Geochemistry of Cenozoic volcanic rocks from Kirin Province, northeast China

CHU-NAN HSU,¹ JU-CHIN CHEN¹ and KUNG-SUAN HO²

¹Institute of Oceanography, National Taiwan University, Taipei, Taiwan 106, R.O.C.

²Department of Geology, National Museum of Natural Science, Taichung, Taiwan 404, R.O.C.

(Received November 9, 1998; Accepted August 23, 1999)

The major volcanic activity in Kirin Province, northeast China occurred in Changpaishan area and lasted from the Miocene to Holocene. The volcanic rocks include basanite, alkali basalt, tholeiite, trachyte, and rhyolite. Ultramafic xenoliths and megacrysts occur in the basanite and alkali basalt. The compatible (Ni, Cr, Sc, V, Co) and incompatible elements (Rb, Li, Th, Hf, La, Lu, Nb, Zr, Y) vary systematically with $100\text{MgO}/(\text{MgO} + \Sigma\text{FeO})$ in the volcanic rocks. Fractional crystallization clearly was important in the magmatic evolution. The volcanic rocks and their ultramafic xenoliths have characteristic Sr and Nd isotopic ratios which fall between DMM and EM-I or EM-II. There are two types of spinel-lherzolite xenoliths in the basalts from Kirin Province: (1) an E-type enriched in LREE with $(\text{La}/\text{Yb})_{\text{N}}$ varying from 6.6 to 8.15; (2) a D-type depleted in LREE with $(\text{La}/\text{Yb})_{\text{N}}$ varying from 0.2 to 0.7 indicating of mantle heterogeneity in the Kirin region. The E-type lherzolites contain higher TiO_2 , K_2O , P_2O_5 , Rb, Sr, Ba, Y, Nb, Ta, Th and U than the D-type lherzolites. The former may have resulted from mantle metasomatic processes.

The tholeiite, alkali basalt and basanite may have been derived from an isotopically similar mantle source through different degree of partial melting at different P-T conditions. The trachyte may be derived from the basalt through fractional crystallization of plagioclase, olivine, clinopyroxene and magnetite.

INTRODUCTION

Cenozoic volcanic rocks of NE China are an important component of the circum-Pacific volcanic belt. The volcanic sequences were deposited in northeast-southwest trending basins which parallel to major tectonic structure in the region. Major volcanic eruptions in Kirin Province (Fig. 1) occurred in the Changpaishan area and lasted from Miocene to Holocene (Liu, 1988). The volcanic rocks include basanite, alkali basalt, tholeiite, trachyte and rhyolite. Ultramafic xenoliths and megacrysts are present in the basanite and alkali basalt. The volcanic association and the mantle-derived xenoliths provide a valuable opportunity to decipher the chemical composition and evolution of the upper mantle, the possible interaction between the crustal materials and the upper mantle, and the origin and evolution of the magmas.

In more detail, the Kirin Province of NE China was strongly influenced by Mesozoic Yenshannian movement which resulted in the formation of NNE-trending structures accompanying granite intrusion. In the Cenozoic, rift-related volcanic activity commenced in the Miocene (20 Ma) and has persisted to historic time (1984 AD) (Liu and Wang, 1987). The major rock types include olivine tholeiite, alkali basalt, basanite, trachyte, and rhyolite. The distribution of volcanic rocks in Kirin Province and the sampling locations involved in the present study are shown in Fig. 1.

PETROGRAPHY

The alkali basalt is grey, compact, and contains ultramafic xenoliths and megacrysts. It is generally porphyritic and has euhedral olivine and pyroxene phenocrysts set in a groundmass of

Fig. 1. Regional location map with sample sites in Kirin Province of NE China.

olivine, clinopyroxene, plagioclase, Fe-Ti oxides and glassy materials. The olivine tholeiite is vesicular and contains plagioclase and olivine (about 0.1 mm in size) phenocrysts set in a groundmass of olivine, plagioclase, opaques and glass. Pyroxenes are not present in the olivine tholeiite. The trachyte is also porphyritic containing phenocrysts of anorthoclase, Na-rich-diopside, olivine, and quartz. The latter are occasionally corroded in contact with the groundmass indicating crystal-liquid interaction.

The ultramafic xenoliths found in the alkali basalt and basanite are mainly spinel lherzolites consisting of olivine, orthopyroxene, clinopyroxene, and spinel.

VOLCANIC ROCK COMPOSITIONS

The chemical analyses of the volcanic rocks and ultramafic xenoliths have been carried out by colorimetric (Si, Al, Ti, P), atomic absorption (Fe, Mg, Ca, Na, K, Mn, Co, Cr, Cu, Li, Ni, Rb, Sr, Zn) inductively coupled plasma mass spectrometry (ICP-MS) (Ba, Hf, Nb, Sc, Ta, Th, U, V, Y, Zr and rare earth elements (REE)) methods at National Taiwan and Tsing-Hua Universities. Calibration curves were constructed using U.S.G.S. standard rocks GSP-1, AGV-1, BCR-1, W-2, BHVO-1, BIR-1, and NBS standard rock basalt. The precision is estimated to be around $\pm 2\%$ for colorimetric and atomic absorption methods and better than $\pm 5\%$ for all ICP-MS analyses.

Fig. 2. A plot of $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. SiO_2 for some volcanic rocks from Kirin Province. Alkaline and subalkaline discriminated boundary is from Le Bas et al. (1986).

Sr and Nd isotopic compositions were measured using a VG 354 mass spectrometer at Academia Sinica, Taipei. Nd isotopic ratios have been normalised to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and are reported relative to 0.511855 for the La Jolla standard. Sr isotopic ratios are normalised to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and are relative to 0.710240 for the SRM987 standard. Uncertainties correspond to the last significant figures and represent 2σ of the mean.

Chemical analyses and the C.I.P.W. norms are listed in Tables 1 and 2. All tholeiites are quartz-normative whereas the basanites are nepheline-normative. The silica contents vary between 43.30% and 69.70% in the basanite and trachyte, and the Mg values $[100 \times \text{MgO}/(\text{MgO} + \Sigma\text{FeO})]$

vary from >1% to 60% indicating considerable differentiation. The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ is >1 in the trachyte, but <1 in the basalts. There is a negative correlation between $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ and SiO_2 (Fig. 2) for the tholeiites and basanites, which may reflect different degrees of partial melting of a similar mantle source (Chen, 1988; Jaques and Green, 1980).

