyen, 1978; Tran et al., 1979; Vu et al., 1989; Nguyen et al., 2000), which also falls in the age interval of Suoi Be complex (176.3 ±0.8, 164 ±0.8, and 117.3 ±0.6 Ma) (Tran et al., 2004).

Pham Duc Luong et al. (2010) extracted zircons from two rhyo-trachytes in the Tu Le complex and three rhyolites in the Ngoi Thia complex for U-Pb isotopic age dating using an LA-ICP-MS. Results showed that the trachytes formed around 114 and 116 Ma, while the rhyolites erupted at 93, 118 and 256 Ma. On this basis, the authors concluded that plutonic-volcanic igneous activities in the Tu Le basin may have occurred in a number of episodes, starting from late Permian to late Cretaceous, but mostly during late Jurassic - early Cretaceous (Pham et al., 2010).

As mentioned above, the $\varepsilon_{Sr(t)}$ and $\varepsilon_{Nd(t)}$, especially the $T_{(DM)}$ of Tram Tau volcanic rocks are much different from those of Mesozoic type-A granite in southwest Yunnan (and elsewhere in northwest Viet Nam) (e.g. Lan et al., 2000 after Gilder et al., 1996, Chung et al., 1997). The assumption that late Jurassic - early Cretaceous Tu Le volcanic rocks formed in southwest Yunnan by intraplate extension were transported to NW Viet Nam should be further studied for more evidence. Moreover, according to the extrusion tectonic model, left lateral extrusion along the ASRRSZ could have caused Indochina block to rotate clockwise (e.g. Tapponnier et al., 1982). However, there is little evidence that Indochina has rotated significantly to compensate for the displacement of an immense crustal block with a total length of about 600 km having taken place in about 30 million years (Cung and Dorobek, 2004; Cung and Geissman, 2013). Above all, while the continental extrusion model alone is not ready to explain the East Sea (South China Sea) opening dynamics, trench roll-back and post-India-Eurasian collision magmatism, alternatively, the mantle extrusion model may account for most of the above phenomena (e.g. Hoang et al., 1996, 2013; Flower et al., 1998, 2001; Royden et al., 2008; Yang and Liu, 2009).

6. Conclusions

From the above descriptions we come to the following conclusions:

Volcanic rocks in Ban Hat Liu and Ban Ho, Tram Tau district (Tu Le Basin) are mostly porphyritic rhyolite, rhyo-trachyte, trachyte and subordinate basalt (or diabase). They belong to the alkaline series, having high to very high abundances of trace elements such as Rb, Th, Nb, Ta and the rare earths.

The $^{87}Sr/^{86}Sr$ isotopic ratios of a set of volcanic samples vary between 0.7257 and 0.8412 forming an isochron that yields an age of 157 ±2.9 Ma and an initial $^{87}Sr/^{86}Sr$ isotopic ratio of 0.708. This age is in good agreement with previously reported radiometric and fossil-based age data (late Jurassic - early Cretaceous) for volcanic rocks in the area.

The Sr and Nd isotopic compositions of volcanic rocks in the Tram Tau district (and Tu Le basin, in general) are highly enriched for a mantle source, suggesting involvement of crustal melts. To produce magmatic melts having $^{87}Sr/^{86}Sr$ ratio from 0.7058 to 0.7094, a mantle-derived melt with strontium isotopic ratio of 0.703 has to mix with crustal melts having $^{87}Sr/^{86}Sr$ isotopic ratios ranging between 0.715 and 0.730 at a percentage range, respectively, of 3÷4% and 2÷5%.

The Sr and Nd isotopic compositions of Tram Tau volcanic rocks are much different from those reported for Mesozoic A-type granites in western Yunnan (Gilder et al., 1996). Along with scanty paleomagnetic evidence of northern Viet Nam's significant extrusion and rotation since the Mesozoic (see above), the model of 600-700 km southeastward extrusion of western Yunnan proposed by Chung et al. (1997) and Lan et al. (2000) would need further investigation.

Regardless of being in good agreement with many previously reported data, in the light of various radiometric age ranges recently reported for Tram Tau felsic volcanic rocks, the Rb-Sr isotopic age in this study may be viewed as a reference. We expect to acquire more radiometric age data for the felsic volcanic rocks using more reliable methods.

Acknowledgments

A Vietnamese version of this manuscript was reviewed by Drs. Nguyen Thanh Van, Tran Trong Hoa and Bui Minh Tam, whose critical comments helped improve the manuscript significantly. This research was conducted under the grant VAST.DTCB.01/12-13 funded by the Vietnam Academy of Science and Technology, to whom we extend our thanks and appreciations. O. Ishizuka and K. Yamanobe (GSJ) are thanked for assistance in the trace element analysis.

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