Island-arc geochemical signatures of Cenozoic alkali-rich intrusive rocks from western Yunnan and their implication*

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Abstract Alkali-rich intrusive rocks in western Yunnan were derived from an enriched lithospheric mantle (EM Ⅱ) source. The data available indicated they are alkali-rich ($K_2O + Na_2O > 8wt\%$) and shoshonitic. Although formed in a within-plate environment they exhibit signatures of arc magmatic rocks, such as high amounts of LILE and LREE relative to the HFSE and HREE, and thus high Ba/Nb, Ba/Zr, Sr/Y, La/Yb ratios as well as mimic chondrite-normalized REE and primitive mantle-normalized trace element patterns of subducted sediments, and they fall in the collision- or arc-related tectonic setting field on all discrimination diagrams. This might suggest the enrichment be related to the substantial extent of sediment contamination by the Mesozoic Tethyan subduction processes.

Key words alkali-rich intrusive rock; western Yunnan; shoshonitic; arc geochemical affinities; enrichment

1 Introduction

Along the Jinshajiang-Ailaoshan fault zone in the "Three-River" (i. e., Lancang River, Nujiang River and Jinsha River) area, Southwest China, there are distributed a large number of alkali-rich intrusions, which constitute an extremely large igneous rock belt extending over 1000 km in length and commonly 50 - 80 km in width (Fig. 1A). Alkali-rich intrusive rocks in the belt including mostly syenite porphyry, monzonitic porphyry, granitic porphyry and trachytic porphyry were formed in a post-collisional rift environment (e. g. Tu Guangzhi et al., 1982; Zhang Yuquan et al., 1987) mainly 40 - 30 Ma ago (e. g. Zhang Yuquan et al., 1987; Zhang Yuquan and Xie Yingwen, 1997; Hu Xiangzhao and Huang Zheng, 1997; Deng Wanming et al., 1998a). They are believed to have been derived from an enriched lithospheric mantle source (e. g. Deng Wanming et al., 1998a, b; Zhang Yuquan et al., 1987; Zhang Yuquan and Xie Yingwen, 1997; Zeng Pusheng et al., 2002). In addition, they are characterized by high alkali abundance ($K_2O + Na_2O > 8wt\%$), potassium-enrichment (mostly $K_2O/Na_2O > 1$) and common lack of hydrated minerals (i. e., biotite, hornblende, etc.), hence are considered to be equivalent to A-type granitoids (e. g. Zhang Yuquan et al., 1987; Hu Xiangzhao and Huang Zheng, 1997; Bi Xianwu, 1999; Bi Xianwu et al., 2000).

In this paper, we present new major and trace element data of alkaline porphyries from the Yanshuiqing rockbody in western Yunnan (Fig. 1B), and illustrate that the alkaline porphyries exhibit significant "arc-related" geochemical signatures, though they were formed in a within-plate environment. It might be suggested that the previously subducted oceanic crust had participated in recycling—a chemical process within the continental upper mantle.

2 Geology of the Yanshuiqing rockbody

The Yanshuiqing rockbody is situated in the center of western Yunnan, about 5 km northeast of the alkali-rich porphyries associated with the Beiya gold deposit. The alkali-rich porphyries of the Yanshuiqing rockbody are composed mainly of syenite porphyries, which were dated by the K-Ar method at 31.87 - 34.19 Ma (n = 5) with an intrusive relationship with the Middle Triassic limestone of the Beiya Formation as Beiya rockbodies do (Fig. 1B). However, different

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** Corresponding author: wukaixing@yahoo. com. cn from most of the Beiya rockbodies, the Yanshuiqing rockbody is barren and thus nearly free from effects of hydrothermal fluids. Moreover, it contains numerous deep-derived metamorphosed mafic-ultramafic enclaves.

Table 1. Major element (wt%) and trace element ($\times 10^{-6}$) analyses of samples from the Yanshuiqing rockbody

