Chinese Science Bulletin 2003 Vol. 48 No. 19 2108—2115

DOI: 10.1360/03wd0463

Carboniferous adakites and Nb-enriched arc basaltic rocks association in the Alataw Mountains, north Xinjiang: interactions between slab melt and mantle peridotite and implications for crustal growth

WANG Qiang, ZHAO Zhenhua, BAI Zhenghua,
BAO Zhiwei, XIONG Xiaolin, MEI Houjun, XU Jifeng
& WANG Yixian

Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
Correspondence should be addressed to Wang Qiang (e-mail: wqiang@gig.ac.cn)

Abstract **Adakites and Nb-enriched arc basaltic rocks (NEABs) are identified to occur within the Carboniferous arc volcanic sequence in the Alataw Mountains, Xinjiang. The adakites, which consist of calc-alkaline dacites and rhyolites, are characterized by strong depletion of heavy rare earth elements (HREEs) (e.g., Yb) and Y, high Sr contents and Sr/Y ratios, either with no Eu anomalies or obvious positive Eu anomalies, apparent positive Sr anomalies, and depleted Nb and Ti. The Alataw adakites are very geochemically similar to the adakites that were presumably derived from partial melting of subducting oceanic crust. The rhyolitic adakite in the Alataw Mountains shows low MgO contents of 0.35% and $Mg^{\#}$ values of about 17. However, the dacitic adakite shows high MgO contents of 2.67% to 3.32% and $Mg^{\#}$ values of 53 to 58, suggesting that the adakite was possibly contaminated by mantle peridotite. On the other hand, the NEABs are characterized by Na-rich ($Na_2O/K_2O > 2.0$), high P_2O_5 and TiO_2 contents, positive to weakly negative Nb anomalies, and non-negative Ti anomalies, suggesting that the NEABs were probably derived from partial melting of mantle peridotite that interacted with slab melt under high geothermal gradient. The Alataw adakites were probably derived from partial melting of oceanic crust on the southern margin of the Junggar plate that was subducted beneath the Bole block in the Carboniferous. The Alataw adakites-NEABs association implies that the partial melting of the subducting oceanic crust and the succedent interactions between the slab melt and peridotite in the mantle wedge possibly took place under the Bole arc in Carboniferous. On the southern margin of the Junggar plate, the Carboniferous subduction of oceanic crust (basin) was possibly extensive in the late Paleozoic era. In the Alataw area, high geothermal gradient possibly occurred in Carboniferous, and partial melting of subducting oceanic crust was a probable mechanism of Carboniferous regional crust growth.**

Keywords: Nb-enriched arc basaltic rocks (NEABs), adakite, slab melting, mantle metasomatism, crust growth, Alataw Mountains, Xinjiang.

Adakites and Nb-enriched arc basaltic rocks (NEABs) in arc setting, which are closely correlated in petrogenesis, have recently been widely followed with interest[1—9]. In general, adakite is derived from partial melting of subducting oceanic crust[1]. When adakitic magma (slab melt) passes through the mantle wedge, the interactions between slab melt and mantle peridotite will occur: slab melt is contaminated by peridotite, meanwhile peridotite is metasomated by slab melt. The NEABs are derived from partial melting of mantle peridotite metasomated by slab melt[3—9]. Petrogenetically, the adakites-NEABs association is different from conventional association of calc-alkaline basalt-basaltic andesite-andesite-dacite-rhyolite in arc setting, which is derived from partial melting of peridotite in the mantle wedge metasomated by fluid released by subducting oceanic crust[10]. Therefore, adakites-NEABs association provides a very important clue to investigating magmatic processes under arc and the interactions between slab melt and mantle peridotite. Adakites from different area in China[11—16], including Devonian adakite on the northern margin of the Junggar plate[13] and Permian adakitic igneous rocks in Awulale area, west Tianshan[16], have been reported. However, so far, no NEAB has been reported in China. Recently, we find that adakite and NEABs coexist in the Carboniferous arc volcanic sequence in the Alataw Mountains, north Xijiang. In this report, we present the characteristics of the adakites and NEABs and discuss their geological significance.

1 Geological setting

The Alataw Mountains are geographically located north of the Bole-Wenquan area, Xinjiang (Fig. 1). Tectonically, they are part of the Bole block, which belongs to the Yili-middle Tianshan microplate of the Kazakhstan plate (Fig. 1). A late Paleozoic block, the Yilianhabiergashan-Dananhu, consisting of oceanic crustal slab, occurs on the northeast of the Bole block (Fig. 1). In the Bole block, the oldest rocks are Proterozoic metamorphic rocks; early Paleozoic and Mesozoic strata are absent, but late Paleozoic (Devonian and Carboniferous) and Cenozoic strata and sedimentary materials are widespread (Fig. 1). The late Paleozoic strata mainly consist of deposits of residual oceanic basin and supra-marine basin[17]. Igneous rocks in the region include large-scale Variscan granitoids and a few late Paleozoic volcanic rocks. The volcanic rocks mainly outcrop in the Halatulukegou and the west side (Frontier Defence Checkpoint-Alataw Pass) of Aibi Lake (Fig. 1). In the Halatulukegou area, the volcanic rocks mainly consist of aubergine and gray dacites, and nip rhyolites, andesites, volcanic breccias, and tufaceous breccias and sedimentary rocks (Fig. 1(b)). Whereas in the Frontier Defence Checkpoint-Alataw Pass area of the west side of Aibi Lake, the volcanic rocks mainly consist of

