Deep-derived enclaves (belonging to middle-lower crust metamorphic rocks) in the Liuhe-Xiangduo area, eastern Tibet: Evidence from petrogeochemistry *

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Abstract Petrological and geochemical studies of deep-derived enclaves from the Liuhe-Xiangduo area, eastern Tibet, showed that the enclaves involve five types of rocks, i. e., garnet diopsidite, garnet amphibolite, garnet hornblendite, amphibolite and hornblendite, whose main mineral assemblages are Grt + Di + Hbl, Grt + Pl + Hbl + Di, Grt + Hbl + Pl, Pl + Hbl, and Hbl + Bt, respectively. The enclaves exhibit typical crystalloblastic texture, and growth zones are well developed in garnet (Grt) in the enclaves. In view of major element geochemistry, the deep-derived enclaves are characterized by high MgO and FeO^*, ranging from 12.00% to 12.30% and 8.15% to 10.94%, respectively. The protolith restoration of metamorphic rocks revealed that the enclaves belong to ortho-metamorphic rocks. The REE abundances vary over a wide range, and $\sum$REE ranges from 53.39 to 129.04 μg/g. The REE patterns slightly incline toward the HREE side with weak LREE enrichment. The contents of Rb, Sr, and Ba range from 8.34 to 101 μg/g, 165 to 1485 μg/g, and 105 to 721 μg/g, respectively. The primitive mantle-normalized spider diagrams of trace elements show obvious negative Nb, Ta, Zr and Hf anomalies. Sr-Nd isotopic compositions of the enclaves indicated that the potential source of deep-derived enclaves is similar to the depleted-mantle, and their $(^{87}Sr/^{86}Sr)_i$ ratios vary from 0.706314 to 0.707198, $(^{147}Nd/^{144}Nd)_i$ ratios from 0.512947 to 0.513046, and $\varepsilon_{Nd}(T)$ values from +7.0 to +9.0, respectively. The potential source of the enclaves is obviously different from the EM2-type mantle from which high-K igneous rocks stemmed (the host rocks), i. e., there is no direct genetic relationship between the enclaves and the host rocks. Deep-derived enclaves in the host rocks belong to mafic xenoliths, and those in the Liuhe-Xiangduo area, eastern Tibet, are some middle-lower crust ortho-metamorphic rocks which were accidentally captured at 20 – 50 km level by rapidly entrained high-temperature high-K magma, whose source is considered to be located at 50-km depth or so.

Key words eastern Tibet; Liuhe-Xiangduo area; deep-derived enclave; middle-lower ortho-metamorphic rock; petrology; geochemistry

1 Introduction

Many investigations have been made on the deep-derived enclaves from Cenozoic high-K igneous rocks in the Liuhe-Xinagduo area, eastern Tibet, by many researchers from different aspects since the 90s of the 20th century (Cai Xinping, 1992; Deng Wanming et al., 1998a; Lü Boxi and Qian Xianggui, 1999; Liu Xianfan et al., 1999; Wang Jianghai et al., 2001; Wang Jian et al., 2003; Wei Qirong and Wang Jianghai, 2004a). But, up to now, there still exists great bifurcation on the origin of deep-derived enclaves from Cenozoic high-K igneous rocks in the Liuhe-Xinagduo area. Four points of view are summarized as follows: (1) garnet- and diopside-bearing ultramafic enclaves are the products of partial melting of the primary mantle, with the involvement of alkali magma (Liu Xianfan et al., 1999); (2) this suite of deep-derived enclaves is of low crust metamorphic rock (Cai Xinping, 1992;

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Deng Wanming et al., 1998a); (3) alkali-rich mafic rocks and pyroxenite enclaves represent alkali-rich ultrabasic-basic rocks, calc-alkalic rock sheets, and wedges derived from partial melting of lherzolite at the top of the enriched mantle (Lü Boxi and Qian Xianggui, 1999); and (4) these deep-derived enclaves belong to middle-low crust metamorphic rocks (Wang Jianghai et al., 2001; Wang Jian et al., 2003; Wei Qirong et al., 2004a).

So, based on the above different viewpoints on those deep-derived enclaves, and according to the newly acquired geochemical data of deep-derived enclaves from Cenozoic high-K igneous rocks in the Liuhe-Xiangduo area, the properties and possible genesis of the enclaves will be discussed in this paper.

2 Geological setting

Tectonic collision between the Indian and Eurasian plates and intracontinental deformation since 55 Ma not only constrained the formation and evolution of the Tibet Plateau (Pan Guitang et al., 1990; Yin An, 2000), but also controlled Cenozoic tectonism and magmatic activity in eastern Tibet (Yin An, 2000; Wang Jianghai et al., 2001).

Cenozoic tectonism in eastern Tibet may have involved three stages: (1) continental subduction during 28 and 40 Ma (Meyer et al., 1998; Wang Jianghai et al., 2001), (2) large-scale transition stretching from 16 to 24 Ma (Harrison et al., 1996); and (3) east-west extension from the present to 16 Ma (Masek et al., 1994; Yin An, 2000; Wang Jianghai et al., 2001). Corresponding to the tectonism, two pulses of Cenozoic high-K magmatism were developed in eastern Tibet (Wang Jianghai et al., 2001): (1) the late-stage magmatic activities (from 0 to 16 Ma) along the southern part of the Honghe River fault belt, and the rocks there are mainly basanite, alkali basalt, trachybasalt and trachyte (Wei Qirong and Wang Jianghai, 2004b), and abundant pyrolite xenoliths were yielded in the Maguan basanite meatus (Mei Houjun, 1966; Shu Xiaoxin, 1995; Sun Hongjuan, 2000); and (2) the early-stage magmatic activities (from 28 to 40 Ma) along the whole Jinshajiang River-Honghe River fault belt, and the rock types there mainly include orthoclase porphyry, quartz-orthoclase porphyry, orthoclase, trachyte, trachyandesite, alkali basalt and shoshonitic lamprophyre (Deng Wanming et al., 1998b; Wang Jian et al., 2003), and those deep-derived enclaves were developed in the late-pulse high-K igneous rocks.

