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Geochemical and Sr–Nd isotopic characteristics of granitic rocks from northern Vietnam

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Abstract

Five major felsic igneous suites from northern Vietnam, with ages from mid-Proterozoic to early Cenozoic, were studied. Representative granitic rocks from the Posen Complex (mid-Proterozoic) and the Dienbien Complex (late Permian to early Triassic) show geochemical characteristics similar to those of calc-alkaline to high-K calc-alkaline I-type granites. However, the former, located in the South China block, has significantly higher initial Nd isotopic ratios [$\varepsilon_{Nd}(T) = +0.7$ to $+1.5$] and older Nd isotopic model ages ($T_{DM} \sim 1.7$ Ga) than the latter [$\varepsilon_{Nd}(T) = -4.7$ to -9.7; $T_{DM} \sim 1.3$–1.5 Ga] which were emplaced south of the Song Ma Suture and thus in the Indochina block. The generation of both complexes may be attributed to subduction-related processes that occurred in two distinct crustal provenances with different degrees of mantle inputs. On the other hand, Jurassic to Cretaceous granitic rocks from the Phusaphin Complex, contemporaneous rhyolites from the Tule Basin, and late Paleogene granitic rocks from the Yeyensun Complex, all exposed in the South China block between the Ailao Shan–Red River shear zone and the Song Ma Suture, display geochemical features similar to those of A-type granites with intermediate $\varepsilon_{Nd}(T)$ values ($+0.6$ to -2.8) and younger T_{DM} ages (0.6–1.1 Ga). These magmas are suggested to have been generated as a consequence of intraplate extension in the western part of the South China block (Yunnan), and to have been transported to their present position by mid-Tertiary continental extrusion along the Ailao Shan–Red River shear zone related to the India–Asia collision. Overall, the isotopic and model age data, reported in this study indicate that in northern Vietnam, the most important crust formation episode took place in the Proterozoic. Likewise, repeated mantle inputs have played a role in the petrogenesis of Phanerozoic granitic rocks. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Southeast Asia comprises several allochthonous continental blocks derived from Gondwanaland. These blocks eventually amalgamated to form the Southeast Asian continent during Paleozoic and Mesozoic time, with amalgamation processes playing a key role in the evolution of the eastern Tethys and surrounding regions (cf. Metcalfe, 1988, 1990). Being one of the major geological discontinuities in Southeast Asia, the Ailao Shan–Red River (ASRR) shear zone extends for over 1000 km and consists of four narrow, high-grade metamorphic gneiss ranges, namely, from southeast to northwest, the Day Nui Con Voi in northern Vietnam, the Ailao Shan, the Diancang Shan and the Xuelong Shan in Yunnan, western China (Fig. 1). The Ailao Shan belt, the longest of these ranges, is fringed to the south by a strip of low-grade schists in which dismembered mafic and ultramafic bodies, generally regarded as remnants of obducted Tethyan oceanic crust and mantle, have been reported (Zhang et al., 1994). Therefore, the ASRR shear zone along which the mid-Tertiary continental extrusion occurred (cf. Tapponnier et

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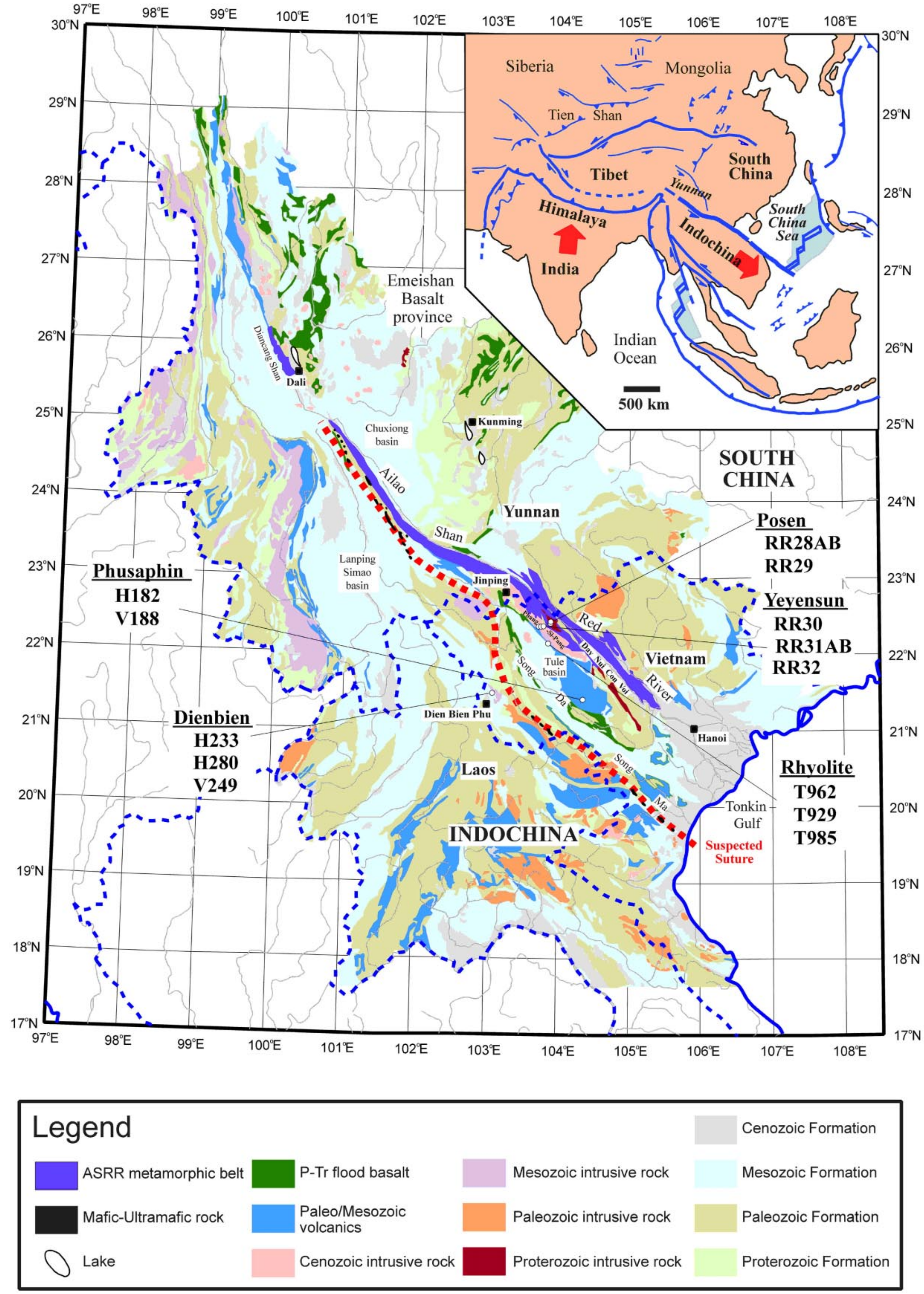

Fig. 1. Sample locality map of granitic rocks from northern Vietnam. The geologic map is modified from the Bureau of Geology and Mineral Resources of Yunnan (1990) and Geologic Society of Vietnam (1988). Inset marks the major Cenozoic fault system in Asia (Tapponnier et al., 1990).

al., 1982, 1990) has often been viewed as a suture between the South China and Indochina blocks (e.g., Leloup et al., 1995). Different suturing ages have been proposed, ranging from Sinian (Precambrian) or Paleozoic (e.g., Metcalfe, 1992; Thanh et al., 1996) to Indosinian (early Triassic) or even late Triassic (e.g., Hutchison, 1989a,b). Based on magmatic and geological correlations, Chung et al. (1997) recently argued that the ASRR shear zone was propagating on the South China continental margin and does not correspond to a suture as alleged. Thus, the plate boundary between South China and Indochina should be located further south and most likely extends along the Song Ma ophiolite belt (Fig. 1).