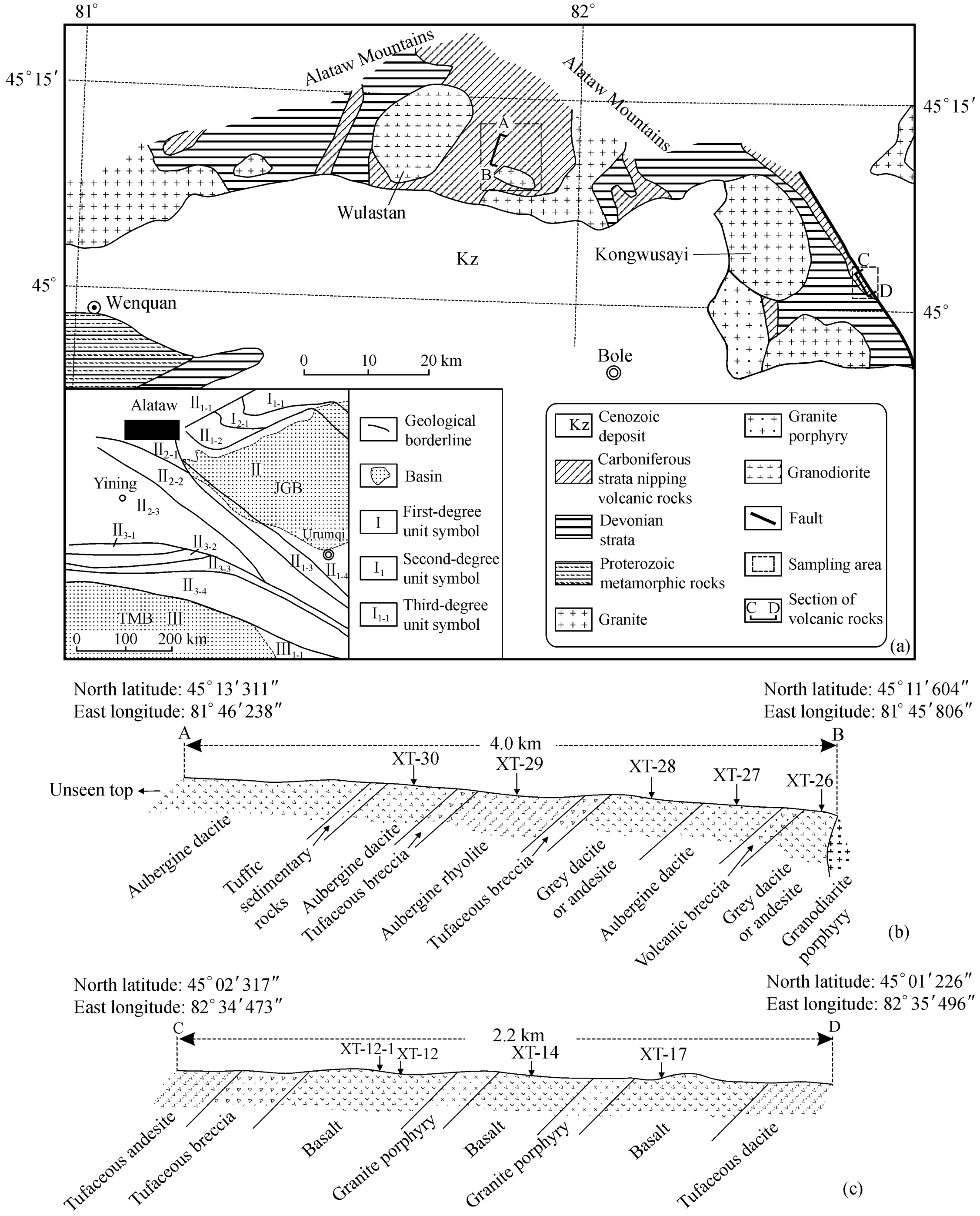

Fig. 1. The geological map of the Alataw Mountains in north Xinjiang (a)[17], sketch map of volcanic rocks section of Halatulukegou area (b) and Frontier Defence Checkpoint-Alataw Pass area of the west side of Aibi Lake (c). The tectonic units of the north of Xinjiang[17]: I, Siberia plate: I_1, Junggar active continental margin block of late Paleozoic forepart: I_{1-1}, Hebuke-Santanghu island arc of late Paleozoic forepart; I_2, North Junggar block consisting of oceanic crustal slab of late Paleozoic forepart; I_{2-1}, Dalabute-Kelamaili block consisting of oceanic crustal slab of late Paleozoic forepart; II_1, Kazakhstan plate: II_1, North Tianshan active continental margin block: II_{1-1}, Tacheng block; II_{1-2}, west Junggar accretion wedge of late Paleozoic; II_{1-3}, Yilianhabiergashan-Dananhu block consisting of oceanic crustal slab of late Paleozoic; II_{1-4}, Bogeda oceanic basin of late Paleozoic; II_2, Yili-middle Tianshan microplate: II_{2-1}, Bole block; II_{2-2}, Keguqinshan-Mishengou arc-trench block; II_{2-3}, Yining rift of late Paleozoic; II_3, South Tianshan active continental margin block of early-middle Paleozoic; II_{3-1}, Haerkeshan trench block of early Paleozoic; II_{3-2}, early Paleozoic accretion wedge in the South side of Haerkeshan; II_{3-3}, Haerkeshan- Kumishen-Kawalabuke block consisting of early Paleozoic oceanic crustal slab; II_{3-4}, Huolashan-eerbinshan block consisting of late Paleozoic oceanic crustal slab; III, Tarim plate: III_1, microplate in the margin of Tarim plate: III_{1-1}, Kuluketage block.

basalts, and nip tufaceous andesites, dacites and breccias (Fig. 1(c)). During late Paleozoic, the volcanic rocks and sedimentary rocks show that the Bole block were probably arc setting, but the Yilianhabiergashan-Dananhu block was probably oceanic basin[17]. The Alataw adakites and NEABs are parts of the Carboniferous arc volcanic rocks.