Sample No.	YS-6	YS-7	YS-11	YS-14	YS-15	YS-16	YS-17	YS-21	Average
Major element									
SiO_2	66.56	67.94	68.92	69.46	68.96	72.05	70.19	71.43	69.44
TiO_2	0.360	0.357	0.237	0.214	0.221	0.209	0.349	0.217	0.271
Al_2O_3	16.48	14.76	15.77	16.03	14.62	13.53	14.02	15.01	15.03
Fe_2O_3	1.04	1.18	0.90	0.83	0.84	0.57	1.06	0.85	0.91
FeO	1.30	0.81	0.60	0.55	0.60	0.55	0.90	0.67	0.75
MnO	0.18	0.16	0.14	0.15	0.15	0.13	0.17	0.17	0.16
MgO	0.64	0.68	0.35	0.29	0.30	0.26	0.68	0.30	0.44
CaO	1.82	1.60	1.58	1.39	1.68	0.89	1.51	0.88	1.42
Na_2O	3.49	3.50	3.44	3.39	3.80	3.67	3.37	3.40	3.51
K_2O	5.11	5.41	4.67	4.79	4.49	5.62	4.81	4.57	4.93
LOI	2.74	3.31	2.95	2.85	3.86	2.37	3.12	2.23	2.93
P_2O_5	0.050	0.100	0.070	0.001	0.001	0.010	0.001	0.001	0.029
Total	99.77	99.81	99.63	99.95	99.52	99.86	100.2	99.73	99.81
$K_2O + Na_2O$	8.6	8.9	8.1	8.2	8.3	9.3	8.2	8.0	8.4
K_2O/Na_2O	1.5	1.5	1.4	1.4	1.2	1.5	1.4	1.3	1.4
Or	31.24	33.27	28.62	29.23	27.82	34.15	29.40	27.77	30.19
Ab	30.55	30.82	30.18	29.62	33.71	31.93	29.49	29.58	30.74
An	9.00	7.58	7.65	7.12	8.73	3.94	7.74	4.48	7.03
Q	21.18	22.29	27.35	27.95	25.84	27.01	27.58	31.68	26.36
Trace element									
V	37.5	38.0	20.3	17.1	19.6	16.5	37.5	17.4	25.5
Sc	9.24	8.82	6.40	6.92	6.84	6.91	8.41	8.75	7.79
Cu	11.5	7.6	5.4	11.7	6.1	5.4	10.5	5.6	8.0
Zn	47.2	46.0	47.7	55.9	46.2	26.5	57.4	30.7	44.7
Cr	26.0	19.6	30.8	24.3	32.4	13.4	19.8	16.8	22.9
Ni	10.4	8.9	12.8	10.4	10.2	5.2	9.6	6.9	9.3
Ga	18.7	18.5	16.8	18.0	18.8	19.0	18.5	19.2	18.4
Rb	209	223	198	216	210	197	221	198	209
Sr	863	871	784	830	808	837	805	828	828
Y	13.3	13.5	10.7	11.2	10.5	10.5	12.9	9.6	11.5
Zr	152	137	141	140	129	135	154	133	140
Nb	10.8	10.6	9.9	9.9	10.4	10.1	11.3	10.3	10.4
Cs	8.96	8.87	4.97	9.20	8.18	4.74	5.68	5.28	6.99
Ba	2103	2079	1936	1966	1875	1847	2009	2029	1981
Hf	4.79	4.59	4.40	4.55	4.26	4.27	5.07	4.47	4.55
Ta	0.61	0.58	0.53	0.54	0.56	0.55	0.64	0.57	0.57
Pb	38.0	34.4	49.3	89.4	46.4	35.8	55.7	34.4	47.9
Th	12.1	12.8	12.9	13.5	14.1	14.2	13.2	12.8	13.2
U	2.90	3.12	3.49	2.62	2.87	2.46	3.50	2.52	2.94
Ga/Al*	2.14	2.36	2.01	2.12	2.43	2.66	2.50	2.42	2.33
Sr/Y	64.9	64.6	73.4	73.8	77.0	79.9	62.6	86.7	72.9
Ba/Nb	194	196	195	199	180	183	178	197	194
Ba/Zr	13.9	15.1	13.7	14.0	14.5	13.7	13.1	15.3	13.9
La	21.4	22.5	15.6	21.5	23.6	21.3	23.7	19.4	21.1
Ce	38.0	40.3	30.1	36.3	40.7	37.0	38.4	33.4	36.8
Pr	4.09	4.27	3.43	3.73	4.03	3.90	4.13	3.61	3.90
Nd	15.2	15.4	13.4	13.5	15.1	13.7	15.7	12.9	14.4
Sm	2.95	2.94	2.55	2.55	2.68	2.55	3.11	2.49	2.73
Eu	0.63	0.59	0.42	0.51	0.46	0.44	0.56	0.40	0.50

Table 1. (to be continued)