It is widely accepted that the geochemical systematics of granitic rocks can provide important information regarding the crustal evolution of the region. The geochemistry of granitic rocks in northern Vietnam, however, is poorly known. Some studies so far available are written in Vietnamese and are hardly accessible to the international community. This shortcoming is one of the key reasons preventing a better understanding of the geotectonic evolution of this region. Nguyen et al. (1995) has shown that both I- and A-type granites may have been emplaced in the Tule Basin during Mesozoic–Cenozoic time. Nevertheless, their petrogenesis and their relations to broadly synchronous granitic rocks from the nearby southeastern and southwestern China continental margins remain uncertain.

In this paper, we report major and trace element compositions and Sr–Nd isotopic data for representative granitic rocks of different ages that were collected between the ASRR shear zone and the Song Ma belt in northern Vietnam. Major goals to be addressed include: What are the chemical characteristics of these Vietnamese granitic rocks? Which kind of tectonic setting may have been involved in the magma generation? Are these granitic rocks geochemically comparable to magmas emplaced in mainland China and if so, what would be the regional tectonic implications? Moreover, this reconnaissance study could form the fundament for future detailed research in this particular region of Southeast Asia.

2. Geologic background

Two tectonic events are generally considered most influential in the geological evolution of northern Vietnam. One is the large scale (~600 km) sinistral displacement along the ASRR shear zone active during ~27–22 Ma (Chung et al., 1997), the other is the suturing between Indochina and South China along the Song Ma belt. The Song Ma belt is characterized by the occurrence of metamorphosed mafic and ultramafic masses, which are widespread as lower Paleozoic greenschists of deep sea origin and unconformably covered in many localities by Devonian redbeds (cf. Hutchison, 1989a,b). These mafic–ultramafic rocks, therefore, have been widely interpreted as ophiolitic fragments, derived from the Paleo-Tethys, owing to the collision of Indochina with South China. Moreover, the Song Ma ophiolite can be correlated with the Shuanggou ophiolite cropping out in the south of the Ailao Shan range (Zhang et al., 1994) and together they delineate the plate boundary between Indochina and South China (Fig. 1). The collision time had previously been thought to be Silurian based on a greenschist metamorphic age of ~455 Ma obtained by the K–Ar method (Tran et al., 1979). However, based on a detailed Ar–Ar dating study, Lepvrier et al. (1997) have shown that all rock members of the Song Ma ophiolite share the same metamorphic age of ~245 Ma. This implies that the suturing between Indochina and South China took place in the earliest Triassic, thus causing the early phase of the Indosinian orogeny, that resulted in regional metamorphism and magmatism (Hutchison, 1989a,b).

In this study, granitic rocks were collected from five major igneous complexes in northern Vietnam, namely, the Posen Complex, Dienbien Complex, Phusaphin Complex, Yeyensun Complex, and volcanics (rhyolites) from the Tule basin, which are located between 21°5′ to 22°30′N and 103°5′ to 104°20′E. The sample localities are shown in Fig. 1. The Dienbien Complex occurs in the Indochina block (i.e. south of the Song Ma Suture), whereas all other complexes are located between the ASRR shear zone and the Song Ma belt in the southern margin of the South China block (Fig. 1).

The Posen Complex is composed of granodiorite–granite migmatite associations. It belongs to Proterozoic magmatism based on the correlated Banngam and Xomgiau complexes having mid-Proterozoic K–Ar ages of 1350–1386 Ma (Phan et al., 1991; Table 11). The Dienbien Complex consists of a diorite–granodiorite–granite association and is late Permian-early Triassic in age. The reported U–Pb ages range 272–386 Ma and K–Ar ages range 221–253 Ma (Phan et al., 1991; Table 11). Our unpublished Ar–Ar amphibole dating gives an age of ~240.4 ± 2.8 Ma. The Phusaphin Complex consists of alkaline granite associations and is late Jurassic to early Cretaceous in age. K–Ar ages of 79–105 Ma have been documented (Phan et al., 1991; Table 12). Jurassic to Cretaceous rhyolites and the intrusives of the Phusaphin Complex can be regarded as a volcano–plutonic association in northwestern Vietnam. The Yeyensun Complex presents a late Cretaceous to Paleogene granodiorite–monzonite–quartz biotite hornblende granite–granite granophyre–granosyenite association. A K–Ar age as young as 42 Ma has been reported for this complex (Phan et al., 1991;

Table 1
Age, modal composition and rock type of the granitic rocks from northern Vietnam

Age	Proterozoic			Permian–Triassic			Jura–Cretaceous		Jurassic–Cretaceous			Cretaceous–Paleogene			
Complex	Posen			Dienbien			Phusaphin		(rhyolite)			Yeyensun			
Sample no.	RR28A	RR28B	RR29	H233	H280	V249	H182	V188	T962	T929	T985	RR30	RR31A	RR31B	RR32
Quartz	30	30	25	38	30	31	15	15	16	10	15	20	30	45	20
K-feldspar	40	36	50	40	40	54	60	75	14		38	62	60	48	65
Plagioclase	10	8	7	5	15	6	5	2			10	3	3	3	5
Amphibole					10										
Biotite	10	8	5	10		5	10				5	10	2	2	3
White mica	3	3	3	3			3		3		2				2
Epidote	3	10	5		1							2	2	1	
Chlorite	1	1	1	2		3									1
Sphene	3	3	1		1			2				1			1
Carbonate			2		1	1	5	4	5	9		1			
Others[a]		1	1	2	2		2	2	62	81	30	1	3	1	3
Rock type[b]	GD	GD	G	G	GD	G	G	G	G	G	G	G	G	G	G

[a] Others: magnetite, ilmenite, pyrite, apatite, rutil and zircon for plutonic rocks and groundmass for volcanic rocks.

[b] GD, granodiorite; G, granite based on Fig. 2.

Table 12). Representative samples of these five associations were collected. In Table 1, the general information on the age, modal composition and rock type of the samples studied is given.

The granitic rocks are medium to fine grained plutonic rocks and porphyritic volcanic rocks. Rocks range in color from grey to red. K-feldspar is the most abundant mineral forming tabular crystals. Quartz is normally interstitial or is intergrown with feldspar forming graphic or myrmekitic textures. Plagioclase is albite to oligoclase. Biotite is the most common mafic mineral and pleochroic from light brown to dark brown. Microprobe analysis shows that it is Fe-biotite. Amphibole occurs in one sample and is pleochroic from green, brownish green to brown. The alteration minerals are white mica, epidote, chlorite and carbonate. The accessory minerals are magnetite, ilmenite, sphene, rutile, pyrite, apatite and zircon. Opaque minerals are mainly magnetite, showing euheral to anhedral crystals. Ilmenite usually coexists with sphene.

3. Analytical techniques

3.1. Whole rock chemistry

Major- and fourteen trace-element (Rb, Ba, Sr, Th, U, Zr, Nb, Y, Cr, V, Ni, Cu, Zn, Ga) concentrations were determined in the Department of Geosciences, Franklin and Marshall College, USA, using X-ray fluorescence (XRF) techniques on fused glass disks and pressed powder briquettes, respectively. Working curves were constructed using at least fifty analyzed geochemical rock standards (Abbey, 1983; Govindaraju, 1994). The amount of ferrous Fe was determined using a modified Reichen and Fahey (1962) method. Concentrations of two of the trace elements (Sc, Co) were determined using ICP–AES spectrometer, also at Franklin and Marshall College. Analytical uncertainties range from 1 to 5% for major elements and from 2 to 10% for minor elements. Details of the analytical procedures can be found in Lan et al. (1995).

The concentrations of eight rare earth elements (REE), Hf and Ta were analyzed at the Institute of Geology, National Taiwan University, Taipei, by the instrumental neutron activation analysis (INAA). The reproducibility is better than 10% (Chung et al., 1989).

3.2. Sr–Nd isotopic data

Samples were analyzed for Sr and Nd isotopic composition as well as Sm and Nd contents using a VG354 mass spectrometer for Sr and MAT262 for Sm and Nd at the Institute of Earth Sciences, Academia Sinica, Taipei. The analytical procedure used is described in Lan et al. (1986) and Shen et al. (1993).