2 Geochemical characteristics of Alataw adakites and NEABs

(i) Alataw adakites. Major and trace elements data of the Alataw adakites are listed in Table 1. The adakites, consisting of calc-alkaline andesite-dacite-sodic rhyolite and corresponding intrusive rocks, are characterized by $SiO_2 \geqslant 56\%$, high Al_2O_3 ($\geqslant 15\%$ at $SiO_2 = 70\%$) and Na_2O ($\geqslant 3.5\%$), strong depletion of heavy rare earth elements (HREEs) (e.g. $Yb \leqslant 1.90\ \mu g \cdot g^{-1}$) and Y ($\leqslant 18\ \mu g \cdot g^{-1}$), high Sr contents (mostly $\geqslant 400\ \mu g \cdot g^{-1}$), high Sr/Y ratios ($\geqslant$ 20—40), and positive Sr and Eu anomaly or no Eu anomaly. They also have Nb, Ta, Ti and P depletion similar to the arc volcanic rocks[1—3]. In the Alataw Mountains, five samples (include four dacites and one rhyolite) were found to have geochemical characteristics of adakites. The dacites show high Al_2O_3 contents (16.71%—18.25%) and low SiO_2 contents (61.23%—63.64%), and the rhyolite has low Al_2O_3 content (13.60%) and high SiO_2 content (72.36%). All of five samples are characterized by sodium-rich (Na_2O=3.74%—4.67%, Na_2O/K_2O = 1.52—3.32) calc-alkaline (Fig. 2(a)), strong depletion of HREE (e.g. Yb = 0.80—1.39 $\mu g \cdot g^{-1}$) and Y (6—13 $\mu g \cdot g^{-1}$), non-negative Eu anomalies (Eu/Eu^* = 0.95—1.34), high Sr contents (379—540 $\mu g \cdot g^{-1}$), positive Sr anomalies (δ_{Sr} = 1.69—2.71) (Table 1, Fig. 3), and low P_2O_5 and TiO_2 contents (Fig. 2(b)) and depletion in Nb and Ti (Fig. 3). In the Sr/Y vs. Y diagram, five samples are plotted in the field of adakitic andesite-dacite different from "normal" arc andesite-dacite (Fig. 4).

(ii) Alataw NEABs. Major and trace elements data of the Alataw NEABs are listed in Table 1. The NEABs consist of arc basalts and basaltic andesites. They are characterized by sodium-rich ($Na_2O/K_2O > 1.00$), higher P_2O_5 and TiO_2 contents and lower La/Nb ratios (mantle-normalized La/Nb ratios ($(La/Nb)_{PN} < 2.0$) relative to normal basalt-basaltic andesite[3—8]. The Alataw NEABs consist of calc-alkaline basalts and basaltic andesites (Fig. 2(a)). They are geochemically characterized by sodium-rich (Na_2O/K_2O = 2.03—8.06), P_2O_5 (0.33%—0.57%) and TiO_2 (2.00%—3.61%) contents higher than those of the typical arc igneous rocks (Fig. 2(b), Table 1), positive Nb-weak negative Nb anomalies ($(La/Nb)_{MN}$ = 0.78—1.74) and no negative Ti anomalies (Fig. 3(a)). The Nb contents (5.87—12.90 $\mu g \cdot g^{-1}$) and Nb/La ratios (0.60—1.34) of the Alataw NEABs are pretty similar to those of the typical NEABs[4—5], and are different from those of normal basalt-basaltic andesite (Fig. 3(b))[9]. In addition, the Alataw NEABs are similar to the Archean NEABs[6,7] in HREE and transition metal contents, but obviously different from the Cenozoic NEABs[2,4,5,8] for the former have higher HREE (e.g. 2.01—5.01 $\mu g \cdot g^{-1}$) and lower transition metal contents (e.g. Cr = 1—217 $\mu g \cdot g^{-1}$ and Ni = 1—146 $\mu g \cdot g^{-1}$), and the latter have lower HREE (e.g. 1.32—1.88 $\mu g \cdot g^{-1}$) and higher transition metal contents (e.g. Cr = 135—250 $\mu g \cdot g^{-1}$ and Ni = 70—190 $\mu g \cdot g^{-1}$) (Table 1).

Table 1 Major and trace elements data of the Alataw adakites and Nb-enriched arc basaltic rocks[a)]

Rock	Adakite					Enriched-enriched arc basaltic rocks					
No.	1	2	3	4	5	6	7	8	9	10	11
Sample	XT-28	XT-27	XT-30	XT-26	XT-29	XT012-1	XT012	XT014	XT017	P154-3	P201
SiO_2	61.90	62.39	63.64	61.23	72.36	54.67	53.62	50.34	53.28	46.07	51.37
TiO_2	0.60	0.66	0.50	0.69	0.32	3.61	3.21	2.97	3.56	2.50	2.00
Al_2O_3	16.71	17.37	17.40	18.25	13.60	12.59	14.23	16.59	15.16	14.43	15.27
Fe_2O_3	2.76	4.03	2.24	2.72	1.50	4.22	5.73	2.92	5.37	4.29	4.71
FeO	1.70	0.90	1.50	1.85	1.80	8.00	7.03	7.96	8.50	9.10	6.36
MnO	0.07	0.03	0.06	0.04	0.04	0.14	0.20	0.03	0.27	0.30	0.23
MgO	2.71	3.32	2.72	2.67	0.35	2.15	2.43	6.56	3.18	5.39	2.47
CaO	5.80	2.62	4.42	2.31	0.96	5.05	5.24	5.66	2.59	8.90	7.29
Na_2O	3.74	4.38	4.11	4.23	4.67	2.96	3.58	2.78	3.26	2.90	3.40
K_2O	1.58	1.32	1.34	1.78	3.07	1.46	1.59	0.59	1.41	0.36	0.55
P_2O_5	0.10	0.05	0.07	0.08	0.06	0.42	0.48	0.33	0.41	0.42	0.57
H_2O	2.07	2.65	1.71	3.18	1.01	1.78	2.29	4.04	1.83	2.80	2.78
CO_2	0.05	0.05	0.07	0.79	0.02	2.83				1.88	2.76
LOI									1.35		

(*To be continued on the next page*)

(*Continued*)

