

Sr, Nd and O isotope geochemistry of the mafic-ultramafic complexes in the southern margin of the Altay orogenic belt and discussion of their sources

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Abstract The Sr, Nd and O isotopic compositions of the Kalatongke and Xibodu mafic-ultramafic complexes from the southern margin of the Altay orogenic belt show that they have similar isotopic compositions, characterized by low ($^{87}\text{Sr}/^{86}\text{Sr}$)_t and high $\varepsilon_{\text{Nd}}(t)$ values (6.3–9.1). It suggests that they were derived from a depleted asthenospheric mantle. However, most of the samples have $\delta^{18}\text{O}$ values >6‰ (5.4‰–10.2‰), indicating crustal contamination. A combination of Sr and O isotopic data shows the incorporation of crustal materials into the depleted mantle. They were produced by the melting of depleted mantle by the incorporation of subducted oceanic crust, and this incorporation might have occurred in the Early Paleozoic in the light of their Nd model ages and regional tectonics. The Kalatongke complex might have undertaken the contamination of the upper crust whereas the Xibodu complex does not have any signature of contamination of the upper crust. In addition, the similarities of the sources of the two complexes, which were located at the northern and southern sides of the regional Irtysh fault zone respectively, suggest that this fault might not be the boundary between the Altay and Junggar orogenic belts.

Keywords mafic-ultramafic complex, Sr, Nd and O isotopes, source region, Altay orogenic belt

In the 1980s, the discovery of a large Kalatongke Cu-Ni deposit in Fuyun County, Xinjiang, was an important achievement for prospecting in NW China, and played an important role in local economics. Although their petrologic,

mineralogical and geochemical characteristics have been studied, their systematic Sr-Nd-Pb isotopic compositions have not been reported. Thus, some important issues such as source and origin of the deposit remain controversial (Wang and Zhao, 1991; Wang et al., 1992; Wang et al., 2002).

The geochemistry of tens of mafic-ultramafic intrusions distributed in a 200 km long, 10–20 km wide belt has hardly been investigated. Although they are spatially consistent with the Kalatongke intrusion, their genetic relation, especially for source regions, is quite debated. In this paper, on the basis of a study of Sr-Nd-O isotope systematics of Nos. 1, 2 intrusions and the Xibodu intrusion that are usually considered potential intrusions for prospecting Cu-Ni deposits, we discuss the nature of their sources, and then try to provide some clues for tectonic evolution.

1 Geology of complexes

The mafic-ultramafic intrusions strike NW, mostly along the south side of the Irtysh deep fault (Fig. 1). The Kalatongke complex is situated on the southern side of this fault whereas the Xibodu intrusion is located on the northern side. The Rb-Sr and Sm-Nd isochron dating on the Kalatongke complex yields the ages of 280–300 Ma (Wang et al., 1992; Li et al., 1998). However, there are no isotope age data of the Xibodu intrusion.

The Kalatongke complex consists of 11 small intrusions, intruding the volcanic-sedimentary clastic rocks of the Lower Carboniferous. Nos. 1, 2 and 3 intrusions are well differentiated, containing economic Cu-Ni ores. They can be divided into (from bottom to top): biotite-amphibole dolerite-gabbro, biotite-amphibole-olivine norite, biotite-amphibole norite,