Table 2
Major (wt%) and trace (ppm) element concentration of granitic rocks from northern Vietnam

Complex	Posen			Dienbien			Phusaphin		J–K rhyolite			Yeyensun			
Sample	RR28A	RR28B	RR29	H233	H280	V249	H182	V188	T962	T929	T985	RR30	RR31A	RR31B	RR32
SiO_2	66.08	68.05	68.73	72.59	69.68	73.90	72.90	74.50	77.23	77.06	74.68	65.64	74.06	83.96	73.94
TiO_2	0.54	0.49	0.48	0.28	0.28	0.13	0.33	0.34	0.22	0.25	0.23	0.79	0.33	0.18	0.19
Al_2O_3	15.88	15.44	14.94	13.54	15.14	14.58	12.77	11.88	11.02	11.21	12.33	14.03	12.44	7.72	13.51
Fe_2O_3	2.29	1.74	1.27	0.43	1.05	0.21	1.19	0.97	1.22	0.79	1.09	3.64	2.57	0.95	1.06
FeO	1.67	1.54	1.38	1.78	1.84	0.86	2.32	1.78	1.07	2.30	1.96	2.46	0.97	0.42	0.80
MnO	0.06	0.05	0.03	0.03	0.07	0.04	0.08	0.12	0.05	0.12	0.05	0.21	0.08	0.02	0.02
MgO	1.25	1.05	1.18	0.49	1.31	0.38	0.45	0.13	0.24	0.08	0.20	0.59	0.07	0.07	0.14
CaO	3.09	2.81	1.88	1.07	3.11	1.07	1.11	0.07	0.36	0.21	0.17	1.65	0.43	0.24	0.81
Na_2O	4.35	4.28	4.17	2.69	3.81	3.31	3.65	2.63	2.63	1.10	3.07	4.85	3.24	1.49	4.13
K_2O	2.71	2.87	3.77	5.32	2.18	5.34	4.21	6.27	4.12	5.32	4.78	4.67	5.51	4.31	4.10
P_2O_5	0.18	0.14	0.14	0.05	0.11	0.09	0.02	0.01	0.00	0.01	0.00	0.14	0.01	0.00	0.01
L.O.I	1.25	1.13	1.90	1.26	1.57	0.61	1.58	1.66	1.24	2.14	0.81	1.16	0.41	0.33	0.40
Total	99.35	99.59	99.87	99.53	100.15	100.52	100.61	100.36	99.40	100.59	99.37	99.83	100.12	99.69	99.11
La	54.1	37.8	36.5	47.35	28.8	9.81	120.7	166.7	88.7	207.6	185.7	104.4	197.7	364.4	75.1
Ce	102.2	76.4	73.2	75.74	55.7	21.3	248.9	327.8	190.6	419.8	321.8	218.4	414.0	725.0	128.0
Nd	54.3	28.6	47.3	31.8	35.0	8.00	134.9	160.6	121.8	243.3	209.4	131.3	135.4	248.8	71.7
Sm	6.20	5.36	5.00	6.28	4.48	2.04	20.4	21.4	16.9	28.8	29.7	15.7	20.6	34.2	7.77
Eu	1.23	1.07	1.08	0.92	1.08	0.77	2.07	1.20	0.76	0.72	1.67	3.21	1.12	1.85	0.96
Tb	0.87	0.67	0.68	1.08	0.78	0.46	2.78	3.60	2.44	3.17	3.76	1.84	1.85	2.42	1.07
Yb	2.26	1.70	1.44	2.41	1.53	1.41	12.2	13.2	11.0	12.0	9.29	6.54	5.21	4.15	3.31
Lu	0.25	0.28	0.28	0.43	0.23	0.19	1.33	1.74	1.52	1.43	1.43	1.06	0.90	0.63	0.53
Rb	67	75	84	156	82	158	108	202	209	176	97	123	164	161	114
Ba	1115	958	1246	760	367	740	277	91	69	43	211	936	362	203	1145
Sr	548	433	429	146	522	153	26	7	13	15	18	123	200	123	462
Th	5.7	6.7	6.0	23.0	13.6	5.5	24.6	38.3	23.4	29.0	28.4	14.4	17.5	31.4	10.2
U	1.3	1.7	2.4	2.9	4.1	1.8	4.3	7.7	5.8	5.0	5.3	2.3	3.1	4.7	3.2
Zr	196	163	169	158	114	58	877	1187	1002	1038	975	514	665	215	380
Hf	6.60	5.82	6.00	5.95	2.84	1.47	24.9	31.5	27.8	25.6	23.9	18.4	20.0	7.72	10.90
Nb	11.1	9.4	9.8	13.8	10.5	9.1	106.2	133.6	116.9	112.1	125.4	87.8	95.1	47.9	30.5
Ta	0.77	0.76	0.70	1	0.71	1.01	7.58	12.1	10.5	8.13	8.99	5.46	5.85	3.35	3.05
Y	19	15	16	25	15	13	100	124	101	107	156	63	44	38	29
Cr	35	12	32	14	19	25	23	4	8	23	11	4	6	< 2	7
V	62	41	46	16	48	8	< 2	6	5	< 2	3	24	10	< 2	12
Sc	9.51	11.0	9.97	0.00	0.00	3.77	0.00	0.00	3.41	0.00	0.00				
Ni	5	3	4	3	5	3	4	4	4	3	6	4	3	2	2
Co	6	5	5	2.3	11	2	< 1	1	4	2	< 1	2	< 1	< 1	< 1
Cu	9	10	2	5	4	1	2	16	1	3	1	5	3	3	2
Zn	44	35	20	41	41	30	54	295	42	180	170	175	91	11	29
Ga	19.0	17.6	16.1	15.8	17.3	13.1	28.3	21.4	34.1	23.1	30.5	29.5	28.2	15.7	17.7
A/CNK	1.01	1.01	1.04	1.12	1.06	1.11	1.01	1.06	1.17	1.41	1.17	0.87	1.03	1.02	1.06

Briefly, aliquots of the fine powder weighing 10–55 mg were spiked for isotope dilution measurements prior to digestion using a mixture of HNO_3 and HF acids in tightly closed teflon jars maintained at a temperature of 120°C for two overnights. The sample solution was subsequently evaporated to dryness and then converted to chloride. This procedure was repeated until careful observation of the sample solution under microscope confirmed that total dissolution was achieved. Sr and REE were separated from major cations using AG50W-X8, 100–200-mesh cation-exchange resin column in a HCl medium. Subsequently, Sm and Nd were separated from other REE using a AG50W-X4, 200–400 mesh cation-exchange resin column with 2-MLA (2-methyllactic acid) medium buffered at pH 4.44 under a pressure of 0.2 kg cm^{-2}. Aqua regia was first used to digest the organic matter in the collected Sm and Nd fractions. It is followed by 30 min UV light exposure after adding one drop of 4 N HNO_3 in each of the collected Sm and Nd fractions before loading them onto individual filaments.

Sr was loaded on a Ta single filament while Nd and Sm were loaded on a Re single filament and analyzed as mono-oxide ions. Samples were oxidized at 1.5 amp in air for 1 min. Oxygen was introduced to the source chamber to enhance oxide emission. The isotopic compositions were measured in jumping multi-collection mode. The isotopic ratios were corrected for mass fractionation by normalizing to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$, respectively. Values for the NBS987 Sr standard yielded $^{87}Sr/^{86}Sr = 0.710240$ with a long-term reproducibility of 0.000038 (95% confidence level) and for the La Jolla (UCSD) Nd standard, yielded $^{143}Nd/^{144}Nd = 0.511867$ with a long-term reproducibility of 0.000028.