Rock	Adakite					Enriched-enriched arc basaltic rocks					
No.	1	2	3	4	5	6	7	8	9	10	11
Sample	XT-28	XT-27	XT-30	XT-26	XT-29	XT012-1	XT012	XT014	XT017	P154-3	P201
Σ	99.79	99.77	99.78	99.82	99.76	99.88	99.63	100.78	100.16	99.34	99.76
$Mg^{\#}$	0.54	0.57	0.58	0.53	0.17	0.25	0.26	0.53	0.30	0.43	0.29
Na_2O/K_2O	2.37	3.32	3.07	2.38	1.52	2.03	2.25	4.71	2.3.2	8.06	6.18
Cr	34	35	24	38	8	12	10	74	14	N.D.	N.D.
Ni	20	20	19	21	4	9	5	39	10	N.D.	N.D.
Co	14	14	13	13	3	34	29	57	32	N.D.	N.D.
Sc	27	14	12	14	3	33	8	33	12	N.D.	N.D.
V	99	113	86	85	18	410	384	283	416	N.D.	N.D.
Rb	43	37	39	57	69	26	3	5	4	N.D.	N.D.
Sr	493	432	540	379	486	368	293	409	354	N.D.	N.D.
Ba	463	618	550	347	863	382	312	91	309	296	179
Y	13	10	10	13	7	46	16	33	17	44	38
Zr	130	134	119	134	124	306	356	203	336	277	271
Nb	4.74	4.94	3.56	5.01	3.64	10.33	10.00	5.87	10.00	12.90	11.10
Hf	3.70	3.59	3.12	3.49	3.20	7.79	7.10	4.74	6.74	N.D.	N.D.
Ta	0.67	0.52	0.38	0.49	0.38	0.72	0.61	0.40	0.58	N.D.	N.D.
Pb	7.79	6.85	8.96	4.97	5.63	6.49	4.92	1.63	4.59	N.D.	N.D.
Th	4.01	4.11	3.37	3.84	3.88	2.41	0.38	0.71	0.43	N.D.	N.D.
U	1.28	1.21	1.10	0.88	1.03	0.61	0.67	0.23	0.58	N.D.	N.D.
La	11.34	7.89	10.08	8.44	11.75	17.36	8.33	9.34	7.49	11.25	17.50
Ce	23.30	16.55	20.58	22.35	20.68	43.63	23.82	26.03	21.70	31.56	42.13
Pr	2.96	2.05	2.51	2.90	2.21	6.58	3.91	4.09	3.61	5.27	6.42
Nd	11.72	8.08	9.89	11.76	7.96	30.12	19.18	20.10	17.78	24.70	26.59
Sm	2.49	1.71	1.99	2.31	1.38	7.43	4.81	5.10	4.60	6.95	6.80
Eu	0.85	0.78	0.73	0.74	0.39	2.50	1.55	1.69	1.53	2.38	1.82
Gd	2.36	1.83	1.97	2.24	1.12	8.58	5.22	6.20	5.00	7.98	7.92
Tb	0.41	0.32	0.33	0.39	0.19	1.45	0.98	1.04	0.94	1.41	1.24
Dy	2.38	1.94	1.91	2.36	1.19	8.61	6.09	6.19	5.84	8.47	6.96
Ho	0.49	0.39	0.38	0.47	0.24	1.74	1.32	1.25	1.26	1.80	1.50
Er	1.34	1.16	1.08	1.35	0.71	4.75	3.79	3.36	3.55	5.24	4.47
Tm	0.21	0.18	0.17	0.21	0.11	0.74	0.55	0.51	0.52	0.78	0.66
Yb	1.39	1.27	1.10	1.37	0.80	4.89	3.34	3.31	3.14	4.67	4.09
Lu	0.24	0.21	0.18	0.24	0.14	0.79	0.52	0.52	0.48	0.72	0.60
ΣREE	61.46	44.36	52.89	57.12	48.86	139.18	83.40	88.74	77.45	113.18	128.70
Sr/Y	38.43	43.42	52.78	29.04	72.42	8.00	18.31	12.42	20.82		
Eu/Eu^*	1.07	1.34	1.14	1.00	0.95	0.96	0.95	0.92	0.98	0.98	0.76
δ_{Sr}	2.15	2.68	2.71	1.69	2.63	0.74	1.01	1.31	1.32		
$(La/Nb)_{PM}$	2.48	1.66	2.94	1.75	3.35	1.74	0.86	1.65	0.78	0.91	1.64
Nb/U	4	4	3	6	4	17	15	26	17		
Ce/U	3	2	2	4	4	7	5	16	5		

a) 1—6, Major elements are analyzed by wet chemical technique in Wuhan geological Experimental Institute, Hubei Province; 7—9, major elements are analyzed by wet chemical technique in Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. 1—9, Trace elements are analyzed by ICP-MS in Guangzhou Institute of Geochemistry, Chinese Academy of Sciences; 10, 11 are from Chen et al.[20]; $Mg^{\#}=100\times Mg^{2+}/(Mg^{2+}+Fe^{2+}$(total Fe)); $Eu/Eu^*=Eu_N/(Sm_N\times Gd_N)^{1/2}$, Eu_N, Sm_N and Gd_N are the chondrite-normalized values, $\delta_{Sr}=2\times Sr_{PM}/(Ce_{PM}+Nd_{PM})$, Sr_{PM}, Ce_{PM}, Nd_{PM} and $(La/Nb)_{PM}$ are the primordial mantle-normalized values. N.D., Not detected.

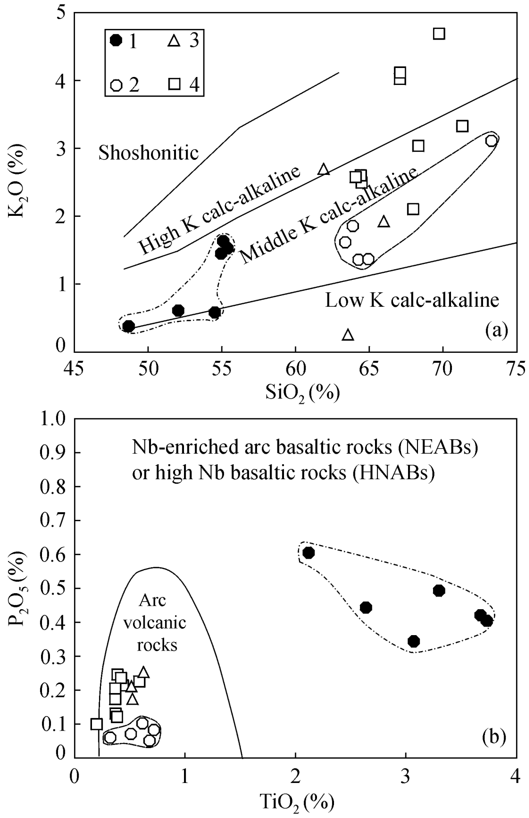

Fig. 2. SiO$_2$-K$_2$O (a) and TiO$_2$-P$_2$O$_5$ (b) diagrams of Alataw volcanic rocks. (b) is from ref. [2]. 1, Alataw NEABs; 2, Alataw adakites; 3, adakites in the northern margin of Junggar plate; 4, Awulale adakitic volcanic rocks.