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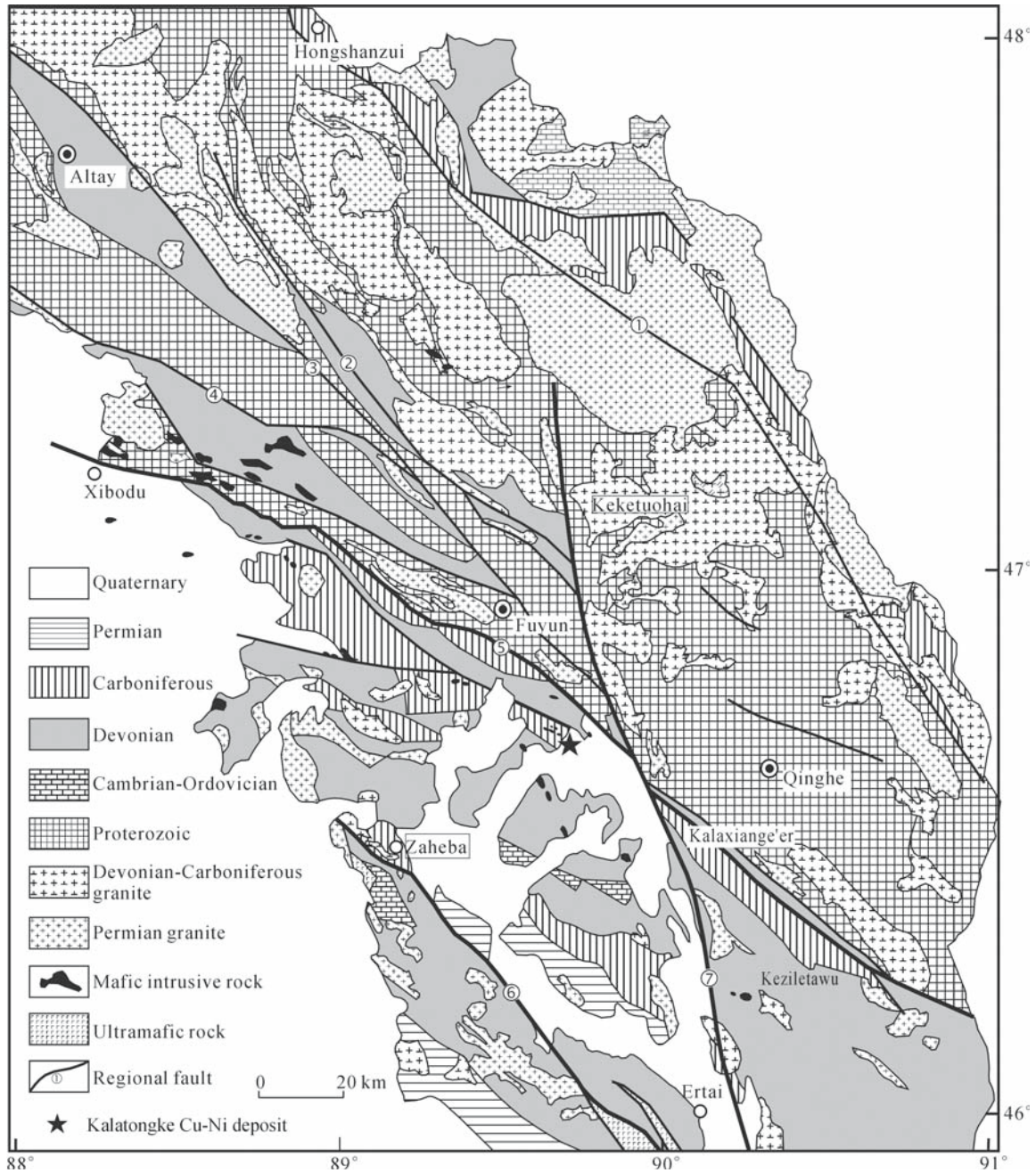


Fig. 1 Sketch geological map of the southern margin of the Altay orogenic belt (modified from Wang et al. (2002))

Fault numbers: ① Nuo'erte fault; ② Basai fault; ③ Abagong fault; ④ Tesibahan fault; ⑤ Irtysh fault; ⑥ Wulunguhe fault; ⑦ Ertai fault

and biotite diorite. All rocks change gradually. Some transition rock types were formed between two rocks, e.g., biotite-amphibole-olivine dolerite-gabbro corresponding to the transition rock between olivine norite and dolerite-gabbro. Biotite-amphibole dolerite-gabbro belongs to marginal lithofacies, forming the crust of the intrusion. The Cu-Ni ores are dominantly hosted in biotite-amphibole-olivine norite and biotite-amphibole norite.