The major elements for the basalts and trachytes are plotted against Mg values in Fig. 3. Silica, Na_2O decrease, whereas CaO increases with increasing Mg values consistent with the fractional crystallization of clinopyroxene and feldspar may have occurred during magmatic differentiation. This is supported by the crystal fractionation calculations using the “Least

Table 1. Major element compositions and C.I.P.W. norms of volcanic rocks and spinel-lherzolite xenoliths from Kirin Province, NE China

Kirin province, Changpaishan area, NE China							
Location	Paitoushan	Changpaishan Fall					
Sample No.	92CW01	92CW02	92CW03	92CW04	92CW05	92CW06	92CW07
Rock type	⁽³⁾ Pumice	TRA	TRA	TRA	TRA	TRA	TRA
SiO ₂ (%)	65.03	69.71	66.40	66.79	68.10	66.01	63.69
TiO ₂	0.49	0.59	0.44	0.61	0.41	0.56	0.48
Al ₂ O ₃	16.24	13.64	14.65	14.59	14.91	16.14	15.50
⁽¹⁾ ΣFeO	4.24	4.33	5.14	4.46	4.30	4.00	4.15
MnO	0.12	0.12	0.17	0.12	0.11	0.11	0.12
MgO	0.26	0.06	0.19	0.04	0.12	0.21	0.21
CaO	1.32	0.74	1.11	0.74	0.76	1.22	1.60
Na ₂ O	5.63	5.95	5.91	6.15	6.11	5.78	5.71
K ₂ O	6.80	5.73	5.82	5.45	5.55	6.47	6.33
P ₂ O ₅	0.11	0.03	0.07	0.03	0.03	0.09	0.09
L.O.I	0.92	0.33	0.35	0.20	0.39	1.33	1.45
Total	101.17	101.24	100.25	99.19	100.77	101.93	99.32
⁽²⁾ Mg value	8.36	1.95	5.31	1.48	3.95	7.43	6.90
K ₂ O/Na ₂ O	1.21	0.96	0.98	0.89	0.91	1.12	1.11
C.I.P.W. NORMS							
Q	3.30	15.64	7.90	9.84	10.06	4.99	3.30
Or	40.22	33.89	34.42	32.24	32.83	38.27	37.44
An	—	—	—	—	—	—	—
Ne	—	—	—	—	—	—	—
Ac	1.82	4.16	4.94	4.30	4.13	1.76	3.45
Mt	1.13	—	—	—	—	1.04	0.27
Il	0.93	1.12	0.84	1.16	0.78	1.06	0.91
Ap	0.24	0.07	0.15	0.07	0.07	0.2	0.20
Cor	—	—	—	—	—	—	—
Ab	45.52	38.13	42.82	44.57	45.66	46.85	44.34
Lc	—	—	—	—	—	—	—
Di	5.15	3.10	4.49	3.11	3.18	4.83	6.50
Hy	1.93	3.05	3.99	3.11	3.39	1.59	1.47
Ol	—	—	—	—	—	—	—
Water	0.92	0.33	0.35	0.20	0.39	1.33	1.45

Remarks:

⁽¹⁾(ΣFeO = FeO + Fe₂O₃/1.111) assuming Fe₂O₃ = 0.15FeO (Middlemost, 1989).

⁽²⁾Mg value = 100 × MgO/(MgO + ΣFeO).

⁽³⁾BAS = basanite; SPL = spinel lherzolite; AOB = alkali olivine basalt; QTh = quartz tholeiite basalt; TRA = trachyte.

squares” program designed by Stormer and Nicholls (1978), indicating that the trachyte can be formed through fractionation of feldspar (58%), clinopyroxene (0.23%), apatite (1%) and Fe-Ti oxides (3%) from the tholeiitic basalt.

The alkali basalts from Antu and the basanite from Wangching have high Mg values, Ni (≤220

ppm) and Cr (≤650 ppm) contents which approach composition appropriate for “primitive magmas” (Hart and Allègre, 1980). The alkali basalts from Chingyu and Paiho on the other hand may have undergone some degree of fractional crystallization.

Table 1. (continued)

Kirin province, Changpaishan area, NE China							
Location	Holung						
Sample No.	92CW08	92CW09	92CW10	92CW11	92CW12	92CW13	92CW14
Rock type	QTh	QTh	QTh	QTh	QTh	QTh	QTh
SiO ₂ (%)	53.35	53.71	54.50	54.35	55.14	52.99	53.56
TiO ₂	2.39	2.42	1.49	1.59	1.78	1.88	1.79
Al ₂ O ₃	15.98	15.66	14.86	14.75	14.86	18.16	18.85
ΣFeO	9.46	9.96	10.19	9.87	9.80	7.48	7.48
MnO	0.13	0.14	0.16	0.14	0.15	0.11	0.11
MgO	5.32	5.60	6.66	6.52	6.57	5.49	5.52
CaO	7.64	7.79	7.49	7.59	7.47	9.73	8.31
Na ₂ O	3.70	3.62	3.29	3.23	3.28	3.29	3.23
K ₂ O	1.10	1.16	0.78	0.62	0.74	0.85	0.84
P ₂ O ₅	0.67	0.63	0.32	0.24	0.32	0.28	0.34
L.O.I	0.11	0.01	0.43	0.16	0.16	0.13	0.13
Total	99.68	100.69	100.16	99.05	100.28	100.40	100.16
Mg value	40.29	40.29	43.93	44.23	44.58	46.86	46.98
K ₂ O/Na ₂ O	0.30	0.31	0.24	0.19	0.23	0.26	0.26
C.I.P.W. NORMS							
Q	2.93	2.73	4.28	5.29	5.73	0.97	3.94
Or	6.51	6.86	4.61	3.67	4.38	5.03	4.97
An	23.71	23.02	23.44	23.88	23.61	32.23	34.41
Ne	—	—	—	—	—	—	—
Ac	—	—	—	—	—	—	—
Mt	2.29	2.41	2.47	2.38	2.36	1.81	1.81
Il	4.54	4.60	2.83	3.02	3.38	3.57	3.40
Ap	1.46	1.38	0.70	0.52	0.70	0.61	0.74
Cor	—	—	—	—	—	—	—
Ab	31.27	30.59	27.81	27.30	27.72	27.81	27.30
Lc	—	—	—	—	—	—	—
Di	8.40	9.77	9.70	10.12	9.46	11.70	3.93
Hy	18.78	18.63	19.33	23.90	22.72	15.53	19.53
Ol	—	—	—	—	—	—	—
Water	0.11	0.01	0.43	0.16	0.16	0.13	0.13