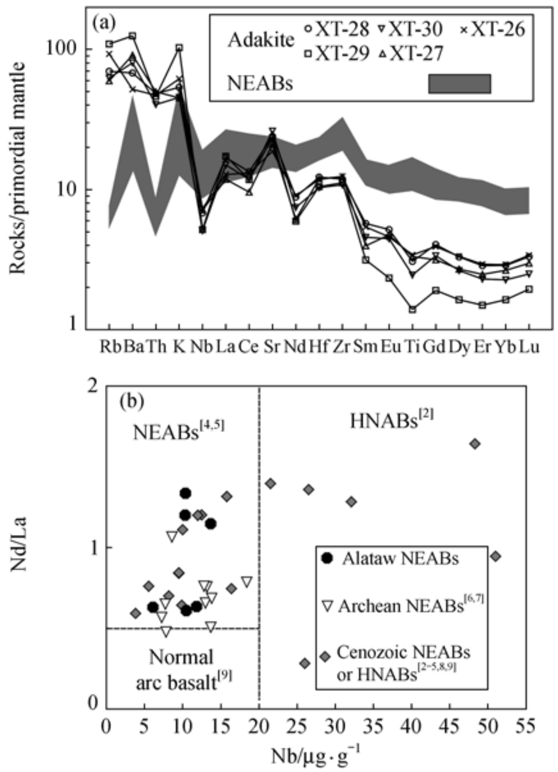

Fig. 3. Primordial mantle-normalized trace elements diagram (values of primitive mantle is from ref. [18]) (a) and Nb-Nb/La diagram (b). The field of high-Nb arc basaltic rocks is from Defant et al.[2]; the field of NEABs is from Sajona et al.[4,5]; the field of normal arc basalt is from Kepezhinskas et al.[9]. The data of the Alataw NEABs are from Table 1; other data in the diagram are from refs. [2—9].

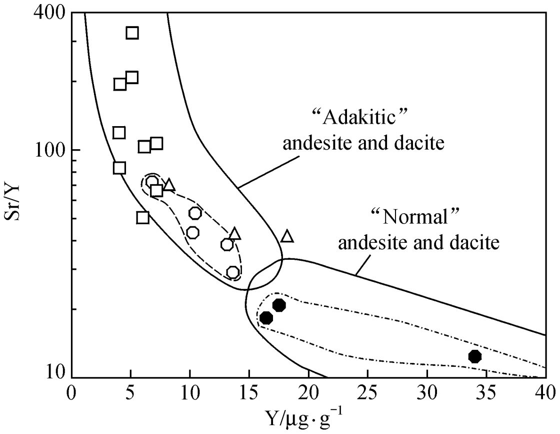

Fig. 4. Y-Sr/Y diagram of igneous rocks[19]

3 Discussion

(i) Petrogenesis of adakites and NEABs. Adakite is initially thought to be intermediate-acid igneous rocks derived from partial melting of subducting oceanic crust under eclogite facies[1]. However, some researches suggested that some rocks with geochemical characteristics of adakite were possibly derived from partial melting of thickened basaltic lower crust under eclogite facies[14,15,21—24]. Adakites formed via above two mechanisms have been reported in the north of Xinjiang[13,16]. Adakites related to partial melting of subducting oceanic crust[13] were formed in early Devonian arc setting on the northern margin of Junggar plate, and the adakites derived from partial melting of thickened basaltic lower crust[16] were formed in Permian post-collision setting of Awulale area. The Alataw adakites occur in the Carboniferous strata, which is different from the formation age of the adakites on the northern margin of Junggar plate and the Awulale adakitic rocks. The Alataw adakites were probably derived from partial melting of subducting oceanic crust, and the obvious interactions between slab melt and mantle peridotite probably took place when slab melt went through the mantle wedge during ascending on the basis of the evidences listed as follows:

(1) The rocks types and series of the Alataw Carboniferous adakites (Fig. 2(a)) accord with that of adakites derived from partial melting of subducting oceanic crust [1,13], but adakitic igneous rocks derived from partial melting of thickened basaltic lower crust are commonly

potassium-rich and alkali-rich[14,15,21—23] (e.g. the Awulale adakitic rocks[16], Fig. 2(a)). The differences of source rocks are possible to result in some differences of their derivants, because the middle oceanic ridge basalt (MORB) commonly has lower potassium and alkali than the continental basaltic rocks. Therefore, the Alataw adakites with low K_2O and high Na_2O contents were most probably derived from partial melting of MORB source.

(2) The Alataw Carboniferous adakites are characterized by strong depletion of HREE (e.g. Yb = 0.80—1.39 μg • g^{-1}) and Y (6—13 μg • g^{-1}), without Eu-obvious Eu anomaly (Eu/Eu* = 0.95—1.34) and distinctly positive Sr anomaly. It is suggested that plagioclases had disappeared and garnets were important residual minerals in the source of the Alataw adakites, due to partial melting of source rocks under eclogite facies. The rare earth elements (REE) compositions and differentiation degree between HREE and light REE of the Alataw adakites are similar to that of Philippine adakites[4], implying that their source rocks might be MORB.