The Xibodu complex is about 2 km long and 0.7–1.3 km wide, striking WNW, intruding the Upper Carboniferous Irtysh Formation, and intruded by late-stage granite at the

northern and southern margins. The complex consists chiefly of amphibole gabbro and amphibole olivine gabbro (norite). In the west, the latter is dominant whereas the former is dominant in the east. In some places, amphibole-olivine gabbro (norite) occurs as xenolith of amphibole gabbro, locally as spherulite. The mineral assemblages under microscope observation are similar to the Kalatongke complex, including amphibole, olivine, clinopyroxene, orthopyroxene and plagioclase, but plagioclase usually accounts for more than 50%. The accessory minerals consist chiefly of magnetite with minor pyrrhotite and pentlandite.

2 Sr-Nd-O isotope compositions

Some relatively fresh representative samples were chosen for Sr, Nd and O isotope analyses after microscope observation. Weathered surfaces and altered zones were removed and the samples were ground in an agate mill, after carefully washing in Millipore water to prevent contamination. The analyzed results are presented in Table 1.

The ($^{87}\text{Sr}/^{86}\text{Sr}$)_i ratios of Nos. 1 and 2 of the Kalatongke intrusion range from 0.703 8 to 0.705 0 (Table 1), averaging 0.704 1, and their $\varepsilon_{\text{Nd}}(t)$ values are in a narrow range, i.e., 6.3 to 8.2 with an average of 7.4. Their $\delta^{18}\text{O}$ values are in a wide range, 5.4‰ to 10.6‰. However, except one doric sample that occurs at the upper part of the intrusion, other samples have narrow $\delta^{18}\text{O}$ values, 5.4‰ to 6.8‰, averaging 6.2‰. The ($^{87}\text{Sr}/^{86}\text{Sr}$)_i of the Xibodu intrusion varies from 0.703 4 to 0.709 0. However, except for one sample, the other three samples have lower ($^{87}\text{Sr}/^{86}\text{Sr}$)_i ratios than the Kalatongke intrusion, 0.703 4 to 0.703 6 with an average value of 0.703 4. Their $\varepsilon_{\text{Nd}}(t)$ values are between 7.5 and 9.1, averaging 8.3, slightly higher than the Kalatongke intrusion. Their $\delta^{18}\text{O}$ (‰) values are quite homogeneous, 6.0 to 6.7, averaging 6.4. Consequently, the two mafic intrusions have similar Sr, Nd and O isotopic compositions, i.e., relatively low initial Sr

isotopic ratios and high $\varepsilon_{\text{Nd}}(t)$ values. In comparison, the Xibodu intrusion has relatively lower initial Sr isotopic ratios and higher $\varepsilon_{\text{Nd}}(t)$ values than the Kalatongke intrusion.

3 Discussion

3.1 Source regions

The nature of the source regions of the Kalatongke complex has been discussed, but remains quite controversial. Wang and Zhao (1991) proposed that it was derived from depleted mantle, and Wang et al. (2002) argued that it should be related to mantle plume. As stated above, both the Kalatongke and the Xibodu complexes have low ($^{87}\text{Sr}/^{86}\text{Sr}$)_i and high $\varepsilon_{\text{Nd}}(t)$, possibly suggesting the derivation of depleted mantle. Although they are plotted in the field of oceanic island basalts (OIB) on the Sr-Nd diagram, their $\varepsilon_{\text{Nd}}(t)$ values are higher than OIB (Fig. 2), implying that they were not derived from a mantle plume. Additionally, the small volume of the intrusions and relatively small total area of the regional mafic intrusions exclude the possibility of a relation to mantle plume. Furthermore, remarkably negative Nb and Ta anomalies on the primitive mantle normalized patterns for the two