Enclave-bearing high-K igneous rocks in the Liuhe-Xiangduo area are exposed in a small Early Tertiary pull-part basin, which are associated with the large-scale Honghe River-Mt. Ailao sinistral strike-slip shear zone, and respectively belong to the Beiya-Liuhe and Jianchuan rock groups (Fig. 1) of the four rock groups, namely the Jianchang, Zhanhe, Beiya-Liuhe and Dali rock groups in the Dali-Jianchuan area. The host rocks are mainly orthoclase porphyry, quartz-orthoclase porphyry, and associated trachyandesite, trachybasalt, and alkali-basalt. Their K-Ar and $^{40}Ar/^{39}Ar$ ages are 26.3 – 36.7 Ma (Zhang Yuquan and Xie Yingwen, 1997) and 28 – 40 Ma (Wang Jianghai et al., 2001), respectively, corresponding to Early Tertiary. Abundant deep-derived mafic enclaves were produced in the high-K rock series in the Liuhe-Xiangduo area. The enclaves are diverse in size, and the larger ones are measured at 6 – 8cm in diameter, the smaller ones at 1 – 2 cm in diameter, with an average of 3 – 4 cm. The enclaves are mainly rounded and subangular in shape. The contact interface between the enclaves and the host rocks (high-K igneous rocks) is distinct, and the chilled rims that are about 2mm in size can be seen in a few of the enclaves.

3 Petrological characteristics

According to the main mineral assemblages of deep-derived enclaves in the Liuhe-Xiangduo area, the xenoliths are classified as five rock types (Wei Qirong and Wang Jianghai, 2004a), i. e., garnet diopsidite, garnet amphibolite, garnet hornblendite, amphibolite, and hornblendite.

(1) Garnet diopsidite: The rock is grayish-black, and exhibits medium-coarse granular crystalloblastic texture and massive structure in the enclaves. It is composed largely of garnet (Grt) and diopside (Di), with minor amounts of hornblende (Hbl), plagioclase (Pl) and phlogolite (Phl). The Grt displays a sorrel color, and an orbicular crystal combination, whose contents in garnet diopsidite range from 20% to 30%. The Grt generally exhibits symplectite texture, consisting of fine green Hbl, Di, chlorite (Chl), albite (Ab) and magnetite (Mt). Most of the Di exhibits sieve texture due to strong retrogressive metamorphism, and Ab and Na-rich Pl were filled in the texture. The Hbl has growth zones, of which the inner zone is composed of green Hbl, while the outer zone is composed of brown Hbl. The green Hbl packs Di and Ab. The accessory minerals are rutile (Rt), ilmenite (Ilm), and minor titanite (Ttn).

(2) Garnet amphibolite: The rock is grayish-green to celandine green in color, and exhibits heterogranular medium-coarse granular crystalloblastic texture and massive structure. Its main minerals are Grt, Pl,

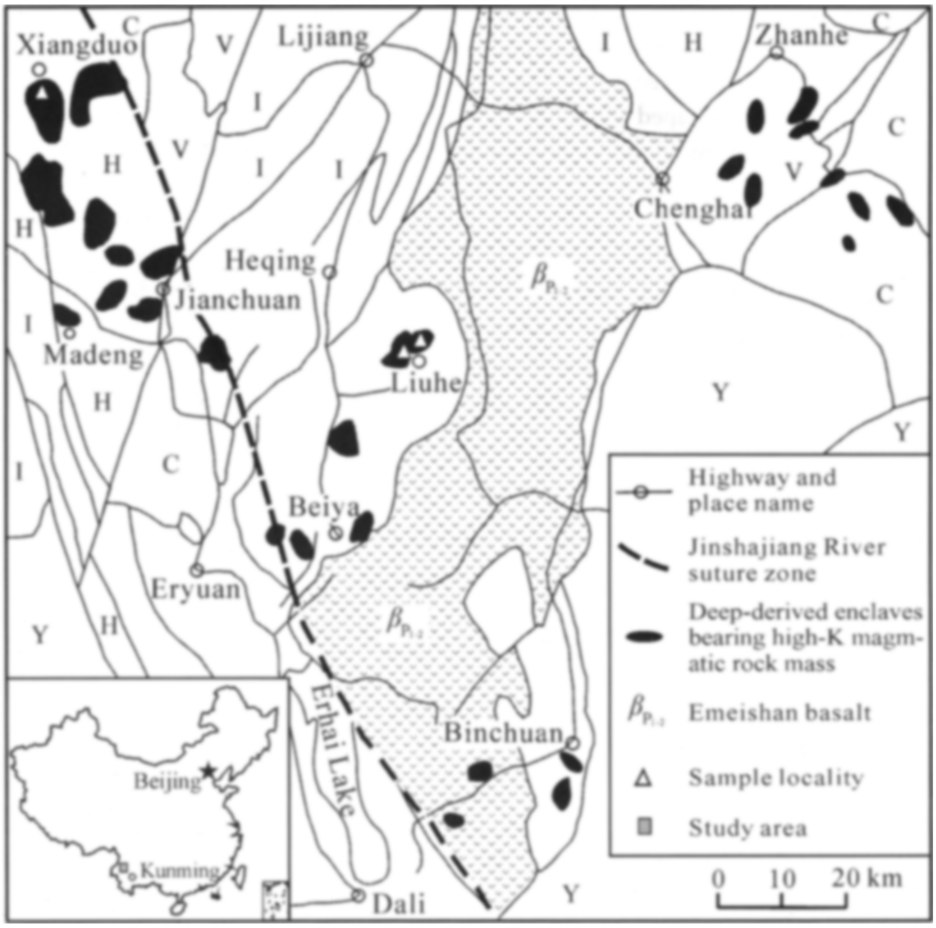

Fig. 1. The geological sketch map of the Liuhe-Xiangduo area, eastern Tibet (modified from Deng Wanming et al., 1998a). H. Himalayan tectonic formation; Y. Yanshanian tectonic formation; I. Indosinian tectonic formation; V. Variscon tectonic formation; C. Caledonian tectonic formation.

and Hbl, with some epidote (Ep) and minor Di and Phl. The Grt has a sorrel color and an orbicular crystal combination, whose contents vary over a large range, with the maximum value up to 30%, and the minimum value around 5% only. The Grt contains quite a number of enclaves, for example, quartz (Qtz), Di, Hbl, and alkali feldspar. The Grt exhibits symplectite texture, consisting of Ab, Ilm, and Mt. The Hbl is green in color and includes two kinds of Hbl, which may be the products of two different generations. The Pl can be classified as two types, one of which is represented by the enclave of Grt and the other is represented by Pl in the matrix, and both of them are Na-enriched Pl or Ab. The Ep is pea green in color and is granular in shape, and retrogressive rims were developed, which consist of fine Ep and Ab grains. The configuration of Ep is very similar to that of orthopyroxene, so the epitode may be derived from retrogressive metamorphism of orthopyroxene. That is because, up to now, no orthopyroxene mineral has been found in the deep-derived mafic enclaves from the Liuhe-Xiangduo area. The accessory minerals present in the garnet amphibolite are Rt, Ilm, and Ttn. The Rt has obvious retrogressive rims composed of Ilm and Ttn, implying that they were retrograded from Rt.