Sample No.	YS-6	YS-7	YS-11	YS-14	YS-15	YS-16	YS-17	YS-21	Average
Gd	2.49	2.48	2.06	2.06	2.10	2.07	2.51	1.98	2.22
Tb	0.40	0.41	0.32	0.33	0.35	0.30	0.38	0.30	0.35
Dy	2.18	2.18	1.91	1.53	1.86	1.68	2.11	1.63	1.89
Ho	0.45	0.45	0.34	0.31	0.35	0.31	0.43	0.33	0.37
Er	1.22	1.21	1.03	0.93	1.00	0.89	1.18	0.92	1.05
Tm	0.18	0.19	0.15	0.13	0.15	0.14	0.17	0.13	0.16
Yb	1.18	1.23	1.01	0.91	0.95	1.00	1.21	0.97	1.06
Lu	0.17	0.16	0.15	0.16	0.14	0.16	0.17	0.13	0.15
ΣREE	91	94	72	84	93	85	94	79	87
LREE/HREE	9.9	10.3	9.4	12.3	12.5	12.0	10.5	11.3	11.0
$(La/Yb)_N$	12.2	12.4	10.5	15.9	16.7	14.4	13.2	13.5	13.6
δEu	0.71	0.67	0.56	0.68	0.59	0.58	0.61	0.55	0.62

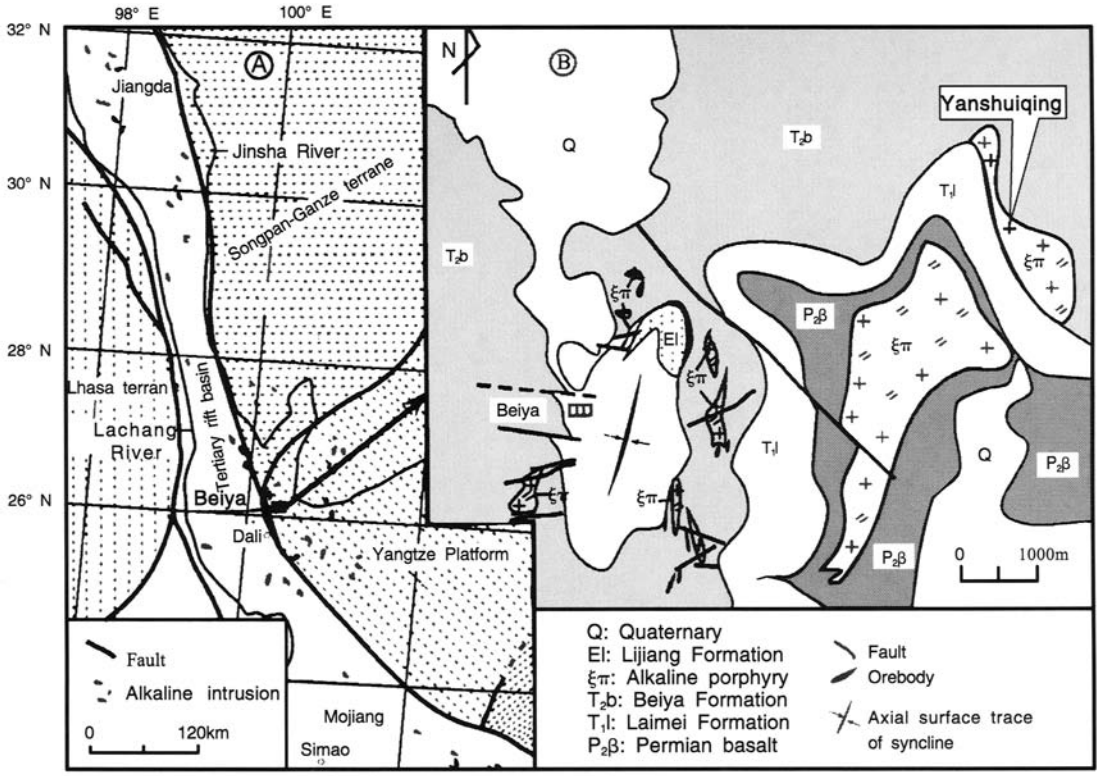

Fig. 1(A). Geological sketch map showing the distribution of alkali-rich intrusions in the Jinshajiang-Ailaoshan alkali-rich intrusive rock belt and the location of the Beiya district (combined and modified from Lü Boxi et al., 1993; Chen Bingwei et al., 1987). (B). Simplified geological map of the Beiya mining district and the Yanshuiqing rockbody (modified from the Third Geological Survey Brigade of Yunnan Province, 1996①).

3 Analytical method and results

Major elements were analyzed by wet chemistry. Trace elements (including REE) were analyzed by ICP-MS, and both analyses were carried out at the Institute of Geochemistry, Chinese Academy of Sciences. Analytical precision and accuracy for most elements measured are estimated to be <10%. Detailed analytical procedures for trace elements and REE were described by Qi Liang and Gregoire (2000). The analytical results are presented in Table 1.