Table 1 Sr, Nd and O isotopic data of mafic-ultramafic rocks from the southern margin of the Altay orogenic belt

No.	Sample No.	Location	Rb/10 ⁻⁶	Sr/10 ⁻⁶	⁸⁷ Rb/ ⁸⁷ Sr	(⁸⁷ Sr/ ⁸⁶ Sr) ₀	2σ/10 ⁻⁶	(⁸⁷ Sr/ ⁸⁶ Sr) _i	Sm/10 ⁻⁶
1	Z2-4	No. 2	26.91	328.2	0.237 0	0.705 454	20	0.704 496	2.84
2	Z2-6	No. 2	40.38	381.0	0.307 0	0.705 133	19	0.703 895	3.07
3	Z2-10	No. 2	35.29	763.0	0.134 0	0.704 514	16	0.703 974	2.10
4	Z2-20	No. 2	31.67	329.0	0.278 0	0.704 877	18	0.703 752	2.24
5	157-12	No. 1	20.27	420.7	0.139 0	0.705 602	18	0.705 039	3.78
6	157-03	No. 1	23.76	299.0	0.230 0	0.704 801	18	0.703 872	3.89
7	157-09	No. 1	15.20	523.3	0.084 0	0.704 171	18	0.703 832	3.34
8	157-13	No. 1	33.47	404.0	0.240 0	0.704 979	17	0.704 011	3.40
9	XB5-7	Xibodu	30.12	552.5	0.158 0	0.708 998	18	0.708 219	1.85
10	XB5-2	Xibodu	2.28	592.9	0.011 1	0.703 369	17	0.703 314	3.35
11	XB5-1	Xibodu	1.85	550.5	0.009 7	0.703 647	18	0.703 599	5.01
12	XB5-4	Xibodu	4.01	584.6	0.019 8	0.703 438	16	0.703 340	1.18

No.	Nd/10 ⁻⁶	¹⁴⁷ Sm/ ¹⁴³ Nd	(¹⁴⁴ Nd/ ¹⁴³ Nd) ₀	2σ/10 ⁻⁶	ε(0)	(¹⁴⁴ Nd/ ¹⁴³ Nd) _i	ε _{Nd} (t)	t _{DM} /Ma	δ ¹⁸ O/‰
1	14.21	0.120 9	0.512 845	12	4.0	0.512 615	6.8	513	10.6 (11.0)
2	15.54	0.119 3	0.512 814	30	3.4	0.512 588	6.3	554	6.6
3	10.97	0.115 8	0.512 878	10	4.7	0.512 658	7.7	435	6.0
4	11.38	0.119 1	0.512 905	11	5.2	0.512 679	8.1	407	5.4
5	19.25	0.118 7	0.512 854	15	4.2	0.512 629	7.1	487	5.9
6	18.05	0.127 8	0.512 927	10	4.6	0.512 653	7.5	409	6.1 (5.9)
7	14.54	0.138 9	0.512 948	9	6.0	0.512 684	8.2	427	6.3
8	16.72	0.123 0	0.512 887	10	4.9	0.512 654	7.6	454	6.8
9	7.85	0.142 5	0.512 978	8	6.6	0.512 707	8.6	384	6.5
10	12.60	0.160 7	0.512 953	9	6.1	0.512 648	7.5	588	6.7
11	19.79	0.153 0	0.512 959	9	6.3	0.512 668	7.9	498	6.3
12	5.00	0.142 2	0.513 003	8	7.1	0.512 733	9.1	329	6.0

Sr and Nd isotopes were carried out by the Institute of Geology and Geophysics, Chinese Academy of Sciences. The Sr and Nd contents were measured by isotope dilution. O isotopes were carried out by the Institute of Mineral Resources, Chinese Academy of Geological Sciences. 287 Ma was adopted for age corrections of Sr and Nd isotopes; $\lambda(\text{Sr}) = 1.39 \times 10^{-11} \text{ a}^{-1}$; $\lambda(\text{Nd}) = 6.54 \times 10^{-12} \text{ a}^{-1}$; t_{DM} is model age of depleted mantle.