(3) Garnet hornblendite: It occurs as the dominant enclaves in the Liuhe-Xiangduo area, greyish-green, medium-coarse in size, granular crystalloblastic in texture, and massive in structure. Most of Grt are of the monocrystal type, a few occur as an orbicular crystal combination, and its contents range from 15% to 30%. The major minerals are Grt and Hbl, while the minor minerals are Di, Pl and Phl in the rock. Grt growth zoning was well developed in the mega-porphyritic Grts, while a lot of envelops of Qtz and Pl were packed in the central part, but no envelop is seen in the marginal part. In the Grt are developed Hbl corona and symplectite texture, consisting of Hbl, Ab and

Mt. The Hbl is green and also is divided into two kinds, which may belong to the products of two different generations. Some Qtz granules were packed in early Hbl. Di grains were metasomatized by deuterogenic Hbl, giving rise to sieve-shaped texture, in which most of the sieve pores were filled by Na-enriched Pl grains, and part of them were filled by high-Ca Pl grains. The accessory minerals are Rt and Ilm. The Rt is characterized by no mixed Ilm.

(4) Amphibolite: The rock is greyish-green in color, medium-coarse in size, granular crystalloblastic in texture, and massive in structure. There is no Grt mineral in this rock. The major minerals are Hbl and Pl, with minor Di and Phl in the rock. The Hbl is green in color, and its content is higher than 50%. The Pl belongs to high-Ca Pl. The accessory mineral is Mt.

(5) Hornblendite: The rock is greenish-black in color, coarse in size, granular crystalloblastic in texture, and massive in structure. There is no Grt mineral in this rock, either. The essential mineral of the rock is Hbl. The growth zones are well developed in Hbl, and the Hbl contents of the rock are over 90%. Only minor biotite (Bt) and Pl were found in the rock. Most of the Bt were converted to chlorite. The Pl was suffered from intensive alteration. The accessory mineral is Mt.

Therefore, petrographical study on deep-derived enclaves from the Liuhe-Xiangduo area showed that the enclaves possess typical structural characteristics of metamorphic rocks, and in the Grt are well developed growth zones. So, these enclaves belong to typical metamorphic rocks.

4 Analysis and discussion

The preparation of samples involved two steps: firstly, the samples were washed with water and naturally dried to remove surficial contaminants, and then were crushed as fine as to be 200 mesh. The major elements in the whole rock of enclaves were tested by the wet chemical analytical method at the Institute of Geochemistry, Chinese Academy of Sciences (IGCAS). The trace elements were analyzed by ICP-MS, while 5 samples were tested at IGCAS, and a piece of (SG2-3) at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS). The analytical method of trace elements is after Liu Ying et al. (1996). Sr-Nd isotopes of the whole rock and monominerals of the enclave (SG2-3) were determined at GIGCAS by MC-ICPMS techniques (the model of the instrument is MicroMass IsoProb). The MC-ICP-MS analyzing techniques used to analyze Sr and Nd isotopes are after Wei Gangjian et al. (2002) and after Liang Xirong et al. (2003), respectively. The results of analysis of major and trace elements, and Sr-Nd isotopes for deep-derived enclaves in the Liuhe-Xiangduo area are listed in Tables 1 – 3, respectively.

Table 1. Major element compositions of deep-derived enclaves from the Liuhe-Xiangduo area (%)

Sample No.	LH01-8	LH01-13	XD01-5-1	LH01-7-1	XD01-2-1
Location	Liuhe	Liuhe	Xiangduo	Liuhe	Xiangduo
SiO_2	47.40	54.55	47.92	45.81	50.98
TiO_2	1.62	0.77	1.10	1.37	0.42
Al_2O_3	10.93	16.28	17.93	11.59	12.59
Fe_2O_3	3.67	3.24	4.39	4.29	3.28
FeO	7.54	4.70	6.08	7.10	5.20
MnO	0.21	0.20	0.31	0.16	0.20
MgO	12.30	4.70	6.90	12.40	12.50
CaO	8.80	5.60	7.70	9.60	7.90
Na_2O	1.25	4.00	1.91	2.11	2.14
K_2O	2.07	2.09	1.02	0.97	0.50
P_2O_5	0.20	0.53	0.25	0.31	0.21
Loss	3.87	2.70	3.86	2.67	2.75
CO_2				1.05	0.70
Total	99.86	99.36	99.37	99.43	99.27

Note: Sample LH01-8 is garnet hornblendite; amphibolite includes samples LH01-13 and XD01-5-1; hornblendite includes samples LH01-7-1 and XD01-2-1.

Table 2. REE and trace element compositions of deep-derived enclaves from the Liuhe-Xiangduo area, eastern Tibet (μg/g)