The compatible trace elements (Ni, Cr, Sc, V, Co) are well correlated with the Mg values in the volcanic rocks from Kirin Province (Fig. 4) consistent with a heritage via extended fractional crystallization. Furthermore, decrease of Rb, Li, Th, Hf, La, Lu, Nb, Y and Zr and the increase of Sr and Ba with increasing Mg values (Figs. 4 and 5) are consistent with this type of genesis.

The REE contents of the volcanic rocks (alkali basalts, basanites, tholeiites and trachytes) and

the spinel-lherzolite xenoliths are listed in Table 2. Chondrite-normalized (Sun and McDonough, 1989) REE patterns for the volcanic rocks and xenoliths are shown in Figs. 6 and 7. The trachytes are strongly enriched in the light rare earth elements (LREE) with $(La/Yb)_N$ $((La/Yb)_{sample}/(La/Yb)_{chondrite})$ varying from 12.4 to 15.2. They also have a large negative Eu anomaly indicating that fractional crystallization of plagioclase may exceed 18% (Sun and Nesbitt, 1978).

Table 1. (continued)

Kirin province, Changpaishan area, NE China							
Location	Holung				Antu		
Sample No.	92CW15	92CW16	92CW17	92CW18	92CW19	92CW20	92CW21
Rock type	QTh	QTh	QTh	QTh	AOB	AOB	AOB
SiO ₂ (%)	53.71	53.56	53.56	54.50	49.99	49.99	51.35
TiO ₂	3.06	3.00	2.39	2.31	2.49	1.46	1.45
Al ₂ O ₃	15.13	14.75	15.63	15.38	15.95	15.45	15.32
ΣFeO	9.74	11.69	9.92	9.76	8.02	8.01	8.04
MnO	0.14	0.18	0.15	0.14	0.15	0.15	0.15
MgO	4.79	5.20	4.79	4.75	8.91	8.65	8.51
CaO	6.55	7.19	6.94	6.77	7.89	7.79	7.96
Na ₂ O	3.30	3.58	3.29	3.35	3.26	3.42	3.28
K ₂ O	1.53	1.69	1.35	1.52	1.93	2.03	2.33
P ₂ O ₅	0.54	1.60	0.64	0.67	0.44	0.50	0.55
L.O.I	0.64	0.25	0.57	0.68	1.39	1.22	1.31
Total	99.13	100.69	99.23	99.85	100.41	98.64	100.24
Mg value	37.13	34.82	36.68	36.87	57.13	56.44	55.95
K ₂ O/Na ₂ O	0.46	0.47	0.41	0.45	0.59	0.59	0.71
C.I.P.W. NORMS							
Q	6.46	2.41	5.88	6.31	—	—	—
Or	9.05	10.00	7.99	8.99	11.42	12.01	13.78
An	21.92	19.15	23.12	22.40	23.15	20.77	20.16
Ne	—	—	—	—	—	—	—
Ac	—	—	—	—	—	—	—
Mt	2.35	2.83	2.39	2.36	1.94	1.93	1.94
Il	5.81	5.70	4.54	4.39	4.73	2.77	2.76
Ap	1.18	3.49	1.40	1.46	0.96	1.09	1.20
Cor	—	—	—	—	—	—	—
Ab	27.89	30.26	27.81	28.31	27.55	28.90	27.72
Lc	—	—	—	—	—	—	—
Di	6.08	5.88	6.23	5.98	10.75	12.04	12.98
Hy	17.75	21.72	19.05	18.95	6.63	4.25	7.15
Ol	—	—	—	—	15.04	17.87	14.74
Water	0.64	0.25	0.57	0.68	1.39	1.22	1.31

The (La/Yb)_N increases from the tholeiite (3.0–17.8) through the alkali basalt (8.0–12.9) to the basanite (12.5–17.8) which may be interpreted as due to different degree of partial melting.

The Sr and Nd isotopic data for a tholeiite (CW-19), alkali basalt (LG-06), basanite (LG-07) and spinel lherzolite xenoliths (LG-03, 04, 11, 15, 16) analyzed in the present study together with the Sr, Nd and Pb isotopic data reported by Xie *et al.* (1988) are listed in Table 3.

The trachytes have ⁸⁷Sr/⁸⁶Sr ranging from

0.70533 to 0.70754, ¹⁴³Nd/¹⁴⁴Nd ranging from 0.512584 to 0.512639 (Xie *et al.*, 1988). The tholeiite analyzed in the present study has ⁸⁷Sr/⁸⁶Sr of 0.704663 and ¹⁴³Nd/¹⁴⁴Nd of 0.512744, whereas the alkali basalts (present study and Xie *et al.*, 1988) have ⁸⁷Sr/⁸⁶Sr ranging from 0.70495 to 0.70513 and ¹⁴³Nd/¹⁴⁴Nd ranging from 0.512503 to 0.512767.