1 and 5. diorite; 2. gabbro diorite; 3. gabbro norite; 4. norite gabbro; 6 and 8. biotite-amphibole norite; 7. dolerite gabbro; 9. amphibole norite; 10 and 11. gabbro norite; 12. olivine norite. To test for accuracy of O isotope, two samples were duplicated for O analyses. The number in the bracket of Z2-4 is duplicated value, and in 157-03 is the oxygen isotope value of clinopyroxene

intrusions and other mafic intrusions (Yang et al., 2003; Zhang et al., 2003) also suggest involvement of the lithospheric mantle or crust, but not derivation of mantle plume.

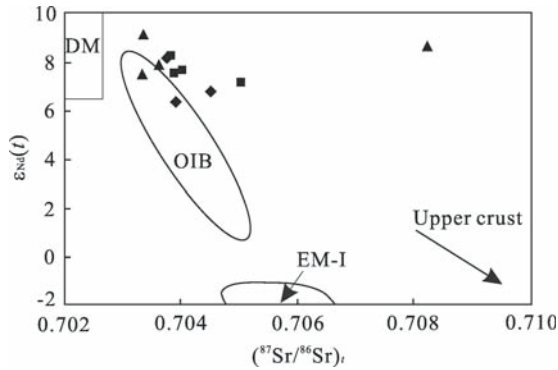


Fig. 2 Sr and Nd isotopic compositions of the mafic-ultramafic complexes in the southern margin of the Altay orogenic belt OIB. Oceanic island basalt; EM-I. I type of mantle member; DM. depleted mantle member.
 ■ No. 1 intrusion of the Kalatongke; ◆ No. 2 intrusion of the Kalatongke; ▲ Xibodu intrusion

In the researched area, both mafic and felsic intrusions forming at different geologic times have positive $\epsilon_{Nd}(t)$ values (Hong et al., 2003). Hong et al. (2003) proposed that they were derived from depleted mantle or the melting of the derivation. Therefore, positive $\epsilon_{Nd}(t)$ values are the common features of all intrusions in the researched area. However, the enrichment of light rare earth elements (LREE) and large ion lithophile elements (LILE) of the mafic-ultramafic complexes related to HREE and HFSE suggests that their primary magmas were not generated directly from the melting of depleted mantle because depleted mantle-derived magmas do not have strong LREE and LILE enrichments (Lightfoot et al., 1993; Wooden et al., 1993). One plausible explanation for this contradiction is the involvement of crust or lithospheric mantle in their source regions, which are relatively homogenous because of their relatively homogeneous isotopic compositions.

It is generally believed that trace elements, Sr, Nd and Pb isotopes are difficult to utilize for distinguishing crust from lithospheric mantle. In contrast, their O isotopes are distinct. For mantle-derived magmas, either from lithospheric mantle or asthenospheric mantle, their $\delta^{18}O$ (‰) values are less than 6, whereas crust-derived magmas have $\delta^{18}O$ (‰) values >6 (Kyser, 1986; Matthey et al., 1994). Therefore, it can be inferred that the two complexes originated from depleted mantle that was crustally incorporated.

There are two possible ways for involvement of crust. One is source mixing, e.g., mixing of the oceanic crust with mantle because of subduction of the oceanic crust, or partial melting of homogenous mixing of subducted oceanic crust with mantle, such as in some oceanic island and large igneous province (Wilson, 1989). The other is crustal contamination within the magma chamber and en route to the surface. James (1981)

proposed a method to distinguish the two types of contamination (Fig. 3). It can be inferred to be mixing of source regions if they are plotted on the concave curves; otherwise crustal contamination if they are plotted on the convex curves. Except for one dioritic sample plotted on the convex curve, others are plotted on the concave curves, suggesting the mixing of source regions for the mafic-ultramafic complexes. In contrast, the diorite in the No. 2 intrusion in the Kalatongke region probably resulted from contamination of the upper crust within the magma chamber.