Sample No.	SG2-3	LH01-8	LH01-13	XD01-5-1	LH01-7-1	XD01-2-1
Location	Liuhe	Liuhe	Liuhe	Xiangduo	Liuhe	Xiangduo
La	8.08	22.89	13.98	12.16	25.63	8.90
Ce	16.50	19.16	28.72	26.05	44.68	19.88
Pr	2.32	6.01	3.58	3.38	4.77	2.41
Nd	10.90	31.96	15.82	15.88	20.75	10.41
Sm	3.36	8.68	3.23	4.24	4.90	2.37
Eu	1.27	2.20	1.21	1.32	1.81	0.64
Gd	4.50	8.72	2.58	4.40	4.52	2.16
Tb	0.885	1.62	0.385	0.772	0.721	0.366
Dy	4.66	10.53	2.03	4.93	4.20	2.30
Ho	1.00	2.15	0.396	1.022	0.818	0.512
Er	2.85	6.47	1.18	2.94	2.12	1.51
Tm	0.429	1.03	0.171	0.436	0.309	0.213
Yb	2.76	6.69	0.922	2.82	1.73	1.52
Lu	0.429	0.930	0.131	0.387	0.226	0.212
ΣREE	59.88	129.04	74.34	80.74	117.16	53.39
LREE	42.49	90.90	66.54	63.04	102.53	44.60
HREE	17.39	38.14	7.80	17.71	14.63	8.79
$(La/Yb)_N$	1.60	2.45	10.88	3.09	10.65	4.21
$(La/Sm)_N$	1.23	1.70	2.79	1.85	3.38	2.43
$(Gd/Yb)_N$	1.23	1.08	2.31	1.29	2.16	1.18
Ce/Ce^*	1.00	0.38	1.01	1.00	0.96	1.09
Eu/Eu^*	1.03	0.76	1.24	0.93	1.16	0.84
Rb	20.7	101	65.0	34.5	8.34	42.6
Sr	288	267	1485	274	165	256
Ba	247	721	624	675	105	452
Th	0.871	0.94	0.407	1.52	3.30	1.22
U	0.473	0.3	0.343	1.51	1.60	4.37
Nb	2.17	30.2	2.88	9.07	16.2	3.85
Ta	0.161	2.06	0.161	0.543	0.849	0.247
K		17177	17343	8464	8049	4149
P		873	2314	1092	1354	917
Zr	38.0	64.9	23.5	91.9	44.9	41.6
Hf	1.05	1.92	0.821	2.72	1.81	1.40
Y	26.6	52.2	10.7	28.3	20.8	13.8
Sc	40.7	32.7	19.8	40.8	42.8	34.0
Ti	8253	9208	6361	9760	9562	2746
V	270	238	189	274	312	204
Cr	408	1113	46.7	283	595	1431
Mn	2675	1813	1665	2525	1123	1301
Fe		84334	59236	78019	85252	63404
Co	41.5	70.9	30.2	54.6	74.9	58.8
Ni	102	584	21.6	73.5	321	332
Cu	21.2	23.7	30.7	123	41.4	52.0
Zn	938	3208	121	184	145	2035

Note: SG2-3 is garnet hornblendite.

Table 3. Sr-Nd isotopic compositions of deep-derived enclaves from the Liuhe area, eastern Tibet

Sample No.	Object tested	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr(2\sigma)$	$(^{87}Sr/^{86}Sr)_i$	
SG2-3	Wr	20.66	277.6	0.2155	0.707320 ± 14	0.707198	
SG2-3	Cpx	7.444	100.3	0.2148	0.706436 ± 14	0.706314	
SG2-3	Grt	0.6418	15.75	0.1180	0.707196 ± 12	0.707129	
Sample No.	Object tested	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{147}Nd/^{144}Nd\ (2\sigma)$	$(^{147}Nd/^{144}Nd)_i$	$\varepsilon_{Nd}(T)$
SG2-3	Wr	3.184	10.366	0.1858	0.512996 ± 09	0.512947	+7.0
SG2-3	Cpx	3.655	12.562	0.176	0.513092 ± 17	0.513046	+9.0
SG2-3	Grt	0.7935	0.4641	1.0342	0.513225 ± 09	0.512954	+7.2

Note: Wr represents the whole rock; Cpx represents clinopyroxene; Grt represents garnet.

4.1 Major element geochemistry

As viewed from Table 1, the contents of SiO_2 and TiO_2 in the garnet hornblendite are low (47.40% and 1.62%, respectively), but the contents of FeO^* ($FeO^* = FeO + 0.9 \times Fe_2O_3$), MgO and CaO are high (10.84%, 12.30%, and 8.80%, respectively). The contents of Al_2O_3, Na_2O, and K_2O are low as well (10.93%, 1.25%, and 2.07%, respectively). So, in view of its major element geochemistry, the garnet hornblendite is characterized by low Si, Ti, Al, and Alk ($Na_2O + K_2O$) and high Mg and Fe.

The contents of SiO_2 in the amphibolite are significantly variable, ranging from 47.92% to 54.55%. The rock is characterized by high contents of Al_2O_3 (16.28% – 17.93%), low contents of TiO_2 (0.77% – 1.10%), medium contents of FeO^* (7.62% – 10.03%), and lower contents of MgO and CaO (4.70% – 6.90% and 5.60% – 7.70%, respectively), but higher and obviously variable contents of Na_2O (1.91% – 4.00%), and low contents of K_2O (1.02% – 2.09%). Therefore, the major element geochemical characteristics of the amphibolite are high Al and Na contents, low Si, Ti, Mg, Ca, and K contents, and medium Fe contents.

The contents of SiO_2, TiO_2, and Al_2O_3 in the hornblendite are low (45.81% – 50.98%, 0.42% – 1.37%, and 11.59% – 12.59%, respectively), those of FeO^*, MgO, and CaO are high (8.15% – 10.96%, 12.40% – 12.50%, and 7.90% – 9.60%, respectively), and those of Na_2O and K_2O are even lower (2.11% – 2.14% and 0.50% – 0.97%, respectively). Therefore, in view of its major element geochemistry, the hornblendite is characterized as being high in Fe, Mg, and Ca, but low in Si, Al, and Alk ($Na_2O + K_2O$).

In summary, deep-derived enclaves from the Liuhe-Xiangduo area are characterized as being low in Si, Ti, Na, K and high in Fe, Mg, and Ca. So, major element chemical characteristics of deep-derived enclaves from the Liuhe-Xiangduo area showed that these enclaves belong to deep-source mafic xenoliths.

Protolith restoration is an important subject of study on metamorphic rocks. It may be indicated that metamorphic rocks would probably be derived from metamorphism of igneous rocks or sedimentary rocks. So, it is helpful to understand the history of evolution of rocks and constrain their tectonic settings. According to the (Al + Fe + Ti) versus (Ca + Mg) diagram (Fig. 2), the results of study for the deep-source mafic enclaves from the Liuhe-Xiangduo area showed that the protolith of the enclaves is a basic igneous rock. Zr versus MgO diagram (Fig. 3) is solely appliable to amphibolite, and the results also revealed that the amphibolite is an ortho-amphibolite.

Therefore, protolith restoration showed that deep-derived enclaves from the Liuhe-Xiangduo area belong to ortho-metamorphic rocks.

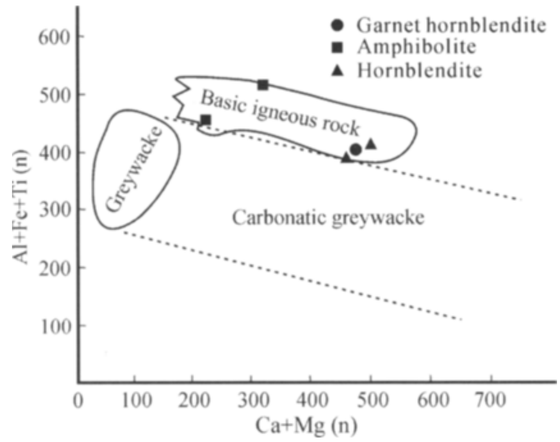

Fig. 2. (Al + Fe + Ti)-(Ca + Mg) diagram of deep-derived enclaves from the Liuhe-Xiangduo area (after Wang Renmin et al., 1987).