4. Results

4.1. Whole rock chemistry

Major, rare earth and other trace element data for the granitic rocks from northern Vietnam are listed in Table 2. Most granitic rocks are subalkaline with molar ratios of $Al_2O_3/(Na_2O + K_2O)$ ranging from 1.07 to 1.57 and peraluminous with aluminium index (A/CNK = molar ratio of $Al_2O_3/(CaO + Na_2O + K_2O)$) ranging from 1.01 to 1.41, except RR30 which is metaluminous. Except for RR30, most granitic rocks are corundum-normative (0.1–3.3%). On an An–Ab–Or

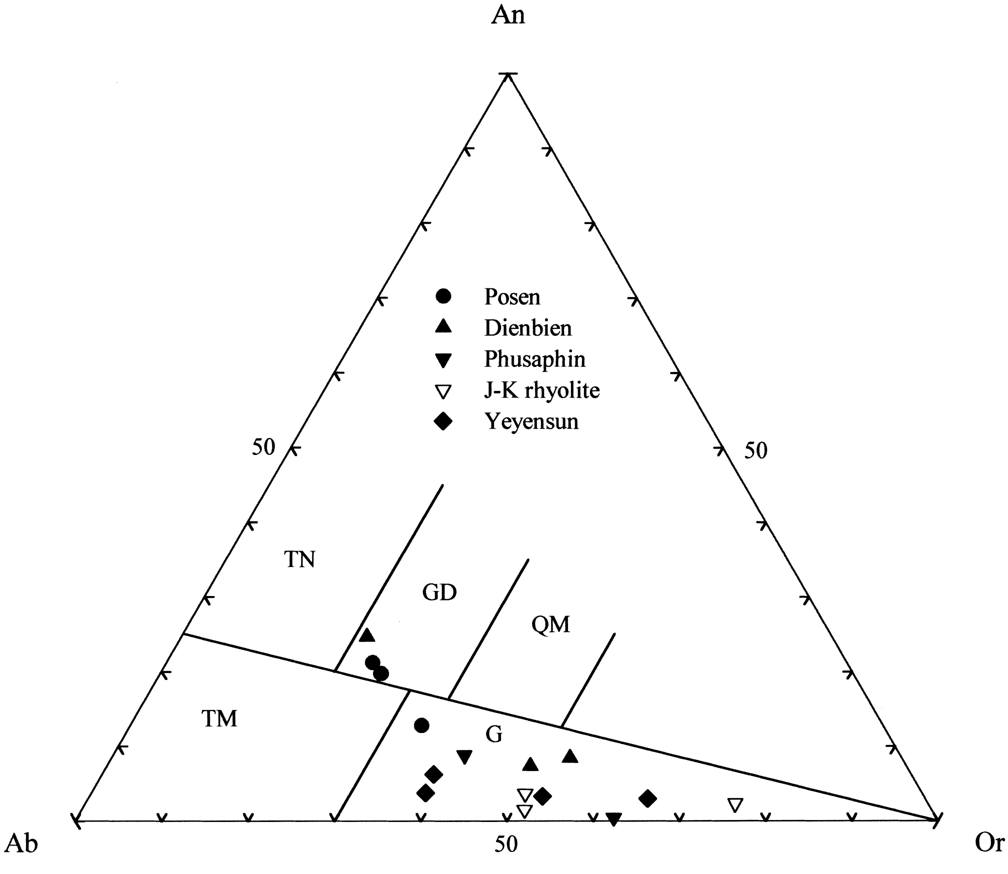

Fig. 2. Classification of granitic rocks from northern Vietnam based on the composition of normative feldspars Ab–Or–An (O'Connor, 1965). G, granite; GD, granodiorite: QM, quartz monzonite; TM, trondhjemite; TN, tonalite.

diagram (Fig. 2) of O'Connor (1965), the majority (80%) of granitic rocks fall in the field of granite. The exceptions are RR28A, RR28B and H280 being granodiorites.

The analyzed granitic samples comprise a diverse range of compositions, with SiO_2 from 65.6 to 84.0 wt%. Based on their chemical characteristics, they can be divided into two groups in the FeO*/MgO and $(K_2O + Na_2O)/CaO$ versus (Zr + Nb + Ce + Y) discrimination diagrams of Whalen et al. (1987). Granitic rocks of the Posen Complex and the Dienbien Complex, both older than the Jurassic in age, belong to unfractionated M-, I- and S-type granites (OGT, Fig. 3) and fractionated granite (FG, Fig. 3) according to the discrimination diagrams of Whalen et al. (1987). Most of these rocks have $Na_2O > K_2O$. They show LREE enriched chondrite-normalized REE patterns (Fig. 4a and b) with $La_N = 31–172$. No significant negative Eu anomalies are observed. Overall, they have similar patterns in the ORG (Ocean Ridge Granite, Pearce et al., 1984)-normalized trace-element plots (Fig. 5a and b), marked by variable enrichments in K, Rb, Ba, Th and Ce and depletions in Ta and Nb. The low value of Y and Yb relative to the normalizing composition is significant. Such characteristic patterns are typical for volcanic arc granites of the I-type. In the tectonic classification diagram of Pearce et al. (1984), the granitic rocks fit into the field of the volcanic arc granite (VAG, Fig. 6). They are classified as calc-alkaline to high-K calc-alkaline I-type granites on the K_2O versus SiO_2 diagram of Peccerillo and Taylor (1976).

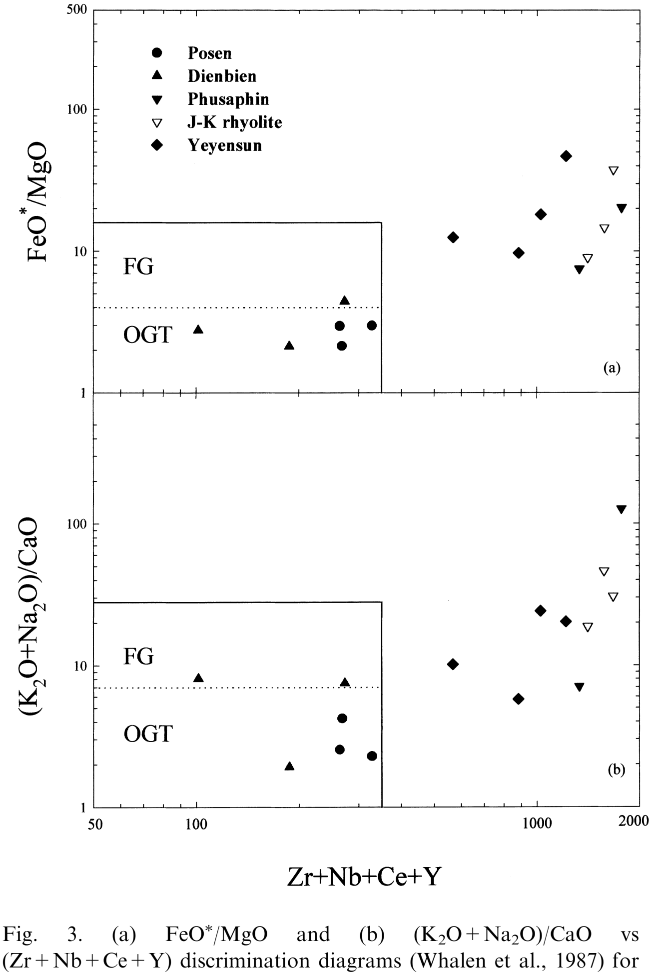

Fig. 3. (a) FeO*/MgO and (b) $(K_2O + Na_2O)/CaO$ vs (Zr + Nb + Ce + Y) discrimination diagrams (Whalen et al., 1987) for granitic rocks from northern Vietnam. FG, fractionated felsic granite; OGT, unfractionated M-, I- and S-type granite.

The granitic rocks of the Phusaphin Complex, Jurassic–Cretaceous rhyolites and the Yeyensun Complex, all younger than Jurassic, plot within the A-type granites field in the discrimination diagrams (Fig. 3). They are rich in the alkalis, with $(K_2O + Na_2O) = 5.8–9.5$ wt%, and K_2O predominating or nearly equal to Na_2O contents. Their chondrite-normalized REE patterns are generally highly LREE enriched (Fig. 4c and d) with $La_N = 238–1156$ and pronounced negative Eu anomalies. These A-type granitic rocks usually have higher REE concentrations than the older I-type granitic rocks. Their ORG-normalized trace-element patterns (Fig. 5c and d) also show generally similar shapes, most displaying enrichments in Rb and Th and depletions in Ba. In addition, from Hf to Yb the patterns are relatively flat and close to that of ORG. ORG-normalized $(Ce/Nb)_N$ ratios are close to 1 and thus no significant Ta–Nb anomaly is observed except for two rocks (RR31A and B) from the Yeyensun Complex, which do show negative spikes for Ta–Nb and Hf–Zr. These A-type granitic rocks usually have higher values of Hf, Zr, Sm, Y and Yb relative to the older I-type granitic rocks and hence have a less steep slope than the older I-type granitic rocks. The A-type granitic rocks plot in the within plate granite (WPG) field (Fig. 6) in the tectonic classification diagram of Pearce et al. (1984).