(3) Among the Alataw adakites, a rhyolite adakite (one sample) shows low MgO content (0.35%) and Mg$^\#$ (17), but dacitic adakites (four samples) have high MgO (2.67%—3.32%) and Mg$^\#$ (53—58). In the SiO_2-MgO diagram (Fig. 5), the MgO contents of four dacitic adakites are higher than those of melts derived partial melting of basalts under 1.0—4.0 GPa pressures, and those of adakites (including north Junggar adakite[13]) derived from partial melting of subducting oceanic crust when their SiO_2 contents are the same. However, the rhyolite adakite is plotted in the field of melts derived partial melting of basalts under 1.0—4.0 GPa pressures (Fig. 5). In addition, the transition metal elements (e.g. Cr, Ni, Co, Sc and V) contents of the rhyolite adakite are distinctly lower than those of the dacitic adakites (Table 1). It is suggested that the interaction between adakitic magma (slab melt) and mantle peridotite could take place when the Alataw adakitic magmas passed through the mantle wedge[3,25]. When adakitic magmas (e.g. the Alataw rhyolite adakite) are contaminated by mantle peridotite, the MgO contents or Mg$^\#$ and transition metal elements contents of contaminated magmas are probably increased and SiO_2 are probably decreased (e.g. the Alataw dacitic adakites) (Fig. 5). The adakites derived from partial melting of oceanic crust commonly have these geochemical characteristics[3], but adakitic rocks derived from partial melting of thickened lower crust do not have such geochemical characteristics (e.g. Mg$^\#$ < 47) due to lack of interactions with mantle peridotite[3,21].

(4) The Alataw NEABs strongly imply that the interactions between slab melt and mantle peridotite probably took place in the Alataw area in the Carboniferous. Normal arc volcanic rocks are commonly characterized by strong depletion of high field strength elements (HFSE) (e.g. apparent Nb and Ti depletion in the primordial mantle-normalized diagram), suggesting that they were derived from partial melting of mantle wedge peridotite metasomated by HFSE-depleted fluid from subducting oceanic crust[9]. However, the Alataw NEABs have geochemical characteristics different from the normal arc volcanic rocks, for instance, high P_2O_5 and TiO_2 contents (Fig. 2(b)), positive Nb-weak negative Nb anomaly ($(La/Nb)_{PN}$ = 0.78—1.74), and no Ti-positive Ti anomalies (Fig. 3), but similar to oceanic island basalt (OIB). So, the Alataw NEABs were not likely derived from partial melting of mantle wedge peridotite metasomated by HFSE-depleted fluid from subducting oceanic crust. In addition, Nb/U (15—26) and Ce/Pb (5—16) of the Alataw NEABs are different from those of oceanic island basalt (OIB) (47 ±10 and 25±5, respectively)[18], which dismissed the possibility that they were derived from OIB-type mantle. Many researches suggest that NEABs were probably derived from partial melting of mantle peridotite metasomated by "sodic melt" (namely, slab melt), which resulted from partial melting of subducting oceanic crust[3—8]. During partial melting of subducting oceanic crust, rutile may be another residual mineral besides residual garnet and pyroxene, which results in the Nb and Ti depletion in some slab melts. However, the fluid released by subducting oceanic crust exhibits much lower Nb and Ti contents than slab melt, because Nb and Ti preferentially reside in melt within melt-fluid coexisting system, e.g. Nb and Ti distribution coefficients between fluid and andesitic melt ($D_{\text{fluid/melt}}$) are less than 0.004—0.005 and 0.005—0.026, respectively[26]). When the slab melt rich in Nb and Ti passes through the mantle wedge, it will interact with the mantle peridotites, and will be contaminated by mantle peridotite (Fig. 5). At the mean time, the interactions between slab melt and mantle peridotite lead to the formation of Nb, Ti and Na_2O-rich amphibole and ilmenite, or amphibole and Fe-rich orthopyroxene[4—7]. Arc basalts

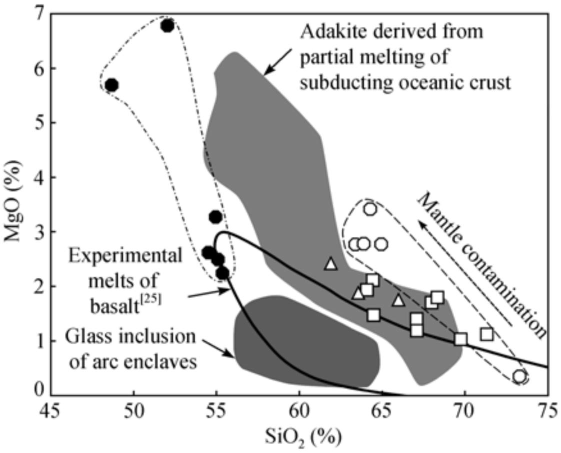

Fig. 5. SiO_2-MgO diagram of adakites and experimental melt of basalt[3].

and basaltic andesites derived from partial melting of the metasomatized mantle (namely, NEABs) may have much higher Nb and Ti contents than the "normal" arc basalt-basaltic andesite[10]. Thus, the Alataw adakites-NEABs association suggests that the interactions between slab melt and mantle peridotites probably took place when slab melt passed through the mantle peridotite.

The HREEs and transition metal element contents of the Alataw NEABs are similar to that of Archean NEABs[6,7] rather than Cenozoic NEABs[1—5,8], so, a petrogenesis similar to Archean NEABs can be inferred. The geothermal gradient was very high in Archean[27], and it was much lower in Cenozoic even though high geothermal gradient might be existed locally. Owing to very high geothermal gradient, the partial melting of the metasomatized mantle peridotite is possible to take place under the plagioclase stability[27,28]. However, in the Cenozoic, the partial melting of the metasomated mantle peridotite with low geothermal gradient is possible to take place under the garnet stability[27,28]. It is the possible reason that the Archean NEABs are richer in HREEs than the Cenozoic NEABs. In addition, the Archean[6,7] and the Alataw Carboniferous NEABs are lower in transition metal elements than the Cenozoic NEABs[1—5,8]. This is possibly related to the melting depth of the metasomated mantle peridotite or the interaction degree between slab melt and mantle peridotite. The bigger the depth, the stronger the interaction, the higher the partial melting degree of mantle peridotite, and the higher the transition metal elements contents of NEABs; on the contrary, the smaller the depth, the weaker the interaction, the lower the partial melting degree of mantle peridotite, and the lower the transition metal elements contents of NEABs. Recently, Martin and Moyen[29] suggested that partial melting depth of the Archean slab (4.5—2.5 Ga) and the interaction degree between slab melt and mantle peridotite were closely related to geothermal gradient: the higher the geothermal gradient, the shallower the melting depth of slab, and the weaker the interaction degree between slab melt and mantle peridotite. Therefore, the high HREEs and low transition metal elements contents of the Alataw NEABs are possibly related to partial melting of mantle peridotite metasomated by slab melt under the plagioclase stability field in high geothermal gradient[27,28], or the shallow location of interaction between slab melt and mantle peridotite[29].