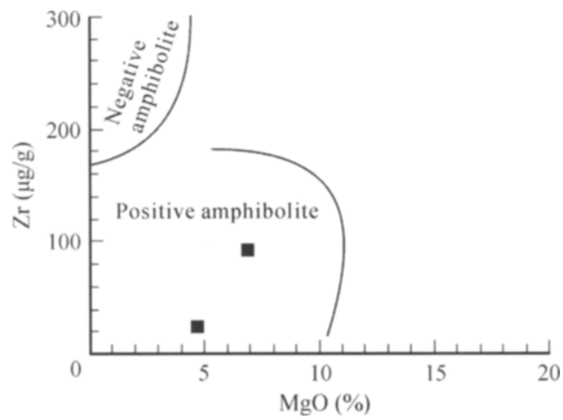

Fig. 3. Zr-MgO diagram of amphibolite enclaves from the Liuhe-Xiangduo area (after Geringer, 1979).

4.2 REE geochemistry

The REE abundances of deep-derived enclaves from the Liuhe-Xiangduo area vary over a wide range, with $\sum$REE ranging from 53.39 – 129.04 μg/g (Table 2), obviously lower than those of the host rocks of enclaves (Deng Wanming et al., 1998b). Except for samples LH01-13 and LH01-7-1 which have experienced strong fractionation between the LREE and the HREE [$(La/Yb)_N$ values are 10.88 and 10.65, respectively], the rest samples have not experienced so remarkable REE fractionation [$(La/Yb)_N$ = 1.60 - 4.21]. But all the samples have undergone obvious fractionation between the LREE and the HREE, with the values of $(La/Sm)_N$ and $(Gd/Yb)_N$ varying from 1.23 to 3.38, and 1.08 to 2.31, respectively. The REE patterns slightly incline toward the HREE side with weak LREE enrichment (Fig. 4). Except for sample LH01-8 which shows remarkable negative Ce anomalies (Ce/Ce^* = 0.38), the rest samples have no Ce anomaly (Ce/Ce^* = 0.96 - 1.09). Samples LH01-8 and XD01-2-1 show negative Eu anomalies, with Eu/Eu^* ratios being 0.76 and 0.84, respectively. But samples LH01-13 and LH01-7-1 show positive Eu anomalies with Eu/Eu^* ratios being 1.24 and 1.16, respectively; the rest samples show no Eu anomaly (Eu/Eu^* = 0.93 - 1.03). So, the REE geochemical characteristics of deep-derived enclaves are significantly different from those of the host rocks in the Liuhe-Xiangduo area (Deng Wanming et al., 1998b).

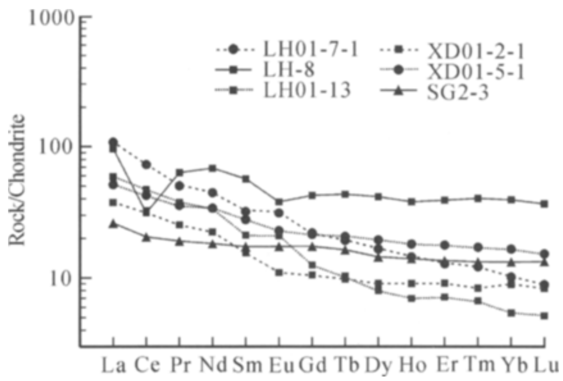

Fig. 4. The chondrite-normalized REE patterns of deep-derived enclaves from the Liuhe-Xiangduo area (after Sun & McDonough, 1989).

4.3 Trace element geochemistry

The abundances of large ion lithophile elements (LILE) such as Rb, Sr and Ba in deep-derived enclaves from the Liuhe-Xiangduo area are very high (Table 2), and the contents range from 8.34 to 101 μg/g, 165 to 1485 μg/g, and 105 to 721 μg/g, respectively. The contents of the radioactive heat-generating element uranium are much higher, but the contents of Th are lower, ranging from 0.30 to 4.37 μg/g and 0.407 to 3.30 μg/g, respectively. High field strength elements (HFSE) such as Nb and Ta are higher in sample LH01-8 (30.2 μg/g and 2.06 μg/g, respectively), but they are lower in the rest samples (2.17 - 16.2 μg/g and 0.161 - 0.849 μg/g, respectively). The contents of high field strength elements (HFSE) such as Zr and Hf are also low, and their contents vary from 23.5 to 91.9 μg/g and 0.821 to 2.72 μg/g, respectively. In the primitive mantel-normalized spider diagrams of trace elements, we can see positive U, K and Eu anomalies and negative Th, Nb, Ta, Zr, Hf and Ti anomalies (Fig. 5), especially remarkable negative Nb, Ta, Zr, Hf anomalies. Remarkable negative Nb anomalies indicated deep-derived enclaves from the Liuhe-Xiangduo area might be derived from the crust, or the enclaves had been contaminated strongly by crustal materials.

The contents of transition elements such as Cr and Ni in deep-derived enclaves from the Liuhe-Xiangduo area are low, but vary over a wide range from 46.7 to 1431 μg/g and 21.6 to 584 μg/g (Table 2), respectively. The primitive mantel-normalized transition element distribution curves show positive Ti anomalies, and negative Cr and Ni anomalies (Fig. 6). The transition element distribution curves are of the W-type (Fig. 6).

4.4 Sr-Nd isotope geochemistry

In order to make a comparison to the host of enclaves, 13 suits of Sr-Nd isotope data for high-K igneous rocks (the host rock) were quoted in this paper to describe the Sr-Nd isotopic characteristics and sources of enclaves in the Liuhe-Xiangduo area (Deng Wanming et al., 1998a). Because the contents of Rb and Sm in high-K igneous rocks from the Liuhe-Xiangduo area are very high, the Sr-Nd isotope data will be revised when source materials of the rocks are discussed in terms of the Sr-Nd isotope data, and the age of 40 Ma will be taken. In comparison to the high-K rocks, Sr and Nd isotope ratios in the whole rocks and monomierals of enclaves will be revised when the age of 40 Ma is taken; the Sr-Nd isotopic compositions of enclaves represent those of the enclaves that were captured by the host rocks at that time.