4.2. *Sr–Nd isotopic data*

The Sr and Sm–Nd data are listed in Table 3. The initial isotopic ratios of the granitic rocks (calculated for different ages as shown in the footnote of Table 3) vary with $\varepsilon_{Nd}(T)$ between +1.5 and −9.7 and $\varepsilon_{Sr}(T)$ between −41 and +572, with different complexes having characteristic ranges of ratios (Fig. 7a). The Posen Complex has the highest $\varepsilon_{Nd}(T)$ (+1.5 to +0.7), followed by decreasing $\varepsilon_{Nd}(T)$ in the Phusaphin Complex and J–K rhyolite (+0.6 to −0.7), the Yeyensun Complex (−1.7 to −2.8) and Dienbien Complex (−4.7 to −9.7). Conversely, in terms of Sr isotopic composition, the Posen Complex shows the lowest $\varepsilon_{Sr}(T)$ of −41 to +3, followed in ascending order by the Yeyensun Complex (+33 to +133) and Dienbien Complex (+86 to +317). The Phusaphin Complex and J–K rhyolite have a large variation of $\varepsilon_{Sr}(T)$ from +139 to +572. As shown in Table 1, the J–K granitic rocks contain

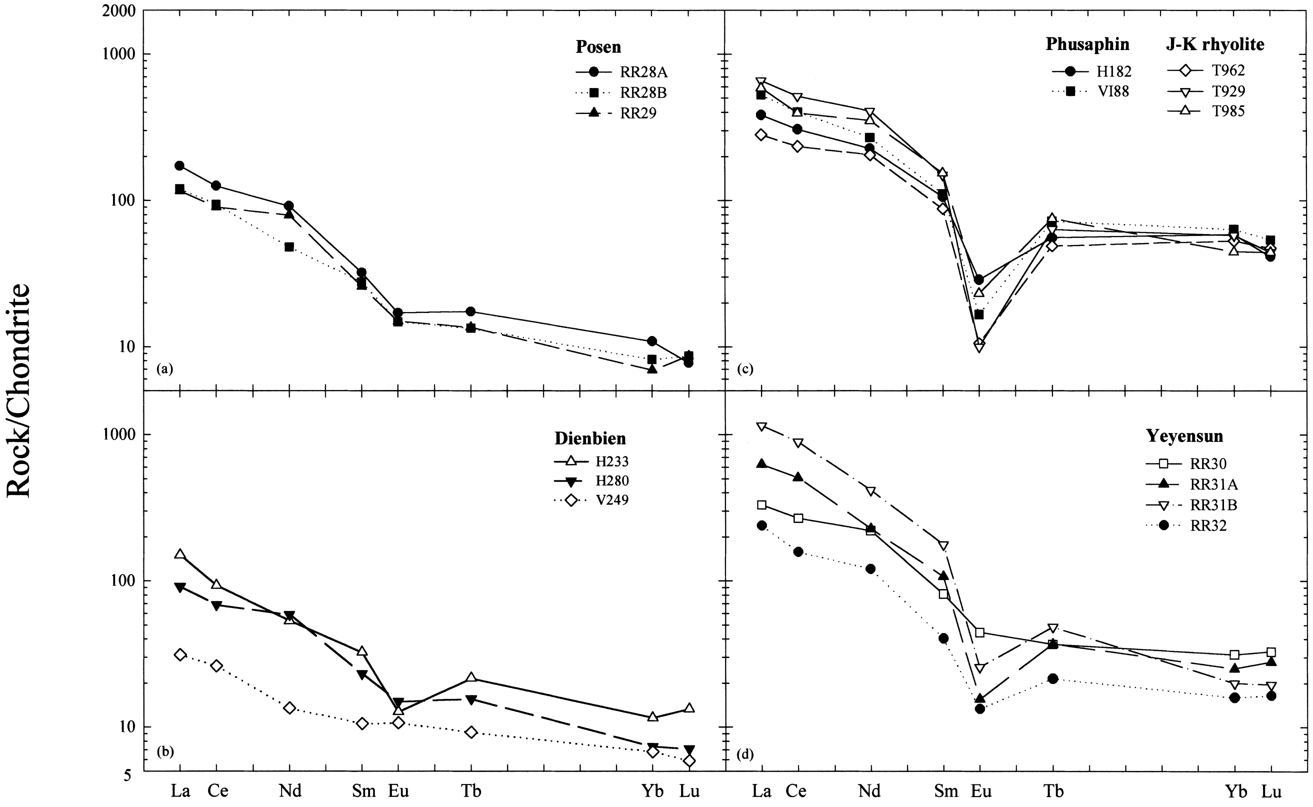

Fig. 4. Chondrite-normalized (Masuda et al., 1973) REE distribution pattern for granitic rocks from northern Vietnam.

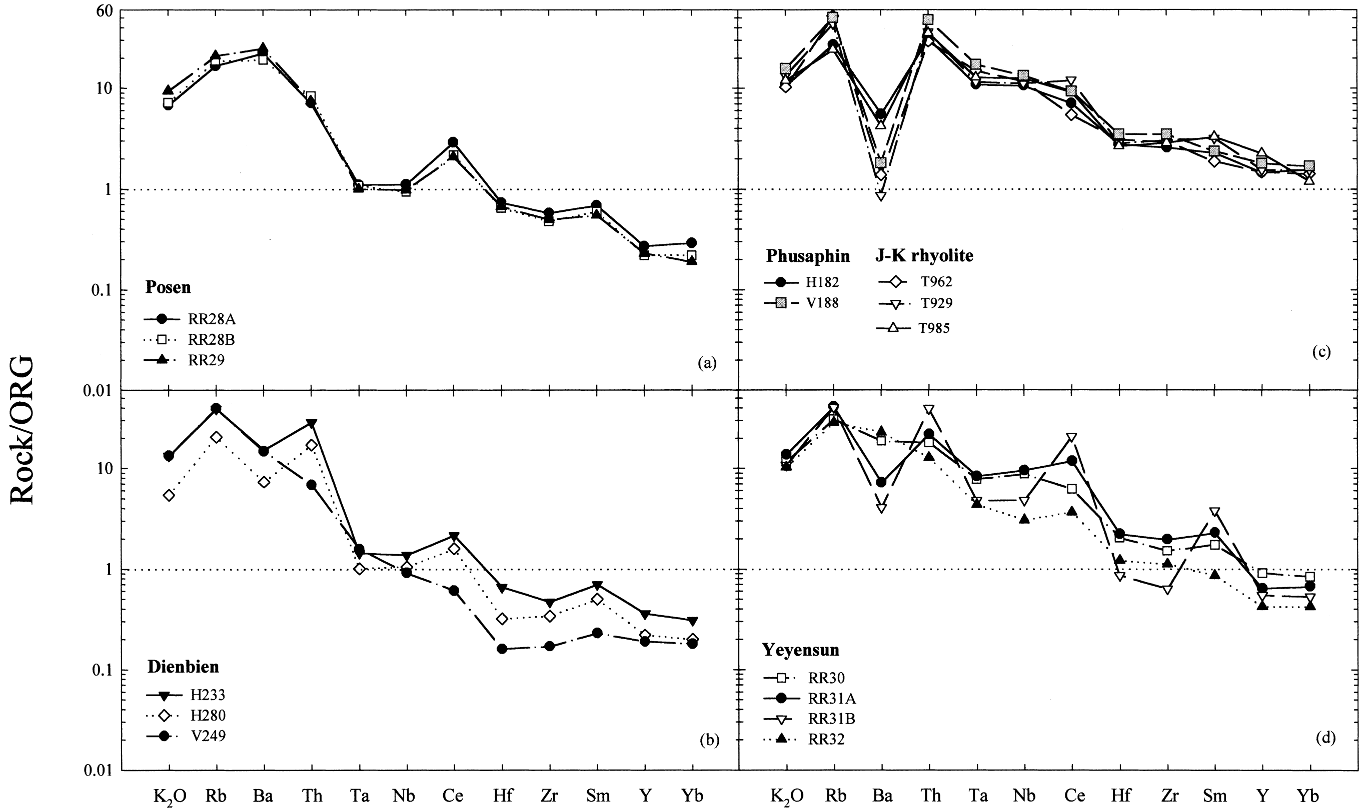

Fig. 5. Ocean ridge granite (ORG, Pearce et al., 1984) normalized geochemical patterns for granitic rocks from northern Vietnam.