The average ⁸⁷Sr/⁸⁶Sr of the tholeiite is 0.70493 which is lower than that of the trachyte (0.70581). However, another trachyte sample X-17 (Xie *et*

Table 1. (continued)

Kirin province, Changpaishan area, NE China							
Location	Antu			Chingyu			
Sample No.	92CW22	92CW23	92CW24	92CW25	92CW26	92CW27	92CW28
Rock type	AOB	AOB	AOB	AOB	AOB	QTh	QTh
SiO ₂ (%)	51.77	52.14	51.92	50.41	50.99	53.71	54.50
TiO ₂	1.33	1.31	1.39	3.10	3.03	1.42	1.21
Al ₂ O ₃	15.01	14.42	15.07	15.95	15.76	15.26	15.63
ΣFeO	7.93	8.27	7.92	11.65	11.30	10.29	10.23
MnO	0.15	0.15	0.15	0.17	0.16	0.15	0.15
MgO	8.85	10.10	9.28	4.48	4.66	6.95	6.90
CaO	8.04	7.88	8.21	5.24	5.22	6.92	6.99
Na ₂ O	3.54	3.26	2.49	3.64	3.50	3.12	3.12
K ₂ O	1.92	1.36	1.82	2.17	2.09	0.41	0.37
P ₂ O ₅	0.44	0.44	0.45	0.65	0.70	0.18	0.18
L.O.I	1.42	1.62	1.50	1.67	1.59	0.27	0.21
Total	100.40	100.94	101.20	99.13	99.02	98.70	99.49
Mg value	57.25	59.43	58.44	31.57	33.12	44.77	44.74
K ₂ O/Na ₂ O	0.54	0.42	0.73	0.60	0.60	0.13	0.12
C.I.P.W. NORMS							
Q	—	—	—	—	—	5.15	5.73
Or	11.36	8.04	10.77	12.84	12.36	2.43	2.19
An	19.36	20.66	24.53	20.73	21.08	26.39	27.52
Ne	—	—	—	—	—	—	—
Ac	—	—	—	—	—	—	—
Mt	1.91	2.00	1.91	2.81	2.73	2.49	2.47
Il	2.53	2.49	2.64	5.89	5.76	2.70	2.30
Ap	0.96	0.96	0.98	1.42	1.53	0.39	0.39
Cor	—	—	—	—	—	—	—
Ab	29.92	27.55	21.04	30.76	29.58	26.37	26.37
Lc	—	—	—	—	—	—	—
Di	14.45	12.74	10.91	1.21	0.60	5.64	5.01
Hy	7.01	17.19	26.84	21.40	22.42	26.87	27.30
Ol	14.91	9.93	0.10	0.57	1.39	—	—
Water	1.42	1.62	1.50	1.67	1.59	0.27	0.21

al., 1988) has considerably higher $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70754). All the other trachytes have similar $^{87}\text{Sr}/^{86}\text{Sr}$ to the basalts. Accordingly, we suggest that with the exception of a few trachytes (i.e., sample X-17), which may have been contaminated by the crustal materials, most trachytes are genetically closely related to the basalts. The difference in chemical compositions among the tholeiite, alkali basalt and trachyte may be interpreted as due to different degree of partial melting and fractional crystallization.

The $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ plots for the volcanic rocks and spinel-lherzolites xenoliths from Kirin Province are shown in Fig. 8. Also shown are the isotopic data of Liaoning ($\sim 41^\circ\text{N}$, $\sim 123^\circ\text{E}$) volcanic rocks and their megacrysts (Liu *et al.*, 1992). It is apparent that the Kirin volcanic rocks have higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ than those of Liaoning volcanic rocks, garnet, and pyroxene megacrysts, indicating that some mantle heterogeneity in NE China. The potassium-rich alkali basalts from Wutalienchih have remarkable

Table 1. (continued)

Kirin province, Changpaishan area, NE China							
Location	Paiho			Wangching			
Sample No.	92P01	92P02	92P03	91WQ1-1	91WQ1-3	91WQ2-1	91WQ2-2
Rock type	AOB	AOB	QTh	BAS	SPL	BAS	SPL
SiO ₂ (%)	50.66	51.07	52.92	45.87	43.30	46.07	43.89
TiO ₂	2.81	2.91	1.52	1.72	0.14	1.64	0.08
Al ₂ O ₃	15.86	15.69	15.27	14.39	2.64	14.60	1.81
ΣFeO	12.61	12.72	10.43	10.54	10.43	10.21	7.50
MnO	0.12	0.15	0.13	0.16	0.13	0.16	0.12
MgO	3.12	3.64	7.06	9.70	40.56	10.91	44.92
CaO	6.18	6.33	8.50	9.68	2.21	9.81	1.26
Na ₂ O	3.69	3.84	3.47	3.92	0.23	3.69	0.15
K ₂ O	2.39	2.39	0.56	2.39	0.05	2.32	0.05
P ₂ O ₅	0.81	0.80	0.75	0.81	0.04	0.75	0.06
L.O.I	2.45	1.93	0.00	1.02	0.00	0.32	0.81
Total	99.71	100.71	100.61	100.20	99.73	100.48	100.65
Mg value	22.89	25.56	44.82	52.48	81.73	56.18	87.32
K ₂ O/Na ₂ O	0.65	0.62	0.16	0.61	0.22	0.63	0.33
C.I.P.W. NORMS							
Q	—	—	1.06	—	—	—	—
Or	14.14	14.14	3.31	14.14	—	13.72	—
An	19.61	18.48	24.40	14.57	—	16.39	—
Ne	—	—	—	13.80	—	13.27	—
Ac	—	—	—	—	—	—	—
Mt	3.04	3.94	2.52	2.55	—	2.47	—
Il	5.34	5.53	2.89	3.27	—	3.12	—
Ap	1.77	1.75	1.64	1.77	—	1.64	—
Cor	—	—	—	—	—	—	—
Ab	31.19	32.45	29.33	7.68	—	6.71	—
Lc	—	—	—	—	—	—	—
Di	1.13	6.87	10.93	23.22	—	22.48	—
Hy	20.36	14.65	24.53	—	—	—	—
Ol	1.21	2.44	—	18.18	—	20.38	—
Water	2.45	1.93	0.00	1.02	—	0.32	—

low ¹⁴³Nd/¹⁴⁴Nd, being derived from a more isotopically enriched mantle source.

All volcanic rocks and their ultramafic xenoliths have regionally distinctive Sr and Nd isotopic ratios, all the data from NE China (Fig. 8) fall between DMM (depleted MORB mantle) and EM-I (enriched-mantle type I) or EM-II (enriched-mantle type II). Therefore, a two-end member mantle mixing model may be useful in considering the petrogenesis of volcanic rocks in NE China.

The ²⁰⁸Pb/²⁰⁴Pb and ²⁰⁷Pb/²⁰⁴Pb vs. ²⁰⁶Pb/²⁰⁴Pb plots for Kirin volcanic rocks are shown in Fig. 9.