The $(^{87}Sr/^{86}Sr)_i$ ratio of the whole rock of garnet hornblendite enclaves from the Liuhe-Xiangduo area is 0.707198 (Table 3); the $(^{87}Sr/^{86}Sr)_i$ ratio of mono-garnet is 0.707129, close to that of the whole rock; but the $(^{87}Sr/^{86}Sr)_i$ ratio of mono-clinopyroxene is so low as to be 0.706314. Therefore, $(^{87}Sr/^{86}Sr)_i$ ratios in the whole rock and monomineral of the enclaves are close to the higher ratio limit of the host rock (Deng Wanming et al., 1998a). It is shown that the enclaves are characterized by higher $(^{87}Sr/^{86}Sr)_i$ ratios.

The $(^{147}Nd/^{144}Nd)_i$ ratio of the whole rock of garnet hornblendite enclaves is very close to that of mono-garnet, being 0.512947 and 0.512954, respectively. The $(^{147}Nd/^{144}Nd)_i$ ratio of mono-clinopyroxene is 0.513046. Therefore, as compared with the high-K igneous rocks, the enclaves are characterized by low

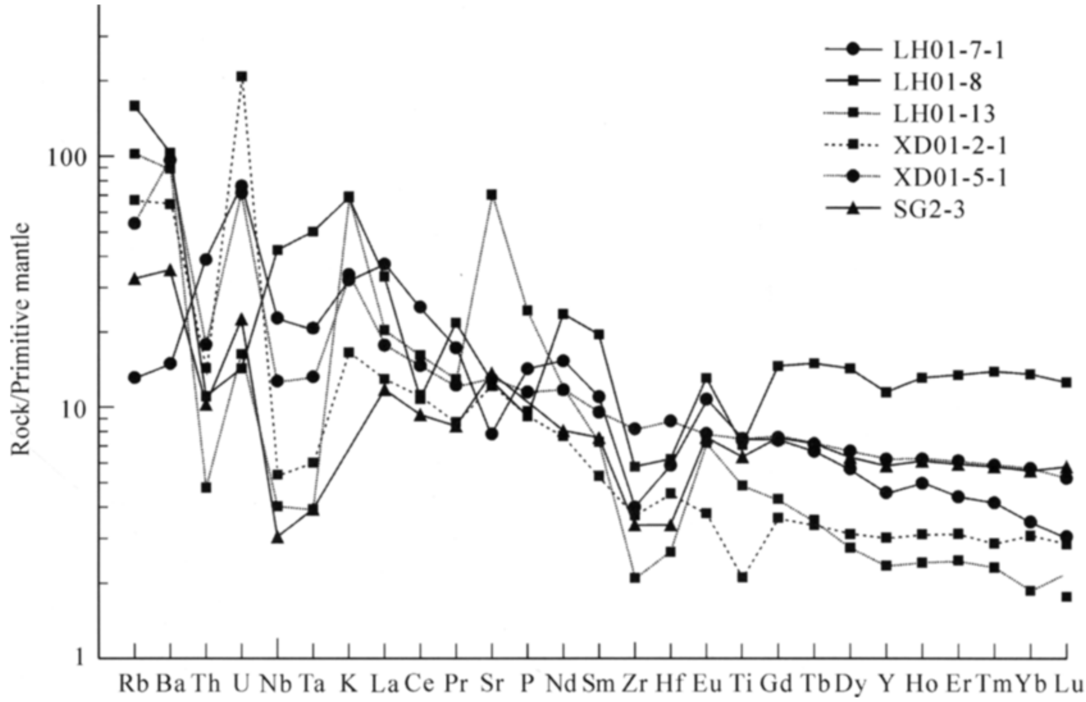

Fig. 5. Incompatible element spider diagrams of deep-derived enclaves from the Liuhe-Xiangduo area (primitive mantle-normalized after Sun & McDonough, 1989).

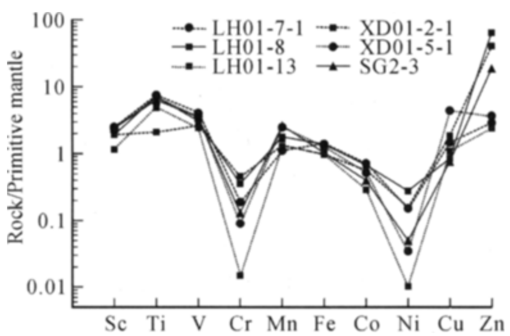

Fig. 6. Transition element distribution curves of deep-derived enclaves from the Liuhe-Xiangduo area (primitive mantle-normalized after Jagoutz et al., 1979).

$({}^{147}Nd/{}^{144}Nd)_i$ ratios (Deng Wanming et al., 1998a), and the $({}^{147}Nd/{}^{144}Nd)_i$ ratios of the whole rock and mono-mineral of the enclaves are similar to those of the source of E-MORB (Saunders et al., 1988). The $\varepsilon_{Nd}(T)$ values of the whole rock and mono-mineral of the enclaves range from +7.0 to +9.0, indicating that the potential source of garnet hornblendite enclaves in the Liuhe-Xiangduo area is similar to a depleted mantle (Zindler & Hart, 1986).

But, the initial $({}^{87}Sr/{}^{86}Sr)_i$ ratios of host rocks from the Liuhe-Xiangduo area range from 0.704184 to 0.707539; $({}^{147}Nd/{}^{144}Nd)_i$ ratios, 0.512265 to 0.512564; and $\varepsilon_{Nd}(T)$ values, −6.3 to −0.4. These facts show that the potential source of the enclaves is obviously different from that of the host rocks.

In the Sr-Nd isotope correlation diagram (Fig. 7), the data points representing the Sr-Nd isotopic composition of whole rock and mono-mineral of the enclaves all fall in the first quartile, precisely revealing that their source is characterized by heavily Sr and Nd isotopic compositions. Because Sr is of high activity, high Sr in enclaves may be ascribed to the late-stage secondary enrichment. If they shift leftwards into the mantle array range, the data points representing the isotopic composition will fall within the area of Hawaii volcanic rocks (Zindler & Hart, 1986). But the data points representing the Sr-Nd isotopic composition of Cenozoic high-K igneous rocks (the host rocks) fall with in the second quartile, strongly revealing their source is characterized by heavily Sr and lightly Nd isotopic compositions, and also indicating their source is similar to the EM2-type mantle (Zindler & Hart, 1986).