significant amounts of carbonate as a secondary alteration mineral. The Sr isotopic ratios of carbonate, indicated by seawater composition, vary from 0.7067 to 0.7090 ($\varepsilon_{Sr}(T) \sim +30$ to $+63$) which are much lower than those of J–K granitic rocks. Thus Sr system disturbed during secondary alteration was probably minimal. The large variation in Nd and Sr isotopic ratios is indicative of the heterogeneous nature for the protoliths of the granitic rocks. Most $^{147}Sm/^{144}Nd$ ratios vary from 0.0716 to 0.1183 except for V249 (0.1542). The granitic rocks of the Posen Complex and the Dienbien Complex, both older than the Jurassic in age, show mid-Proterozoic crustal residence ages of 1.3–1.8 Ga. In contrast, the granitic rocks of the Phusaphin Complex, the J–K rhyolites and Yeyensun Complex, all younger than Jurassic, have late Proterozoic T_{DM} or crustal residence ages of 0.6–1.1 Ga.

5. Discussion and conclusions

5.1. Source characteristics of the granitic rocks

The Sm–Nd isotopic compositions of granitic rocks investigated in this study are displayed in Fig. 7b. It shows that the granitic rocks may be subdivided into three groups in accordance with their ages. Group I consisting of A-type granitic rocks of the Phusaphin Complex, the J–K rhyolites and Yeyensun Complex, all younger than Jurassic, has the youngest, late Proterozoic T_{DM} ages (0.6–1.1 Ga) and highest $\varepsilon_{Nd}(0)$ values (−3.4 to −1.4). Group II consisting of the Dienbien Complex shows young mid-Proterozoic T_{DM} ages (1.3–1.5 Ga) and intermediate $\varepsilon_{Nd}(0)$ values (−7.1 to −11.0). Group III, consisting of the Posen Complex, presents old mid-Proterozoic T_{DM} ages (~1.7 Ga) and low $\varepsilon_{Nd}(0)$ values (−15.7 to −17.0). The relatively depleted nature of the Nd isotopic composition and the younger Nd model ages for Phanerozoic rocks relative to the Proterozoic rocks indicate that significant proportions of newly formed juvenile material must have been involved in the petrogenesis of Phanerozoic granitic rocks of northern Vietnam. In Fig. 7b, the granitic rocks of the Phusaphin Complex, the J–K rhyolites and the Yeyensun Complex (Group I) plot above those of the Posen Complex and toward the left, while those of the Dienbien Complex (Group II) plot toward the upper right in the direction of the direct mixing line with depleted mantle (DM) material. Intra-oceanic-arc material can have a Nd isotopic composition similar to DM but have much lower Sm/Nd. Thus, different mantle material must have been

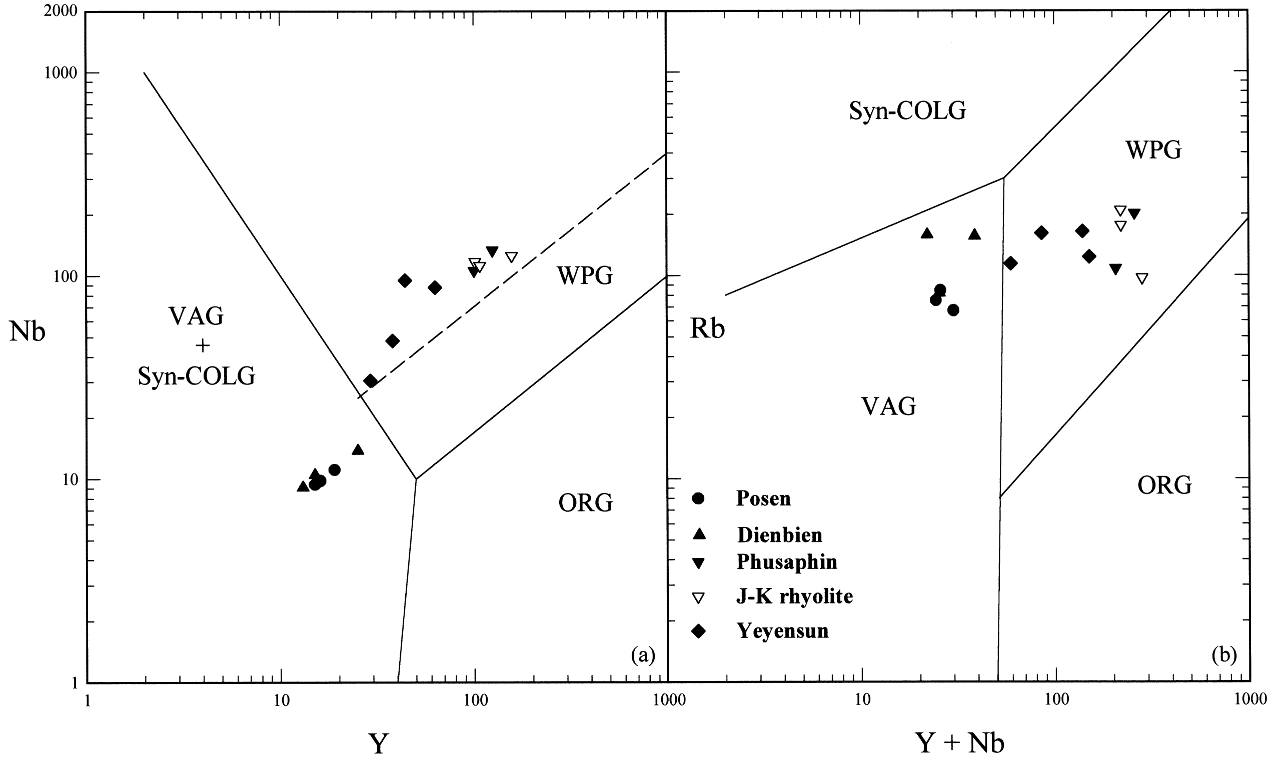

Fig. 6. (a) Nb vs Y and (b) Rb vs Y + Nb discriminate diagrams for granitic rocks from northern Vietnam showing the tectonic classification suggested by Pearce et al. (1984). ORG, ocean ridge granite; Syn-COLG, syn-collision granite; VAG, volcanic arc granite; WPG, within plate granite.

Table 3
Sr and Sm–Nd data for granitic rocks from northern Vietnam

Sample	$^{87}Sr/^{86}Sr \pm 2\sigma_m$	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm 2\sigma_m$	$\varepsilon_{Nd}(0)$[a]	T_{DM}[b] (Ga)	$\varepsilon_{Sr}(T)$[c]	$\varepsilon_{Nd}(T)$[c]
Posen complex									
RR28A	0.71015 4	5.58	35.85	0.0941	0.511768 28	−16.97	1.76	+2.93	+0.78
RR28B	0.71128 4	4.71	29.96	0.0951	0.511809 28	−16.17	1.72	−21.57	+1.40
RR29	0.71116 4	5.28	32.87	0.0971	0.511829 28	−15.78	1.72	−41.28	+1.45
Dienbien complex									
H233	0.72682 4	5.19	27.03	0.1161	0.512272 28	−7.14	1.37	+167.24	−4.76
H280	0.71210 4	3.93	20.08	0.1183	0.512190 28	−8.74	1.53	+86.10	−6.34
V249	0.73698 4	2.04[d]	8.00[d]	0.1542	0.512074 28	−11.00	**	+316.49	−9.71
Phusaphin complex									
H182	0.73919 4	20.4[d]	134.9[d]	0.0914	0.512542 28	−1.87	0.76	+139.32	+0.08
V188	0.91009 4	21.4[d]	160.6[d]	0.0806	0.512494 28	−2.81	0.75	+473.88	−0.66
J–K rhyolite									
T962	0.81556 4	16.9[d]	121.8[d]	0.0839	0.512562 28	−1.48	0.69	+214.01	+0.61
T929	0.81486 4	28.8[d]	243.3[d]	0.0716	0.512529 28	−2.13	0.67	+571.72	+0.18
T985	0.74819 4	29.7[d]	209.4[d]	0.0858	0.512551 28	−1.70	0.71	+162.51	+0.36
Yeyensun complex									
RR30	0.71575 4	15.7[d]	131.3[d]	0.0723	0.512518 28	−2.34	0.68	+133.04	−1.71
RR31A	0.71138 4	20.6[d]	135.4[d]	0.0920	0.512504 28	−2.61	0.81	+75.23	−2.08
RR31B	0.71165 4	34.2[d]	248.8[d]	0.0831	0.512463 28	−3.41	0.80	+67.65	−2.83
RR32	0.70846 4	6.54	34.39	0.1155	0.512463	−3.41	1.07	+33.89	−1.91

[a] $\varepsilon_{Nd}(0) = [(^{143}Nd/^{144}Nd)_{sample}/0.512638 - 1] \times 10^4$.