The Pb isotopic data were adapted from Liu *et al.* (1992), Zhang *et al.* (1991), Zhou and Armstrong (1982) and Tatsumoto *et al.* (1992). Most samples lie above the NHRL (Northern Hemisphere Reference Line) defined by Hart (1984). The Δ7/4 Pb and Δ8/4 Pb values range from −1 to 15 and 47 to 160, respectively indicating the existence of Dupal anomaly (Dupré and Allègre, 1983) in NE China. Overall, the Kirin volcanic rocks have lower ²⁰⁸Pb/²⁰⁴Pb and ²⁰⁶Pb/²⁰⁴Pb than those of the SE China basalts (Peng *et al.*, 1986; Tu *et al.*, 1991, 1992; Lan *et al.*, 1994), but they overlap with the Japan Sea basalt field defined by Okamura *et al.* (1998).

Table 1. (continued)

Kirin province, Changpaishan area, NE China							
Location	Wangching						
Sample No.	91WQ2-3	91WQ2-4	91WQ3-1	91WQ3-2	91WQ4	91WQ5-1	91WQ5-2
Rock type	BAS	BAS	BAS	SPL	BAS	BAS	SPL
SiO ₂ (%)	47.70	47.99	45.67	44.48	45.87	47.41	48.20
TiO ₂	2.03	2.01	1.71	0.11	1.72	2.09	0.41
Al ₂ O ₃	14.65	14.70	14.07	1.67	14.59	15.02	1.65
ΣFeO	9.58	9.49	10.43	9.13	10.43	9.45	8.00
MnO	0.16	0.16	0.16	0.14	0.16	0.16	0.13
MgO	9.49	9.27	10.39	41.46	10.39	9.30	39.53
CaO	9.23	8.85	9.68	2.48	9.13	9.15	2.17
Na ₂ O	3.65	3.69	3.69	0.60	3.77	3.86	0.51
K ₂ O	2.02	2.14	2.39	0.08	2.32	1.99	0.18
P ₂ O ₅	0.81	0.76	0.73	0.02	0.62	0.80	0.05
L.O.I	0.07	0.00	0.58	0.00	0.20	0.00	0.14
Total	99.39	99.05	99.50	100.16	99.20	99.23	100.97
Mg value	54.32	53.97	54.45	83.93	54.45	54.15	85.04
K ₂ O/Na ₂ O	0.55	0.58	0.65	0.13	0.62	0.51	0.34
C.I.P.W. NORMS							
Q	—	—	—	—	—	—	—
Or	11.95	12.66	14.14	—	13.72	11.77	—
An	17.59	17.19	14.73	—	16.00	17.74	—
Ne	6.95	6.54	13.23	—	12.59	8.24	—
Ac	—	—	—	—	—	—	—
Mt	2.32	2.29	2.52	—	2.52	2.29	—
Il	3.86	3.82	3.25	—	3.27	3.97	—
Ap	1.77	1.66	1.59	—	1.35	1.75	—
Cor	—	—	—	—	—	—	—
Ab	18.03	19.11	6.77	—	8.64	17.41	—
Lc	—	—	—	—	—	—	—
Di	18.91	17.95	23.42	—	20.72	18.50	—
Hy	—	—	—	—	—	—	—
Ol	17.96	17.83	19.26	—	20.19	17.55	—
Water	0.07	—	0.58	—	0.20	—	—

COMPOSITION OF THE ULTRAMAFIC XENOLITHS

Four fresh spinel-lherzolite xenoliths found in alkali basalt and basanite have been chemically analyzed, and their compositions are listed in Tables 1 and 2. The Sr and Nd isotopic data of the spinel-lherzolites are listed in Table 3. The spinel lherzolites consist mainly of olivine (Fo₉₄Fa₆ ~ Fo₉₁Fa₉), orthopyroxene (En₉₁Fs₈Wo₁ ~ En₈₈Fs₁₀Wo₂), clinopyroxene (Wo₃₅En₆₀Fs₅ ~ Wo₄En₅₀Fs₄) and chromium spinel (Cr/Cr + Al = 0.08~0.25).

The $100 \times \text{Mg}/(\text{Mg} + \Sigma\text{Fe})$ values of the spinel lherzolites range from 87 to 91% indicating they are mantle-derived xenoliths. Table 4 summarizes the chemical compositions of Kirin spinel lherzolite xenoliths as compared with the spinel lherzolite of continental lithospheric mantle (McDonough, 1990), and primitive mantle (Sun and McDonough, 1989).

The spinel-lherzolites from Kirin Province have two distinct chondrite-normalized REE patterns (Fig. 7). Spinel lherzolite 92WQ5-2 is relatively enriched in LREE (hereafter defined as the E-type) whereas spinel lherzolite 92WQ3-2 is rela-

Table 2. Trace element and REE contents in volcanic rocks and spinel-lherzolite xenoliths from Kirin Province, NE China