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① The Third Geological Survey Brigade of Yunnan Province. A program report on survey and evaluation of Au, Pb, Zn and Ag mineral resources in the Ninglang-Lijiang-Heqing mineralized area, Yunnan Province, 1996.

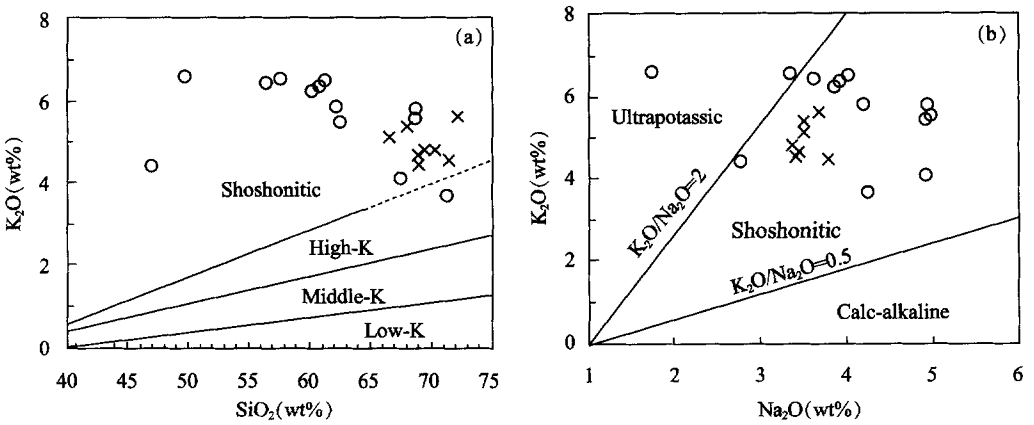

Fig. 2. (a) Plots of K_2O vs. SiO_2 (Peccerillo and Taylor, 1976), and (b) K_2O vs. Na_2O (Turner et al., 1996) for the alkali-rich porphyries from western Yunnan. Data sources: crosses (×) are for this study; circles (○) are for Deng Wanming et al. (1998a, b).

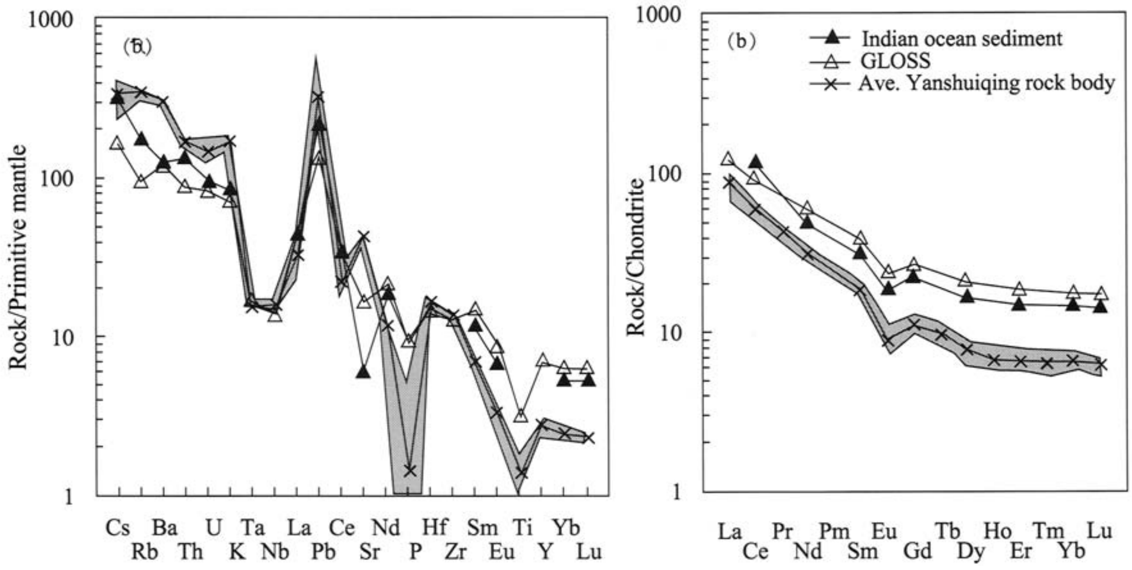

Fig. 3. (a) Primitive mantle-normalized trace element and (b) chondrite-normalized REE patterns for the range (shaded field) and average of the Yanshuiqing rockbody in comparison with oceanic sediments. Indian Ocean sediment (sample V28-343, Ben Othman et al., 1989); GLOSS (globe subducting sediment, Plank and Langmuir, 1998).