[b] Crustal residence model age assuming derivation from a depleted mantle source with present ε_{Nd} of +10, $T_{DM} = 1/\lambda \times \ln\{1 + [(^{143}Nd/^{144}Nd)_{sample} - 0.51315]/[(^{147}Sm/^{144}Nd)_{sample} - 0.2137$, $\lambda = 0.00654\ Ga^{-1}$, samples with $^{147}Sm/^{144}Nd > 0.15$ having meaningless T_{DM} ages and shown by **.

[c] Initial isotopic ratios calculated assuming different ages: 1350 Ma for Posen Complex; 240 Ma for Dienbien Complex; 145 Ma for Phusaphin Complex and J–K rhyolite; 40 Ma for Yeyensun Complex, $\varepsilon_{Nd}(T) = [I_{Nd}(T)/(^{143}Nd/^{144}Nd)_{CHUR}(T) - 1] \times 10^4$ $I_{Nd}(T) = (^{143}Nd/^{144}Nd)_{sample} - (^{147}Sm/^{144}Nd)_{sample}[\exp\lambda T - 1]$ $(^{143}Nd/^{144}Nd)_{CHUR}(T) = 0.512638 - 0.1967[\exp\lambda T - 1]$.

[d] Sm and Nd concentrations obtained by INAA method with analytical errors of ~10%, others obtained by ID method with uncertainties of 0.5%.

involved in the sources of Group I and Group II rocks. As discussed by Jahn et al. (1990), the model ages of young granitic rocks, regardless of the input of recent mantle components, are likely to reflect their approximate crustal residence times.

5.2. Correlation with South China and its tectonic implications

The I-type granitic rocks of the mid-Proterozoic Posen Complex are tentatively thought to be geneti-

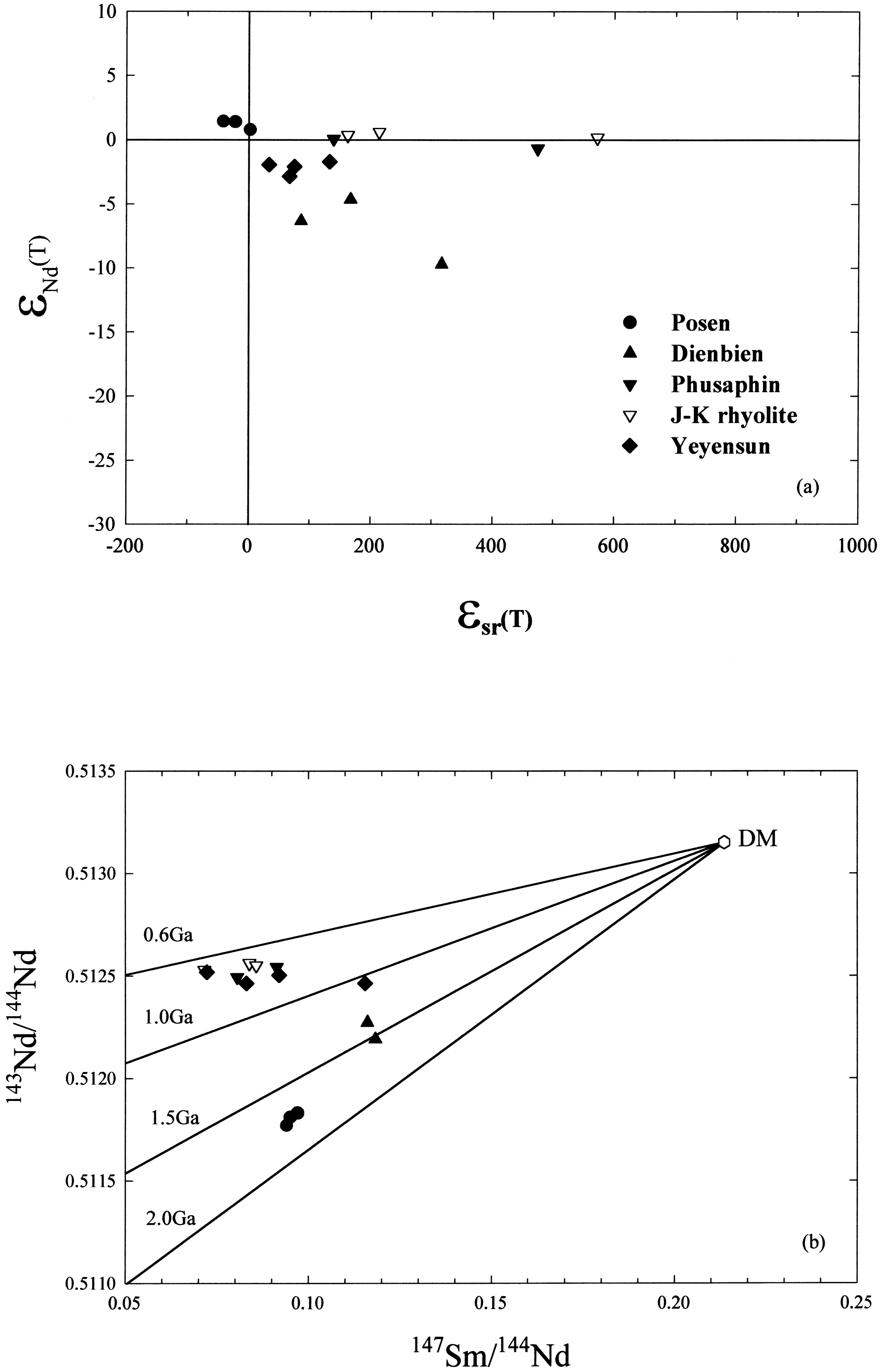

Fig. 7. (a) Initial ε_{Nd}(T) vs ε_{Sr} (T) for granitic rocks from northern Vietnam, and (b) present Sm–Nd isotopic composition of granitic rocks from northern Vietnam. Model ages, assuming depleted mantle sources (DM) can be calculated from the slope of the tie line connecting DM and any individual data point. Four reference lines corresponding to model ages of 0.6, 1.0, 1.5 and 2.0 Ga are shown.

cally linked with the assemblage of the Rodinia Supercontinent (Li et al., 1996). If we adopt the first Proterozoic crust-forming event of western South China (Yangtze block) to start at ~2.1 Ga (Chen and Jahn, 1998), the Nd isotopic compositions of the granitic rocks of the Posen Complex fall roughly on the Nd isotope evolution trends of the known Proterozoic rocks (Fig. 8). Thus, remelting of Paleo- to Meso-Proterozoic crustal rocks, without significant input of mantle-derived material, accounts for their isotopic signature. Discrepancy occurs for the granitic rocks of the Posen Complex, being S-type on the basis of Nd isotopic compositions and I-type on the basis of trace element characteristics. Another alternative petrogenetic model for the Posen Complex is that the granitic rocks may be derived by melting of older crustal sources but with a significant input of mantle component during magma genesis. Older crustal source rocks are waiting to be found to justify this alternative. Zircon geochronology is in progress to find the oldest rock in northern Vietnam.