Kirin province, Changpaishan area, NE China							
Location	Paitoushan	Changpaishan Fall					
Sample No.	92CW01	92CW02	92CW03	92CW04	92CW05	92CW06	92CW07
Rock type	Pumice	TRA	TRA	TRA	TRA	TRA	TRA
Rb (ppm)	136	241	187	251	234	139	147
Sr	2.0	1.3	3.4	2.7	0.7	0.7	0.7
Ba	159	11	38	10	14	110	128
Li	18.3	42.1	26.9	44.3	42.7	16.1	14.5
Sc	5.4	2.1	5.0	2.2	3.1	5.1	5.5
V	1.7	0.2	1.7	0.2	0.1	0.6	0.8
Cr	2.1	5.0	3.6	0.7	1.4	5.0	0.7
Ni	3.4	3.4	3.4	3.4	3.4	3.5	3.4
Co	2.4	3.7	2.4	4.6	1.5	5.0	3.7
Zn	115	188	182	192	190	124	124
Cu	4	2	3	3	2	1	2
Y	44	94	86	117	149	49	55
Zr	484	1206	1147	1239	1284	763	796
Hf	13.55	35.52	28.29	35.10	35.20	20.24	20.24
Nb	68.8	178.1	130.4	183.1	188.7	86.0	88.7
Pb	14.7	27.3	20.5	26.7	28.1	14.1	14.9
Cd	0.26	0.46	0.24	0.40	0.49	0.25	0.21
Th	12.14	28.06	18.73	30.09	28.87	12.78	13.12
La	60.2	126.3	97.2	141.1	166.8	64.9	77.6
Ce	123.0	242.4	191.3	262.4	298.8	133.5	151.3
Nd	64.9	119.6	97.2	127.7	146.6	69.6	76.1
Sm	11.45	20.88	16.83	21.99	25.28	11.96	12.81
Eu	0.79	0.33	0.43	0.33	0.38	0.59	0.64
Tb	1.60	3.25	2.64	3.42	4.19	1.73	1.82
Yb	3.25	6.44	5.64	7.13	8.71	3.49	3.66
Lu	0.51	1.01	0.90	1.09	1.32	0.57	0.61
Sr/Nd	0.031	0.011	0.035	0.021	0.005	0.01	0.009
Zr/Nb	7.04	6.77	8.79	6.77	6.81	8.87	8.97
Th/Nb	0.18	0.16	0.14	0.16	0.15	0.15	0.15
Zr/Hf	35.8	34.0	40.5	35.3	36.5	37.7	39.3
Ba/Th	13.1	0.4	2.0	0.3	0.5	8.6	9.7
Ba/Nb	2.31	0.06	0.29	0.06	0.07	1.28	1.44
Sm/Yb	3.52	3.24	2.98	3.08	2.90	3.42	3.50
Ba/La	2.6	0.1	0.4	0.1	0.1	1.7	1.6
Ce/Pb	8.36	8.88	9.31	9.82	10.63	9.48	10.13
*(La/Yb) _N	13.3	14.1	12.4	14.2	13.7	13.3	15.2

*(La/Yb)_N: Chondrite normalized ratio (Sun and McDonough, 1989).

tively depleted in LREE (hereafter defined as the D-type) indicating there is significant chemical heterogeneity within the northeastern China mantle. The REE pattern for a clinopyroxene megacryst from Kirin area (Fig. 7) is relatively depleted in LREE with respect to HREE, but has

flat MREE. The REE contents of the clinopyroxene megacryst are higher than for the spinel-lherzolite xenoliths.

The E-type spinel lherzolites have (La/Yb)_N = 6.6–8.15 whereas the D-type spinel-lherzolites have (La/Yb)_N = 0.2–0.7. The HREE contents in

Table 2. (continued)

Kirin province, Changpaishan area, NE China							
Location	Holung						
Sample No.	92CW08	92CW09	92CW10	92CW11	92CW12	92CW13	92CW14
Rock type	QTh	QTh	QTh	QTh	QTh	QTh	QTh
Rb (ppm)	21	21	18	17	18	17	15
Sr	601	539	351	317	330	762	890
Ba	611	591	292	272	305	295	302
Li	8.0	7.4	9.0	9.6	9.6	8.0	7.4
Sc	20.2	21.2	21.3	23.0	24.0	18.0	17.5
V	170	174	151	158	166	137	136
Cr	167	182	338	329	340	170	182
Ni	69	80	151	137	144	98	93
Co	40.3	35.0	40.8	40.8	45.7	31.8	37.6
Zn	105	108	109	108	112	81	77
Cu	28	25	44	39	41	29	31
Y	24	24	22	22	23	16	16
Zr	121	124	92	86	97	115	117
Hf	3.46	3.55	2.95	2.77	3.02	3.37	3.34
Nb	19.3	19.5	12.3	10.9	12.7	14.9	15.3
Pb	3.7	5.1	4.2	4.2	5.7	3.9	4.5
Cd	0.15	0.38	0.10	0.17	0.67	0.11	0.13
Th	1.87	1.89	1.87	1.61	1.94	1.70	1.72
La	19.4	18.8	12.1	11.3	12.7	14.6	14.6
Ce	40.4	40.6	25.6	22.7	26.7	30.2	30.4
Nd	29.6	29.2	18.0	16.9	18.6	21.5	21.4
Sm	6.25	6.27	4.22	4.23	4.56	4.38	4.37
Eu	2.43	2.40	1.49	1.50	1.59	1.52	1.52
Tb	0.95	0.94	0.78	0.78	0.82	0.63	0.64
Yb	1.43	1.48	1.56	1.60	1.62	1.10	1.10
Lu	0.22	0.22	0.25	0.24	0.25	0.17	0.17
Sr/Nd	20.5	18.5	19.5	18.7	17.7	35.4	41.6
Zr/Nb	6.31	6.34	7.47	7.95	7.61	7.70	7.63
Th/Nb	0.10	0.10	0.15	0.15	0.15	0.11	0.11
Zr/Hf	35.1	34.8	31.1	31.2	32.0	34.1	35.0
Ba/Th	327	312	157	169	157	174	176
Ba/Nb	31.8	30.3	23.8	25.1	24.0	19.8	19.7
Sm/Yb	4.38	4.24	2.71	2.65	2.82	3.97	3.99
Ba/La	31.6	31.4	24.1	24.0	23.9	20.1	20.7
Ce/Pb	11.04	8.00	6.05	5.41	4.72	7.66	6.69
(La/Yb) _N	9.7	9.1	5.6	5.1	5.6	9.5	9.5

these two types of spinel lherzolites are similar (Table 2).

The E-type spinel lherzolites contain higher TiO_2 , K_2O , P_2O_5 , Rb, Sr, Ba, Y, Nb, Ta, Th, U and LREEs than the D-type spinel lherzolites indicating that they may represent the products of different degree of mantle metasomatism and/or different degree of partial melting. Notably, phlogopite

and amphibole were found in spinel lherzolite xenoliths in Wangching area of Kirin Province (Ou and Chao, 1987) which provides support for the suggestion that mantle metasomatism in the Kirin area. The E-type spinel lherzolites have higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ than the D-type spinel lherzolites (Table 3), possibly reflecting the different degrees of mantle metasomatism.