(ii) Geodynamic significances. The genesis of adakites-NEABs association is mainly related to subducting and melting of young and hot oceanic crust[1,2,4,5]. So, the occurrence of the Alataw Carboniferous adakites-NEABs association implies that the subducting of young oceanic crust possibly took place in the north of Xinjiang. The late Devonian-Carboniferous is an important period when the tectonic situation of plate changed in Xinjiang and the neighboring area[17,30—32]. Firstly, the Paleo-Asian ocean was entirely closed on the north margin of Junggar plate[30]. Secondly, oceanic basin was opened on the south margin of Junggar plate; Carboniferous Asian ocean or north Tianshan ocean[30,31] or late Devonian-early Carboniferous narrow oceanic basin[17,32] were formed along Yilianhabierga-Dananhu area, and the Bayinggou ophiolite is their oceanic crustal relic[17,30—32]. In the Bole block, the oldest rock is Proterozoic metamorphic rocks; early Paleozoic and Mesozoic strata are absent, and the late Paleozoic strata mainly consist of deposits of residual oceanic basin and supra-marine basin, and arc volcanic rocks[17]. The late Paleozoic volcanic rocks and sedimentary rocks in the Bole block were possibly formed in arc setting; on the northeast of the Bole block the Yilianhabiergashan-Dananhu block consisting of oceanic crustal slab was the possible oceanic basin in the late Paleozoic, and arc and oceanic basin only occurred in pairs (Fig. 1). In late Devonian-Carboniferous[17] or Carboniferous[30—32], the oceanic crust in the Yilianhabiergashan-Dananhu area subducted southwards or southwestwards. In the west of subducting zone, oceanic crust subducted underneath the Bole block[17], and partial melting of subducting slab took place simultaneously. When slab melt passed through the mantle wedge, the interactions between slab melt and mantle peridotite was responsible for formation of the Alataw adakites-NEABs. Therefore, the occurrence of the Alataw Carboniferous adakites-NEABs association implies that the Carboniferous was a possible important period of oceanic crust subduction in the Yilianhabiergashan-Dananhu area.

In addition, large-scale crustal growth of Central Asia has been widely studied[16,20,33—37], but controversies exist on the mechanisms of crustal growth. Coleman[33] thought that the post-collision granites occurring around the Junggar basin were derived from partial melting of residual oceanic crust. Sengör et al.[34] considered that nearly half of the gigantic Central Asian Orogenic Belt was derived from the mantle by lateral accretion of arc complex and microcontinent, and the formation of new crust was mainly related to oceanic crust subduction processes. Recently, many researches have suggested that the petrogenesis of post-collision granites in gigantic Central Asian Orogenic Belt were most probably related to underplating of massive basaltic magma, magmatic mixing or assimilation and fractional crystallization, and continental crust mainly grew vertically in post-collision setting[16,20, 35—37]. Adakite is closely related to crustal growth, and many researches suggested that partial melting of subducting oceanic crust under high geothermal gradient play an important role in Archean crustal growth[1,27]. The occurrence of Devonian adakite on the north margin of the Junggar plate[13], the Alataw Carboniferous adakite and NEABs suggest that partial melting of subducting oceanic crust could be another important mechanism of Phanerozoic crustal growth in north Xinjiang. In addition, the petrogenesis of the Alataw Carboniferous NEABs also implied that the Alataw area was possibly in a setting with high geothermal gradient, which probably favored the crustal growth.

Acknowledgements This work was supported by the Major State Basic Research Program of China (Grant No. 2001CB409803), the National Natural Science Foundation of China (Grant Nos. 40273019 and 40172028), the National "305" Program (Grant No. 96-915-03-02), and the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant Nos. KZCX2-102 and KZCX2-SW-117).