4 Major and trace element geochemistry

Alkali-rich intrusive rocks in western Yunnan are alkali-rich ($K_2O + Na_2O > 8$wt%) and potassic. On the plots of K_2O vs. SiO_2 and K_2O vs. Na_2O they fall in the field of shoshonitic rocks (Fig. 2); they are also characterized by high amounts of LILE (i. e., Cs, Rb and Ba) and LREE relative to the HFSE (i. e., Nb, Ta and Ti) and HREE, weakly negative Eu anomalies or no Eu anomaly (Deng Wanming et al., 1998b), exhibiting mimic chondrite-normalized REE and primitive mantle-normalized trace element patterns of subducted sediments, which suggested the contamination by crustal materials either in the source area or during the uprising process of the magma (Table 1, Fig. 3). Their major and trace element compositions defined systematic differentiation trends on variation diagrams (Figs. 4 and 5), most oxides, such as CaO, MgO, FeO*, P_2O_5 and TiO_2, and Ba, Rb and Nb decrease with increasing SiO_2, whereas other oxides, such as K_2O, Na_2O, Al_2O_3, MnO exhibit bothered trends.

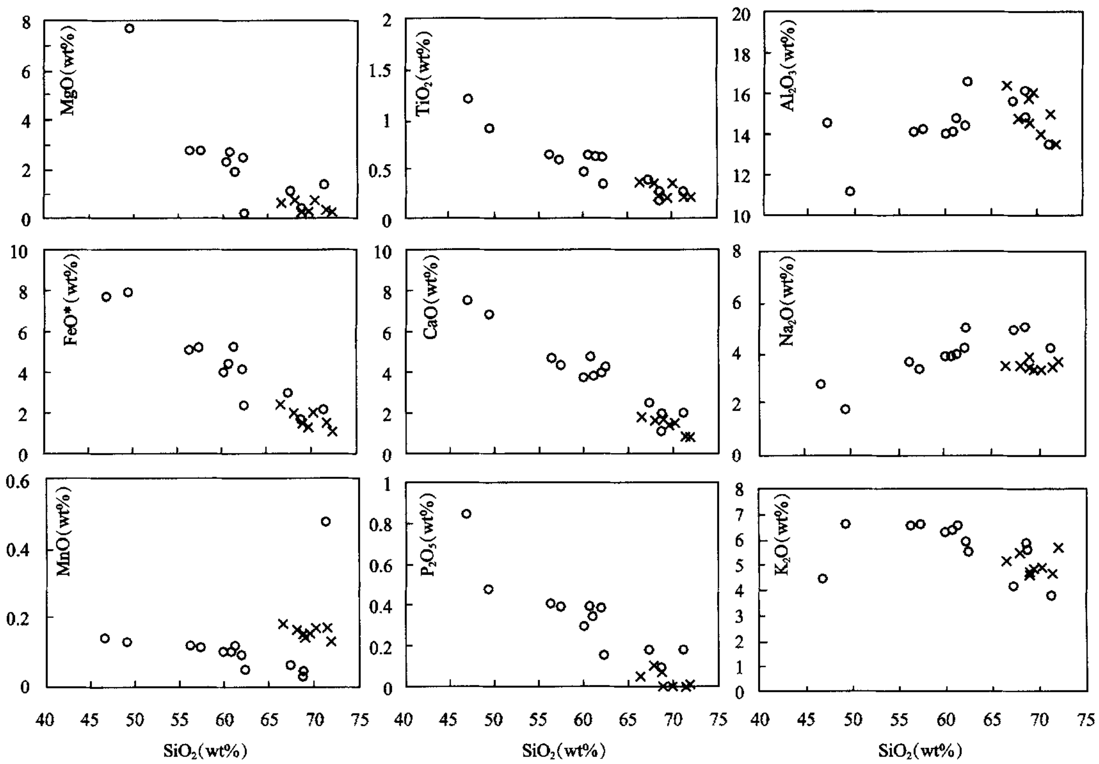

Fig. 4. Harker diagrams of alkali-rich porphyries from western Yunnan (explanations are the same as in Fig. 2).