The I-type granitic rocks of the late Permian to early Triassic Dienbien Complex are located south of the Song Ma ophiolite zone and thus in the Indochina block. The Song Ma ophiolite belt represents the oceanic crust and mantle of the eastern Paleo-Tethys and can be correlated with the Shuanggou ophiolite in Yunnan (Chung et al., 1998b). The I-type granitic rocks of the Dienbien Complex represent a part of the magmatic arc along the Indochina continental margin. Their petrogenesis is tentatively attributed to subduction-related processes in relation with the closure of the Paleo-Tethys and/or suturing between South China and Indochina. A detailed study of these rocks is in progress.

Due to the limited documentation at present, we can not identify the counterparts in western Yunnan that may correlate with the A-type granitic rocks of the Phusaphin Complex and the J–K rhyolites in northern Vietnam. The granitic rocks of western Yunnan are mainly S-type in nature for Jurassic to Cretaceous granitic rocks (Zhang and Xie, 1995). In contrast, abundant Jurassic to Cretaceous granitic rocks have been documented in the eastern part of South China. The latter vary from S- to I- and A-type granites, with the late Jurassic peraluminous S-type granites being dominant throughout the interior of South China (Li, 2000). The A-type granites, however, occur mainly in the coastal region of South China, along some major fault belts. They were emplaced through the earliest Cretaceous (~140 Ma) to late Cretaceous (~90 Ma) as a result of the lithospheric extension (Li, 2000). However,

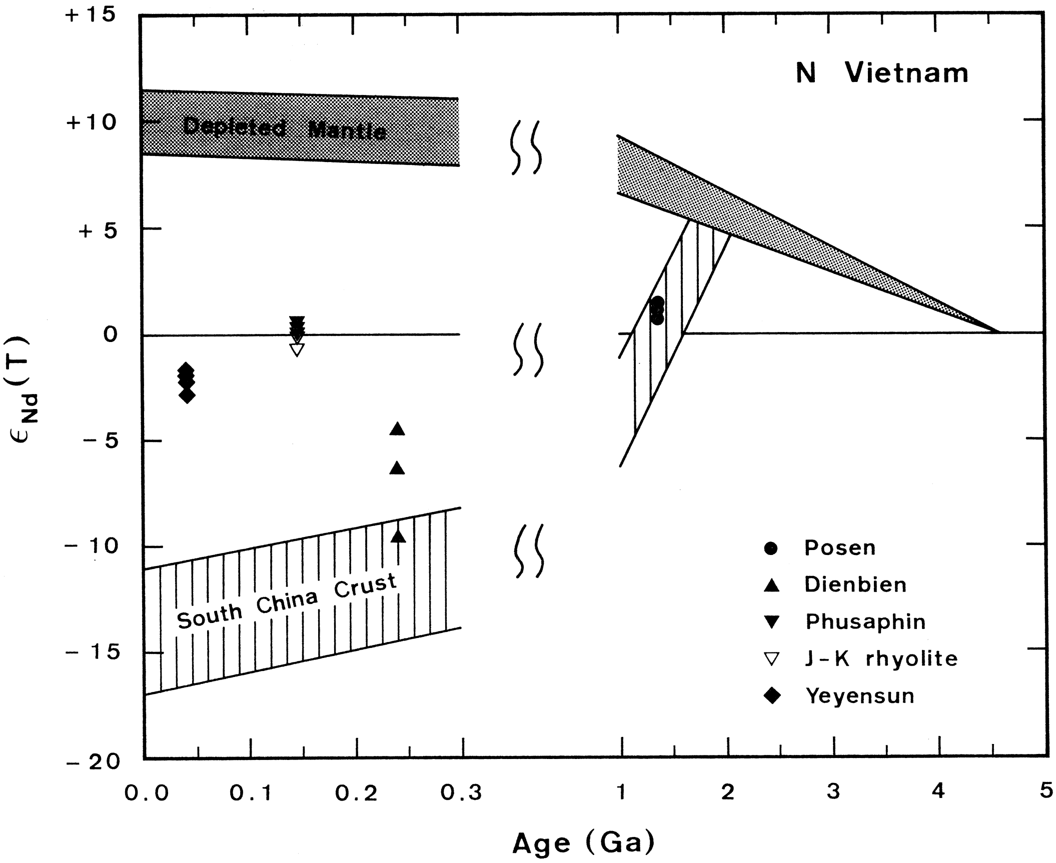

Fig. 8. Nd isotopic evolution diagrams for granitic rocks from northern Vietnam.

based on the similarity of lack of depletions in the high field strength elements (Nb, Ta and Ti), we speculate that Permian–Triassic Emeishan flood basalts in western Yunnan (Chung and Jahn, 1995; Chung et al., 1998a) may serve as the source material for a generation of Jurassic to Cretaceous A-type granitic rocks of the Phusaphin Complex and J–K rhyolites in northern Vietnam. Detailed study of Jurassic to Cretaceous extension related rocks are in progress.

The extension-related A-type granitic rocks of the Yeyensun Complex in northern Vietnam are considered to have a close relationship to those in western Yunnan (in the western part of South China; Zhang and Xie, 1995), but not to be related to those of the eastern part of South China where no Paleogene granites occur. This observation is compatible with the results of Chung et al. (1997) and supports a sinistral offset of ~600 km for northern Vietnam along the ASRR shear zone after ~30 Ma. Similar to the Paleogene high-potassic mafic magmas in northwestern Yunnan and northwestern Vietnam (Chung et al., 1997), the A-type granitic rocks of the Yeyensun Complex could have been formed by intraplate extension (Chung et al., 1997) in conjunction with the SE Asian tectonic history after the India–Asia collision, which probably began as early as 60 My ago (Lee and Lawver, 1995).

The granitic rocks of the Phusaphin Complex, the Jurassic–Cretaceous rhyolites and the Yeyensun Complex, having anomalously high Sm (7.7–34.2 ppm) and Nd (71.7–248.8 ppm) concentrations, show many common characteristics with the enriched Sm–Nd Mesozoic granites from SE China studied by Gilder et al. (1996). They have high $\varepsilon_{Nd}(T)$ values (+0.6 to −2.8), variable $\varepsilon_{Sr}(T)$ values (+33 to +572), relatively young T_{DM} ages (0.6–1.1 Ga) and are A-type granitic rocks. These granitic rocks, having similar source provenance (Fig. 7b), outcrop along the extensional Mesozoic Tule basin. Hence, the model of Gilder et al. (1996) on isotopic evolution and basin formation may also apply to the Mesozoic to Cenozoic granitic rocks in northern Vietnam.

5.3. Crustal evolution of northern Vietnam

The T_{DM} data shown in Table 3 and Fig. 7b indicate that the bulk of northern Vietnam was formed in the Proterozoic. This observation reinforces the idea that northern Vietnam belongs to the southern extension of South China. Chen and Jahn (1998) reported that South China shows little vestige of Archean crustal history except at the northern margin of the western South China (Yangtze block) and northeastern part of eastern South China (Cathaysian block). Hence, northern Vietnam, similar to most of South China, was formed during the Proterozoic. However, mixing of Archean and younger protoliths could also produce Proterozoic model ages. Zircon geochronology in progress will help to verify the presence of Archean rocks in northern Vietnam.

The crustal evolutionary history of this part of northern Vietnam is tentatively illustrated in Fig. 8. Northern Vietnam began its crustal evolution since the Precambrian. Around 240 Ma, the earliest injection of mantle input was admixed into the recycled sediments to produce granitic rocks. The fresh mantle input in the form of oceanic crust and mantle of the eastern Paleo-Tethys resulted from the suturing between South China and Indochina. Later at around 145 Ma, the extension following the suturing of South China and Indochina brought a second mantle input to mix with the sediments and produce the granitic rocks. Finally at around 40 Ma, the extension resulting from the India–Asia collision caused another mantle input to mix with the recycled sediments generating granitic rocks. For the extension-related events, the fresh mantle input was in the form of intra-oceanic mantle material. Thus, mantle inputs made an important contribution to the petrogenesis of Phanerozoic granitic rocks in northern Vietnam.

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