References

1. Defant, M. J., Drummond, M. S., Derivation of some modern arc magmas by melting of young subducted lithosphere, Nature, 1990, 347: 662—665.
2. Defant, M. J., Jackson, T. E., Drummond, M. S. et al., The geochemistry of young volcanism throughout western Panama and southeastern Costa Rica: an overview, J. Geol. Soc. (London), 1992, 149: 569—579.
3. Defant, M. J., Xu, J. F., Kepezhinskas, P. et al., Adakite: some variations on a theme, Acta Petrologica Sinica, 2002, 18(2): 129—142.
4. Sajona, F. G., Maury, R. C., Bellon, H. et al., Initiation of subduction and the generation of slab melts in western and eastern Mindanao, Philippines, Geology, 1993, 21: 1007—1010.
5. Sajona, F. G., Maury, R. G., Bellon, H. et al., High Field Strength element enrichment of Pliocene-Pleistocene island arc basalts, Zamboanga Peninsula, Western Mindanao (Philippines), Journal of Petrology, 1996, 37: 6693—726.
6. Hollings, P., Kerrich, R., An Archean arc basalt-Enriched-enriched basalt-adakite association: the 2.7 Ga confederation assemblage of the Birch-Uchi greenstone belt, Superior Province, Contributions to Mineralogy and Petrology, 2000, 139: 208—226.
7. Polt, A., Kerrich, R., Magnesian andesites, Enriched-enriched basalt-andesites, and adakite from late-Archean 2.7 Ga Wawa greenstone belts, Superior Province, Canada: implications for Late Archean subduction zone petrogenetic processes, Contrib. Mineral Petrol., 2001, 141: 36—52.
8. Aguillon-Robles, A., Caimus, T., Bellon, H. et al., Late Miocene adakite and Nb-enriched basalts from Vizcaino Peninsula, Mexico: indicators of East Pacific Rise subduction below southern Baja California, Geology, 2001, 29: 531—534.
9. Kepezhinskas, P. K., Defant, M. J., Drummond, M. S., Progressive enrichment of island arc mantle by melt-peridotite interaction inferred from Kamchatka xenoliths, Geochim. Cosmochim. Acta, 1996, 60: 1217—1229.
10. Gill, J. B., Orogenic andesite and Plate tectonics, Berlin: Springer, 1981, 1—100.
11. Wang, Q., Xu, J. F., Wang, J. X. et al., The recognization of adakite-type gneisses in the North Dabie Mountains and its implication to ultrahigh pressure metamorphic geology, Chinese Science Bulletin, 2000, 45(21): 1927—1933.
12. Xu, J. F., Wang, Q., Yu, X. Y., Geochemistry of high-Mg Andesite and Adakitic andesite from the Sanchazi block of the Mian-Lue ophiolitic melange in the Qinling Mountains, central China: Evidence of partial melting of the subducted Paleo-Tethyan crust and its implication, Geochemical Journal, 2000, 34: 359—377.
13. Xu, J. F., Mei, H. J.,Yu, X. Y. et al., Adakite related to subduction in the northern margin of Junggar arc for the Late Paleozoic: Products of slab melting, Chinese Science Bulletin, 2001, 46(15): 1312—1316.
14. Zhang, Q., Wang, Y., Qian, Q. et al., The characteristics and tectonic-metallogenesis significances of the adakite in Yanshanian period from eastern China. Acta Petrologica Sinica (in Chinese with English abstract), 2001, 17(2): 236—244.
15. Zhang, Q., Qian, Q., Wang, E. Q. et al., An east China Plateau in mid-ate Yanshanian period: implication from adakite, Chinese Journal of Geology (in Chinese with English abstract), 2001, 36(2): 248—255.
16. Xiong, X. L., Zhao, Z. H., Bai, Z. H. et al., Adakite-type sodium-rich rocks in Awulale Mountain of West Tianshan: significance for the vertical growth of continental crust, Chinese Science Bulletin, 2001, 46(10): 811—816.
17. Xiao, X. C., Tang, Y. Q., Feng, Y. M. et al., The tectonics of the north Xinjiang and neighboring area (in Chinese with Eanglish abstract), Beijing: Geological Press, 1992, 1—169.
18. Sun, S. S., McDonough, W. F., Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and Processes, Mamgmatism in the Ocean Basins (eds. Saunders, A. D., Norry, M. J.), Geol. Soc. Special Publications, 1989, 42: 313—345.
19. Stern, C. R., Kilian, R., Role of the subducted slab, mantle wedge and continental crust in the generation of adakite from the Austral Volcanic Zone, Contrib. Miner. Petrol. 1996, 123: 263—281.
20. Chen, J. F., Zhou, T. X., Xie, Z. et al., Formation of positive $\varepsilon_{\mathrm{Nd}}$ (*T*) granitoids from the Alataw Mountains, Xinjiang, China, by mixing and fractional crystallization: implication for Phanerozoic crustal growth, Tectonophysics, 2000, 328: 53—67.
21. Atherton, M. P., Petford, N., Generation of sodium-rich magmas from newly underplated basaltic crust, Nature, 1993, 362: 144— 146.
22. Drummond, M. S., Defant, M. J., Kepezhinskas, P. K., The petrogenesis of slab derived trondhjemite-tonalite-dacite/adakite magmas, Trans. R. Soc. Edinburgh: Earth Sci, 1996, 87: 205—216.
23. Smithies, R. H., The Archean tonalite-trondhjemite-granodiorite (TTG) series is not an analogue of Cenozoic adakite, Earth and Planetary Science Letters, 2000, 182, 115—125.
24. Wang, Q., Zhao, Z. H., Xiong, X. L. et al., Crustal growth and the melting of mafic lower crust: evidence from the Shaxi adakitic sodic quartz diorite-porphyrites, in Anhui Province, China, Geochimica (in Chinese with English abstract), 2001, 30(3): 353—362.
25. Rapp, R. P., Shimizu, N., Norman, M. D. et al., Reaction between slab-derived melts and peridotite in the mantle wedge: experimental constraints at 3.8 Gpa, Chemical Geology, 1999, 160: 335—356.
26. Kepper, H., Constraints from partitioning experiments on the composition of subduction-zone fluids, Nature, 1996, 380: 237—240.
27. Martin, H., Adakitic magmas: modern analogues of Archean granitoids, Lithos, 1999, 46: 411—429.
28. Kepezhinskas, P. K., Defant, M. J., Drummond, M., Na metasomatism in the island-arc mantle by slab melt-peridotite interaction: evidence from mantle xenoliths in the north Kamchatka arc, Journal of Petrology, 1995, 36: 1505—1527.
29. Martin, H., Moyen, J. F., Secular changes in tonalite-trondhjemite-granodiorite composition as markers of the progressive cooling of earth, Geology, 2002, 30: 319—322.
30. Huang, J. Q., Jiang, C. F., Wang, Z. X., Plate tectonics and accordion-type movement, Xinjiang Geological Science (in Chinese), 1990, 1(1): 3—16.
31. He, G. Q., Li, M. S., Liu, D. Q. et al., Paleozoic evolution and metallogenesis in Xinjiang, China (in Chinese with English abstract). Urumuqi: Xinjiang People Press, 1994, 1—437.
32. Gao, J., He, G. Q., Li, M. S., Paleozoic orogenic processes of Xitianshan orogenic belt, Earth Science (in Chinese with English abstract), 1997, 22(1): 27—32.
33. Coleman, R. G., Continental growth of Northwest China, Tectonics, 1989, 8: 621—635.
34. Sengör, A. M. C., Natal'in, B. A., Burtman, V. S., Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia, Nature, 1993, 364: 299—307.
35. Han, B. F., Wang, S. G., Jahn, B. M. et al., Depleted-mantle magma source for the Ulungur River A-type granites from north Xinjiang, China: geochemistry and Nd-Sr isotopic evidence, and implication for Phanerozoic crustal growth, Chem. Geol., 1997, 138: 135—159.
36. Jahn, B. M., Wu, F. Y., Chen, B., Massive granitoid generation in Central Asia: Nd isotope evidence and implication for continental growth in the Phanerozoic, Epidodes, 2000, 23: 82—92.
37. Wu, F. Y., Jahn, B. M., Wilde, S. et al., Phanerozoic crustal growth: Sr-Nd isotopic evidence from the granites in northeastern China, Tectonophysics, 2000, 328: 89—113.

(Received April 28, 2003)