Table 2. (continued)

Kirin province, Changpaishan area, NE China							
Location	Holung				Antu		
Sample No.	92CW15	92CW16	92CW17	92CW18	92CW19	92CW20	92CW21
Rock type	QTh	QTh	QTh	QTh	AOB	AOB	AOB
Rb (ppm)	32	32	27	34	74	84	85
Sr	425	479	425	438	822	795	809
Ba	542	1124	507	561	537	546	573
Li	11.8	8.5	12.8	11.8	9.6	9.6	10.1
Sc	22.9	22.7	20.5	22.0	28.7	30.6	32.6
V	172	207	161	175	216	229	236
Cr	135	77	142	140	601	608	634
Ni	66	31	64	61	143	141	138
Co	31.8	35.9	41.7	34.1	39.4	40.8	44.8
Zn	117	119	123	123	78	78	83
Cu	27	17	28	28	44	41	38
Y	34	41	32	35	21	22	22
Zr	217	195	199	223	142	153	154
Hf	6.15	5.34	5.99	6.46	3.87	4.09	4.05
Nb	19.2	35.4	18.9	20.3	28.9	30.7	30.6
Pb	9.5	7.5	7.9	6.8	7.1	7.	6.1
Cd	0.16	0.22	0.16	0.38	0.18	0.28	0.22
Th	2.57	4.06	2.51	2.76	3.49	3.76	3.74
La	25.3	42.9	23.7	26.8	21.3	22.4	22.9
Ce	56.9	91.1	53.4	59.4	44.5	46.6	47.3
Nd	41.1	61.4	40.1	43.4	27.6	28.1	28.8
Sm	8.70	11.51	8.43	8.95	5.17	5.32	5.40
Eu	2.54	4.35	2.49	2.71	1.60	1.58	1.68
Tb	1.25	1.62	1.26	1.33	0.74	0.78	0.79
Yb	2.21	2.22	2.13	2.29	1.53	1.59	1.62
Lu	0.33	0.34	0.34	0.34	0.24	0.25	0.26
Sr/Nd	10.3	7.8	10.6	10.1	29.8	28.3	28.1
Zr/Nb	11.27	5.50	10.50	10.98	4.91	4.96	5.02
Th/Nb	0.13	0.11	0.13	0.14	0.12	0.12	0.12
Zr/Hf	35.3	36.5	33.1	34.4	36.7	37.3	37.9
Ba/Th	211	277	202	203	154	145	153
Ba/Nb	28.2	31.8	26.8	27.7	18.6	17.7	18.7
Sm/Yb	3.94	5.19	3.95	3.91	3.38	3.34	3.33
Ba/La	21.5	26.2	21.4	20.9	25.2	24.4	25.1
Ce/Pb	6.01	12.21	6.74	8.78	6.29	6.04	7.70
(La/Yb) _N	8.2	13.9	8.0	8.4	10.0	10.1	10.1

DISCUSSION

Using the partition coefficient for La and Yb between minerals (olivine, orthopyroxene, clinopyroxene and garnet/spinel) and liquid proposed by McKay (1985), Kelemen *et al.* (1993) and Hart and Dunn (1993) and the partial melting equation of Maaloe (1994), we estimated

that the degrees of partial melting of mantle lherzolites for the basanite, alkali basalt and tholeiite in Kirin Province of NE China to be 5.6%, 10% and 18% respectively. Notably, this is consistent with trend observed in Fig. 2 as the total alkalis contents generally decrease with increasing degree of partial melting.

The Sr/Nd, Zr/Nb, Th/Nb, Zr/Hf, Ce/Pb,

Table 2. (continued)

Kirin province, Changpaishan area, NE China							
Location	Antu			Chingyu			
Sample No.	92CW22	92CW23	92CW24	92CW25	92CW26	92CW27	92CW28
Rock type	AOB	AOB	AOB	AOB	AOB	QTh	QTh
Rb (ppm)	73	64	78	48	47	11	10
Sr	809	843	897	391	384	337	337
Ba	568	517	507	847	844	226	216
Li	10.1	8.5	8.5	11.8	13.4	9.6	9.6
Sc	34.9	32.9	38.4	25.2	25.4	28.3	28.6
V	239	223	252	257	262	189	187
Cr	619	655	636	9	11	318	333
Ni	137	197	149	6	8	139	140
Co	45.7	43.9	43.9	38.1	39.9	39.0	43.5
Zn	78	77	78	136	137	105	104
Cu	37	30	41	14	13	33	34
Y	23	21	21	42	43	25	24
Zr	150	137	127	292	290	86	80
Hf	3.94	3.49	3.25	7.29	7.17	2.33	2.17
Nb	30.5	27.1	22.2	49.3	48.4	7.5	6.9
Pb	6.0	6.0	7.7	9.1	7.3	3.1	2.9
Cd	0.18	0.18	0.20	0.21	0.19	0.14	0.13
Th	3.55	3.07	2.69	4.98	5.02	1.13	1.08
La	22.7	20.6	17.2	44.5	44.9	11.9	7.8
Ce	47.2	43.7	37.0	91.4	90.9	25.5	17.2
Nd	28.3	25.9	23.8	53.0	52.8	16.3	13.1
Sm	5.28	5.05	4.65	9.68	7.28	3.91	3.62
Eu	1.65	1.54	1.44	2.89	2.97	1.39	1.32
Tb	0.78	0.72	0.69	1.43	1.43	0.81	0.73
Yb	1.56	1.41	1.54	2.53	2.50	1.54	1.47
Lu	0.25	0.24	0.24	0.40	0.41	0.26	0.24
Sr/Nd	28.6	32.5	37.7	7.4	7.3	20.7	25.7
Zr/Nb	4.93	5.06	5.73	5.92	6.00	11.41	11.60
Th/Nb	0.12	0.11	0.12	0.10	0.10	0.15	0.16
Zr/Hf	38.1	39.3	39.2	40.0	40.5	36.8	36.8
Ba/Th	160	169	189	170	168	200	199
Ba/Nb	18.6	19.1	22.8	17.2	17.4	30.1	31.3
Sm/Yb	3.38	3.59	3.02	3.82	2.91	2.54	2.46
Ba/La	25.0	25.2	29.5	19.0	18.8	19.1	27.7
Ce/Pb	7.80	7.26	4.77	10.09	12.51	8.23	5.86
(La/Yb) _N	10.4	10.5	8.0	12.6	12.9	5.5	3.8

Sm/Yb, Ba/Nb and Ba/Th vs. Th plots for volcanic rocks from Kirin Province are shown in Fig. 10. In the Zr/Nb and Th/Nb vs. Th plots, most of alkali basalts and tholeiites fall within the EM-I field defined by Weaver (1991). With the exception of the basanites, the Zr/Hf and Ce/Pb are generally constant (Zr/Hf = 40, Ce/Pb = 15) and can be correlated with the EM-I ratios (Weaver, 1991). The

basanites fall within the EM-I field defined by Weaver on plots of Ba/Th and Ba/Nb vs. Th.