Therefore, the Sr-Nd isotope correlation diagram (Fig. 7) shows that the potential source of the enclaves is different from that of the host rocks, i.e., there is no direct genetic connection between the enclaves and the host rocks. Deep-derived enclaves in the high-K igneous rocks (the host rocks) belong to mafic xenoliths, which were captured incidentally by high temperature high-K magma at the time it rapidly moved upwards. This cognition is consistent with the

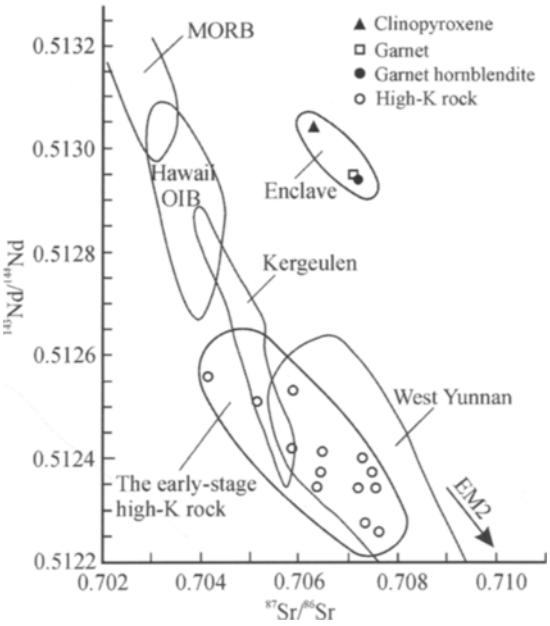

Fig. 7. Sr-Nd isotope correlation diagram of deep-derived enclaves and Cenozoic high-K igneous rocks from the Liuhe-Xiangduo area. High-K igneous rocks after Deng Wanming et al., 1998a; West Yunnan after Zhu Bingquan, 1998; MORB, Hawaii OIB and Kergeulen after Zindler & Hart, 1986; MORB. mid-ocean ridge basalt; OIB. oceanic island basalt; EM2. enriched mantle II.

process in which chilled rims of the enclaves were formed.

The equilibrium temperature and pressure conditions of the enclaves show that their equilibrium temperatures and pressures range from 510 to 950 ℃, and 0.64 to 1.50 GPa (Wei Qirong and Wang Jianghai, 2004c) (equivalent to 20 – 50 km depth), respectively. If the 40-km depth is regarded as the crust thickness of the Liuhe-Xiangduo area (Liu Futian et al., 2000), then enclaves in the high-K igneous rocks should come from the middle-lower crust, i. e., the enclaves belong to the middle-lower crust metamorphic rocks. The *P-T* conditions of the enclaves still suggest the depth of the potential source of the high-K igneous rocks is at least 50 km.

So, the genesis of deep-derived enclaves in the high-K igneous rocks in the Liuhe-Xiangduo area may be suggested as follows: tectonic collision between the Indian and Eurasian plates caused strike-slip pushing of the Indosinian block east-southwards during the time period from 28 to 40 Ma. The strike-slip pushing of the block led to continental subduction (Meyer et al., 1998; Yin An, 2000; Wang Jianghai et al., 2001), as a result, some middle-lower crust metamorphic rocks were accidentally captured at 20 – 50 km level by rapidly entrained high-temperature high-K magma along the deep-giant rift pass resultant from strike-slip and pull-part processes during which the high-K magma was formed at about 50-km depth.

5 Conclusions

According to the above discussions, some conclusions can be drawn as follows:

(1) Deep-derived enclaves in the Liuhe-Xiangduo area can be divided into five rock types, i. e., garnet diopsidite, garnet amphibolite, garnet hornblendite, amphibolite and hornblendite, whose main mineral assemblages are Grt + Di + Hbl, Grt + Pl + Hbl + Di, Grt + Hbl + Pl, Pl + Hbl, and Hbl + Bt, respectively. Enclaves have typical structural characteristics of metamorphic rocks and in the Grt are well developed growth zones. So they belong to metamorphic rock enclaves. Major element geochemical studies have shown that the enclaves are characterized by high Fe and Mg contents. So, the enclaves are mafic enclaves. Protolith restoration showed that the enclaves are ortho-metamorphic rock enclaves.

(2) The potential source of enclaves is similar to that of the Hawaii volcanic rocks, belonging to a depleted mantle. But the potential source of the host rocks of enclaves is similar to the EM2-type mantle. So, there is no direct genetic correlation between the enclaves and the host rocks. Deep-derived enclaves in the Liuhe-Xiangduo area belong to middle-lower crust metamorphic rocks, whose equilibrium temperatures and pressures range from 510 to 950 ℃, and 0.64 to 1.50 GPa (equivalent to a 20 – 50-km depth), respectively. They stemmed from some middle-lower crust orthometamorphic rocks which were accidentally captured at 20 – 50-km level by rapidly entrained high-temperature high-K magma at the depth of over 50 km.

References

Cai Xinping (1992) Discovery of deep-derived xenoliths in Cenozoic alkali-rich porphyries along the margin of the Yangtze platform and its significance [J]. *Scientia Geologica Sinica.* **27**, 183 – 189 (in Chinese with English abstract).

Deng Wanming, Huang Xuan, and Zhong Dalai (1998a) Alkali-rich porphyry and its relation with intraplate deformation of northern part of Jinsha River belt in western Yunnan, China [J]. *Science in China* (Series D). **41**, 297 – 305.

Deng Wanming, Huang Xuan, and Zhong Dalai (1998b) Petrological characteristics and genesis of Cenozoic alkali-rich porphyry in west Yunnan, China [J]. *Scientia Geologica Sinica.* **33**, 412 – 425 (in Chinese with English abstract).

Geringer G. J. (1979) The origin and tectonic setting of amphibolites in part of Namaqua metamorphic belt, south Africa [J]. *Transvaal Geological Society of South Africa.* **82**, 287 – 303.

Harrison T. M., Leloup P. H., Ryerson F. J., Tapponnier P., Lacassin

R., and Chen W. J. (1996) Diachronous initiation of transtension along the Ailao Shan-Red River shear zone, Yunnan and Vietnam. In *The Tectonic Evolution of Asia* (eds. Yin An and T. M. Harrison) [C]. pp. 208 – 226. Cambridge University Press, New York.