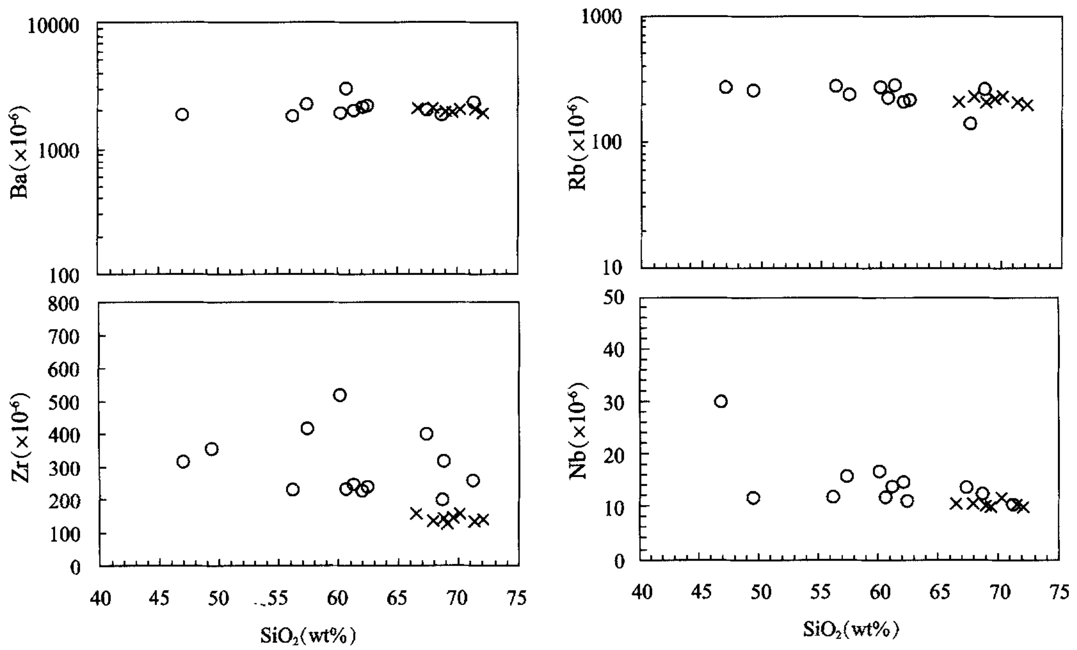

Fig. 5. Diagrams of the selected trace elements vs. SiO_2 for the alkali-rich porphyries from western Yunnan (explanations are the same as in Fig. 2).

5 Geochemical affinities with arc magmatic rocks

Alkali-rich intrusive rocks from western Yunnan fall within the field of volcanic arc granites on Nb-Y, Ta-Yb discriminant diagrams (Fig. 6). On R_1-R_2 tectonic setting discrimination diagram (Fig. 7) they fall within the field of late orogene and syn-collision. On tectonic setting discrimination diagrams constructed for

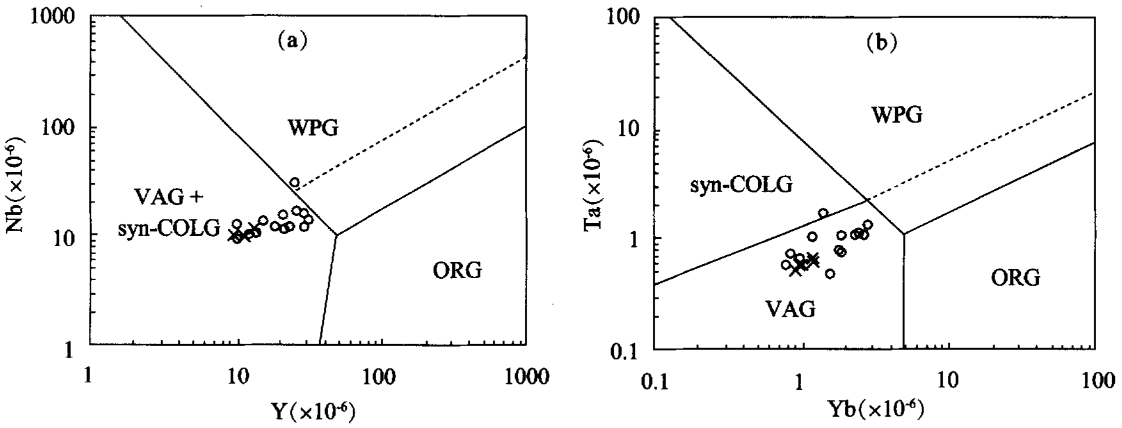

Fig. 6. (a) Nb-Y, (b) Ta-Yb discrimination diagrams of syn-collision granites (syn-COLG), volcanic arc granites (VAG), plate granites (WPG) and ocean ridge granites (ORG) (Pearce et al., 1984). The explanations are the same as in Fig. 2.