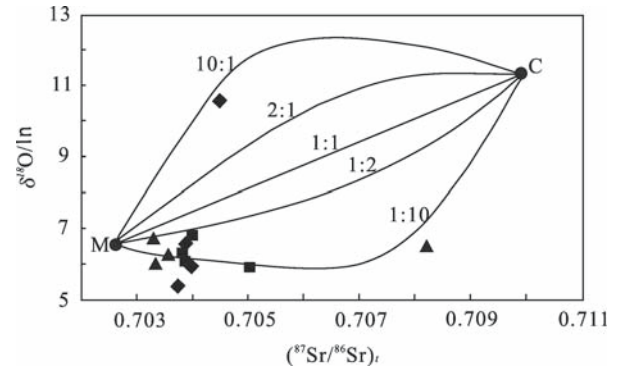


Fig. 3 Variation of $\delta^{18}O$ versus $(^{87}Sr/^{86}Sr)_t$ for the mixing of mantle (M) and crustal (C) components (after James (1981)) The depleted mantle represents the mantle components because the isotopic data of the intrusions indicate the depleted mantle rather than primitive mantle whereas average crustal component is used to represent the whole crust. The legend is the same as in Fig. 2.

Although the isotope and trace element geochemistry of the mafic-ultramafic complexes in the area is consistent with subduction-related magmas, these complexes were not generated by subduction, but by extension after orogenic movement (Li, 1991). This can be plausibly interpreted by the involvement of ancient subducted oceanic crust incorporated into the depleted asthenospheric mantle, which caused a relative homogeneity of elements and isotopes. Nd model ages can provide some constraints on the ages of subduction of oceanic crust. The two intrusions have similar Nd model ages, ranging from 329 to 588 Ma with an average age of 457 Ma, i.e., 409 to 554 Ma for the Kalatongke complex, and 329 to 588 Ma for the Xibodu complex. Their average Nd model ages are 461 Ma and 450 Ma respectively, much earlier than their emplacement. This suggests that the oceanic crust subducted in the Early Paleozoic, consistent with regional tectonic setting (Li, 1991).

3.2 Tectonic setting

The tectonic setting of the researched area remains controversial (Ye et al., 1998; Wang et al., 2000). Some workers proposed that the boundary between the Altay and Junggar orogenic belts is the Irtylish fault whereas others argued for Wulunguhe fault. The evidence for the former is based on the different deformation of the strata at the two sides of the Irtylish fault, while the major evidence for the latter is the

presence of ophiolite along the Wulunguhe fault. As stated above, the similar characteristics of the source regions of the Kalatongke and Xibodu complexes, which are distributed at the southern and northern sides of the Irtylish fault respectively, indicate the similar deep geological characteristics along this fault. In addition, their similar Nd model ages also suggest their similar tectonic evolution history during the Early Paleozoic. Consequently, the Irtylish fault is unlikely to be the boundary between the Altay and Junggar orogenic belts, which is also supported by the absence of definite ophiolite along the fault. In contrast, mafic-ultramafic intrusions have not been recognized at the southern side of the Wulunguhe fault, but ophiolite occurred along the fault. This suggests that the Wulunguhe fault is likely the boundary between two tectonic units.

4 Conclusions

First, both the Kalatongke and Xibodu complexes originated from depleted asthenospheric mantle, which contained subducted oceanic crust during the Paleozoic. The Kalatongke complex was contaminated by the upper crust within a magma chamber and en route to the surface.

Second, the similar sources and Nd model ages of the Kalatongke and Xibodu complexes which were distributed in the southern and northern sides of the Irtylish fault possibly indicate similar tectonic settings. Thus, the Irtylish fault is unlikely to be the boundary between the Altay and Junggar orogenic belts, but more likely the Wulunguhe fault where ophiolite occurred.

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