Jagoutz E., Palme H., Baddenhausen H., Blum K., Cendales M., Dreibus G., Spottel B., Lorenz V., and Wanke H. (1979) The abundances of major, minor and trace elements in the earth's mantle as derived from primitive ultramafic nodules [J]. *Geochim. Cosmochim. Acta.* **11**, 2031 – 2050.

Liang Xirong, Wei Gangjian, Li Xianhua, and Liu Ying (2003) Precise measurement of $^{147}Nd/^{144}Nd$ and Sm/Nd ratios using multiple-collectors inductively coupled plasma-mass spectrometer (MC-ICPMS) [J]. *Geochimica.* **32**, 91 – 96 (in Chinese with English abstract).

Liu Futian, Liu Jianhai, Zhong Dalai, He Jiankun, and You Qingyu (2000) The subducted salb of Yangtze continental block beneath the Tethysan orogen in western Yunnan [J]. *Chinese Science Bulletin.* **45**, 466 – 471.

Liu Xianfan, Zhan Xinzhi, Gao Zhenmin, Liu Jiajun, Li Chaoyang, and Su Wenchao (1999) Deep xenoliths in alkalic porphyry, Liuhe, Yunnan, and implications to petrogenesis of alkalic porphyry and associated mineralizations [J]. *Science in China* (Series D). **42**, 627 – 635.

Liu Ying, Liu Haichen, and Li Xianhua (1996) Simultaneous and precise determination of 40 trace elements in rock samples using ICP-MS [J]. *Geochimica.* **25**, 552 – 558 (in Chinese with English abstract).

Lü Boxi and Qian Xianggui (1999) Petrology study on deep-derived enclaves from Cenozoic alkalic volcanic rocks and alkali-rich porphyries in western Yunnan [J]. *Yunnan Geology.* **18**, 127 – 143 (in Chinese with English abstract).

Masek J. G., Isacks B. L., Fielding F. J., and Browaeys J. (1994) Rift flank uplift in Tibet: Evidence for a viscous lower crust [J]. *Tectonics.* **13**, 659 – 667.

Mei Houjun (1966) Olivine basalt and camptonite with peridotite xenoliths from Maguan, Yunnan [J]. *Scientia Geologica Sinica.* **1**, 50 – 63 (in Chinese with English abstract).

Meyer B. P., Tapponnier L., Bourjot F., Metivier Y., Gaudemer G., Peltzer S. M., and Chen Z. T. (1998) Crustal thickening in Gansu-Qinghai, lithospheric mantle subduction, and oblique, strike-slip controlled growth of the Tibet Plateau [J]. *Geophysical Journal International.* **135**, 1 – 47.

Pan Guitang, Wang Peisheng, and Xu Yaorong (1990) *Cenozoic Tectonic Evolution of Qinhai-Xizang Plateau* [M]. pp. 32 – 70. Geological Publishing House, Beijing (in Chinese).

Saunders A. D., Norry M. J., and Tarney J. (1988) Origin of MORB and chemically depleted mantle reservoirs: Trace elements constraints [J]. *Journal of Petrology* (Special Lithosphere Issue). 415 – 445.

Shu Xiaoxin (1995) The genesis of Cpx-peridotitic xenoliths in basanite of Maguan, Yunnan Province [J]. *Acta Petrologica et Mineralogica.* **14**, 47 – 51 (in Chinese with English abstract).

Sun Hongjuan (2000) *The Cenozoic Potassic Magmatism in Eastern Tibet and Southeast Yunnan Province* [D]. Ph. D. dissertation. pp. 52 – 56. Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing (in Chinese).

Sun S. S. and McDonough W. F. (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In *Magmatism in the Ocean Basins* (eds. A. D. Saunders and M. J. Norry) [M]. pp. 345. Geological Society Special Publication, London.

Wang Jian, Li Jianping, Wang Jianghai, and Ma Zhihong (2003) Geological implications for the deep-derived mafic enclaves from Cenozoic shoshonitic rocks in Jianchuan-Dali area, West Yunnan [J]. *Chinese Journal of Geochemistry.* **22**, 58 – 73.

Wang Jianghai, Yin An, Harrison T. M., Grove M., Zhang Yuquan, and Xie Guanghong (2001) A tectonic model for Cenozoic igneous activities in the eastern Indo-Asian collision zone [J]. *Earth and Planetary Science Letters.* **188**, 123 – 133.

Wang Renmin, He Gaopin, Chen Zhenzhen, Zheng Songyan, and Geng Yuansheng (1987) *Illustration Discriminance on Protolith of Met' + amorphic Rock* [M]. pp. 25. Science Press, Beijing (in Chinese).

Wei Gangjian, Liang Xirong, Li Xianhua, and Liu Ying (2002) Precise measurement of Sr isotopic composition of liquid and solid base using (LP) MC-ICPMS [J]. *Geochimica.* **31**, 295 – 299 (in Chinese with English abstract).

Wei Qirong and Wang Jianghai (2004a) Study on petrology and mineralogy of mafic deep-derived enclaves in Liuhe-Xiangduo area, eastern Tibet [J]. *Journal of Mineralogy and Petrology.* **24**, 17 – 28 (in Chinese with English abstract).

Wei Qirong and Wang Jianghai (2004b) Geochemical characteristics of Cenozoic basaltic high-K volcanic rocks from Maguan area, eastern Tibet [J]. *Chinese Journal of Geochemistry.* **23**, 57 – 64.

Wei Qirong and Wang Jianghai (2004c) Equilibrium P-T conditions of mafic deep-derived enclaves and its significance in Liuhe-Xiangduo area, eastern Tibet [J]. *Advances in Earth Science.* **19**, 722 – 731 (in Chinese with English abstract).

Yin An (2000) Mode of Cenozoic east-west extension in Tibet suggesting a common origin of rifts in Asia during the Indo-Asian collision [J]. *Journal of Geophysical Research.* **105**, 21745 – 21759.

Zhang Yuquan and Xie Yingwen (1997) Geochronology of Ailaoshan-Jinshajiang alkali-rich intrusive rocks and their Sr and Nd isotopic characteristics [J]. *Science in China* (Series D). **40**, 524 – 529.

Zhu Bingquan (1998) *Theory and Application of Isotopic Systematics in Earth Sciences* [M]. pp. 194 – 215. Science Press, Beijing (in Chinese).

Zindler A. and Hart S. (1986) Chemical geodynamics [J]. *Annual Reviews of Earth and Planetary Science.* **14**, 493 – 571.