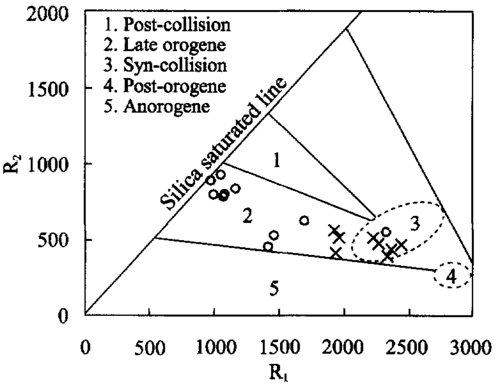

Fig. 7. $R_1 - R_2$ diagram of alkali-rich porphyries from western Yunnan (Batchelor and Bowden, 1985). R_1. $4Si - 11(Na + K) - 2(Fe + Ti)$; R_2. $6Ca + 2Mg + Al$.

potassic igneous rocks they also fall within the field of arc-related rocks (Fig. 8). They seem to be independent from within-plate on all the discrimination diagrams, though they were formed in the within-plate environment (Deng Wanming et al., 1998a). They also show "arc-related" signatures with very high Ba/Nb ratios (61 - 254), as Gill (1981) recognized that high Ba/Nb > 28 is the most significant geochemical characteristic feature of island-arc magmas. In addition, they belong to shoshonitic series that commonly formed during the late stage of arc evolution (Morrison, 1980).

6 Discussion and conclusions

Any type of rocks has its own distinctive major- and trace-element signatures, which are usually used as the criteria of discrimination. Although many trace elements show a large range of absolute values from A-type to another, A-type granites are ubiquitously low in Al_2O_3, MgO, CaO, Sr, Sc, V, Ni, and Cr, and high in SiO_2, K_2O, Na_2O, Zr, Y, Nb, LREE and Ga (e.g. Collins et al., 1982; Whalen et al., 1987; Sylvester, 1989; Eby, 1990). Alkali-rich intrusive rocks from western Yunnan are significantly different from the typical A-type granites in those elements except commonly high $K_2O + Na_2O$, though they undoubtedly belong to A-type granites as far as the exact within-plate tectonic setting where they were formed is concerned. Their geochemical departure from typical A-type granites to arc magmatic rocks might suggest an unconventional geochemical process had happened in the source area of A-type granites in western Yunnan.

Studies in the past 20 years on island-arc rocks strongly indicated that materials derived from subducted slab (consists of igneous oceanic crust carrying a carapace of oceanic sediment) are important components for arc magmatism (e.g. White and Patchett, 1984; Hawkesworth et al., 1993, 1997; Van Bergen et al., 1992; Ishikawa and Nakamura, 1994; Vroon et al., 1995; Kepezhinskas et al., 1995; Ishikawa and Tera, 1997; Walker et al., 2000; Churikova et al., 2001), confirming that island-arc magmatism mostly resulted from the lowering of melting point of peridotite within the wedge of the mantle above subducting slabs owing to the introduction of fluids from the dehydration of subducting oceanic crust (Perfit et al., 1980). During the subduction of oceanic crust, incompatible elements and water from subducted sediments and altered basalts partially recycled in fluids and/or melts to the overlying mantle wedge (e.g. Gill, 1981; Pearce, 1983; White and Dupre, 1986; Hawkesworth

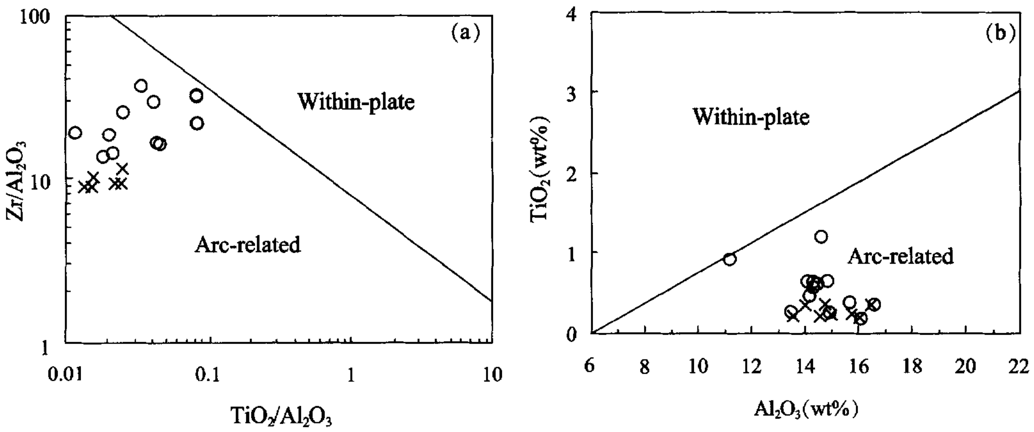

Fig. 8. Discrimination diagrams of potassic igneous rocks indicating an arc-related tectonic setting for alkali-rich porphyries from western Yunnan (Mueller and Groves, 1993). (a) Zr/Al_2O_3 vs. TiO_2/Al_2O_3; (b) TiO_2 vs. Al_2O_3.

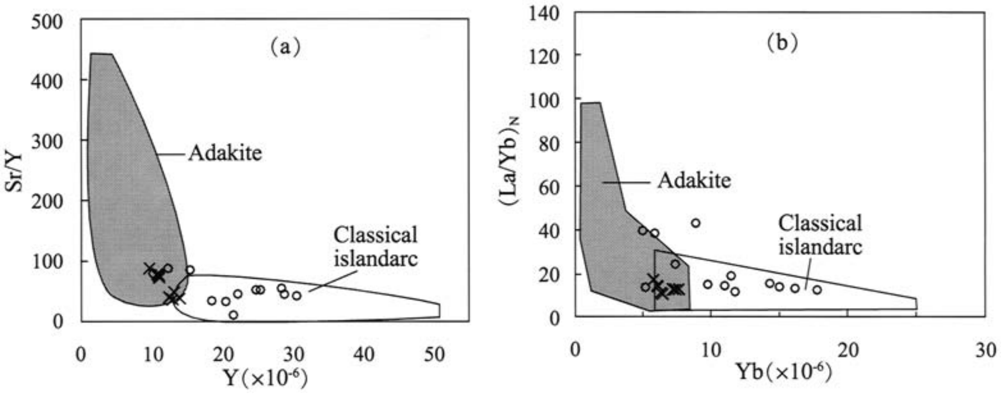

Fig. 9. (a) Sr/Y vs. Y and (b) $(La/Yb)_N$ vs. Yb_N diagrams (Martin, 1999) (the explanations are the same as in Fig. 2).

et al., 1991), resulting in distinctive LILE-enrichment signatures and even REE and trace-element patterns of subduction zone magmas mimicking subducted sediments. Alkali-rich intrusive rocks are strongly enriched in LILE (e.g. K, Rb, Sr, Cs, Ba) and LREE and depleted in HFSE (e.g. Ti, Y, Zr, Nb, Hf, Ta), displaying similar chondrite-normalized REE and primitive mantle-normalized trace element patterns of subducted sediments (Fig. 3). Moreover, they fall in a transitional area from classical island arc to adakites on Sr/Y-Y and La/Yb-Yb diagrams (Fig. 9). These might suggest they are subduction-related. In addition, much higher Ba/Zr ratios are also considered to be associated with the involvement of Ba-rich lithospheric mantle produced by supra-subduction processes (Menzies et al., 1991).

Alkali-rich intrusive rocks and their associated volcanic rocks have the initial $^{87}Sr/^{86}Sr$ values of 0.7058 – 0.7094 and εNd values of –0.62 – –6.4 (Zhu Bingquan et al., 1992; Deng Wanming et al., 1998a; Zhang Yuquan and Xie Yingwen, 1997). Such isotopic compositions are distinct from those of the asthenosphere, most probably indicative of the lower lithosphere, i.e., they were derived from a metasomatized and/or enriched lithospheric mantle (EM II) source during crustal extension related to a large-scale strike-slip movement in the area (e.g. Zhu Bingquan et al., 1992; Deng Wanming et al., 1998a; Zhang Yuquan et al., 1987; Zhang Yuquan and Xie Yingwen, 1997; Zeng Pusheng et al., 2002). However, any old enriched lithospheric mantle could not have survived the thermo-tectonic processes associated with continental flood volcanism (Emeishan flood basalt volcanism) that affected the same part of the western Yangtze craton 250 Ma ago (Xu Yigang et al., 2001), and the EM type-II mantle with high Rb/

Sr and $^{87}Sr/^{86}Sr$ ratios is commonly considered to be a by product of the migration of water-rich fluids or melts enriched in K, Rb and Ba associated with subduction zones (Sun and McDonough, 1989). Thus, there is much possibility that the enrichment has been induced by subduction processes following the Emeishan flood basalt volcanism, which are the processes of Mesozoic Tethyan subduction.

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