It is evident from Fig. 11 there is an enrichment in the incompatible elements abundances from tholeiite through alkali basalt to basanite, although there is considerable overlap from Sr to Lu. The basanites have high incompatible element abundances defining spidergrams that are similar

Table 2. (continued)

Kirin province, Changpaishan area, NE China							
Location	Paiho			Wangching			
Sample No.	92P01	92P02	92P03	91WQ1-1	91WQ1-3	91WQ2-1	91WQ2-2
Rock type	AOB	AOB	QTh	BAS	SPL	BAS	SPL
Rb (ppm)	43	40	8	42	3	37	4
Sr	253	346	461	876	5	830	2
Ba	894	842	213	874	4	823	3
Li	25.4	21.5	15.7	12.9	5.7	12.9	7.1
Sc	15	15	15	28	9	28	11
V	197	196	127	224	55	226	61
Cr	18	15	196	403	3218	472	4344
Ni	164	140	148	180	2095	205	2033
Co	28.1	27.6	33.9	37.8	108.8	38.3	95.2
Zn	134	153	101	80	46	81	48
Cu	40	41	59	74	27	62	27
Y	50.4	36.9	19.1	28.2	2.1	28.2	2.6
Zr	278	270	87	191	11	186	11
Hf	6.17	5.90	2.34	3.32	0.36	3.31	1.21
Nb	41.4	41.1	9.0	55.8	1.2	52.3	1.5
Ta	2.90	2.71	0.60	1.88	0.07	1.89	0.20
Pb	59.5	8.8	2.6	5.4	0.2	12.7	0.2
Cd	0.3	0.27	0.08	0.15	0.05	0.19	0.04
Th	5.37	4.97	1.00	4.98	0.07	4.65	0.64
U	1.16	1.01	0.22	1.13	0.02	1.22	0.06
La	65.1	43.7	7.9	45.3	0.1	45.6	3.0
Ce	94.0	76.3	16.3	73.6	1.3	73.1	5.7
Nd	61.7	46.4	13.8	37.6	1.1	36.6	2.8
Sm	11.24	8.68	3.84	6.54	0.32	6.25	0.49
Eu	3.44	2.81	1.58	2.25	0.09	2.12	0.13
Tb	1.69	1.14	0.62	1.01	0.05	1.02	0.05
Yb	3.23	2.39	1.23	1.83	0.28	2.01	0.26
Lu	0.57	0.43	0.20	0.30	0.05	0.29	0.04
Sr/Nd	4.1	7.5	33.4	23.3	4.5	22.7	0.7
Zr/Nb	6.7	6.6	9.7	3.4	8.7	3.6	7.2
Th/Nb	0.13	0.12	0.11	0.09	0.05	0.09	0.42
Zr/Hf	45.1	45.8	37.1	57.6	29.7	56.0	9.1
Ba/Th	167	169	213	176	60	177	5
Ba/Nb	21.6	20.5	23.7	15.7	3.3	15.8	2.0
Sm/Yb	3.48	3.64	3.12	3.58	1.16	3.11	1.88
Ba/La	13.7	19.3	27.0	19.3	49.8	18.1	1.0
Ce/Pb	1.6	8.7	6.4	13.8	6.6	5.8	38.0
(La/Yb) _N	14.5	13.1	4.6	17.8	0.2	16.2	8.1

to OIB (Hart, 1984). On the basis of their trace element characteristics, these rocks are supposed to have been derived from an EM-I source. Fan and Menzies (1994) concluded that the lithospheric mantle in the Kirin Province is vertically zoned i.e., the deeper part (close to the asthenosphere) was highly metasomatized. The K

and Ba peaks apparent in the spidergram are consistent with mantle metasomatism.

The trachyte may have been derived from the basalt through fractional crystallization of plagioclase, olivine, clinopyroxene, alkali feldspar and magnetite. However, the trachytes have higher $^{87}\text{Sr}/^{86}\text{Sr}$ (0.705129–0.70754, Xie *et al.*, 1988)

Table 2. (continued)

Kirin province, Changpaishan area, NE China							
Location	Wangching						
Sample No.	91WQ2-3	91WQ2-4	91WQ3-1	91WQ3-2	91WQ4	91WQ5-1	91WQ5-2
Rock type	BAS	BAS	BAS	SPL	BAS	BAS	SPL
Rb (ppm)	42	42	37	4	38	44	4
Sr	632	713	807	5	841	1197	67
Ba	785	797	831	4	601	774	51
Li	6.9	6.9	14.3	3.6	12.9	4.2	6.3
Sc	29	27	27	6	16	25	5
V	211	202	218	22	145	178	24
Cr	449	483	422	2126	392	551	2624
Ni	153	166	213	2115	197	154	1972
Co	40.8	47.9	39.8	95.7	41.7	50.2	101.1
Zn	79	81	80	39	85	79	46
Cu	33	32	58	19	38	31	9
Y	25.5	24.9	27.8	1.4	22.1	23.8	2.9
Zr	177	179	189	11	159	170	18
Hf	3.36	3.18	3.10	0.25	3.22	4.65	0.38
Nb	52.4	52.0	53.4	1.4	42.1	47.4	3.1
Ta	1.87	1.74	1.74	0.06	1.71	n.d.	n.d.
Pb	4.0	3.2	4.8	2.7	5.7	4.5	1.0
Cd	0.19	0.19	0.15	0.08	0.15	0.30	0.07
Th	4.66	4.59	4.35	0.11	4.37	4.74	0.59
U	1.10	1.07	1.03	0.02	1.01	n.d.	n.d.
La	44.1	41.9	40.6	0.3	40.7	34.0	3.2
Ce	72.6	68.9	66.6	1.6	66.7	58.9	8.4
Nd	37.2	35.9	35.0	1.2	35.5	33.7	2.4
Sm	6.61	6.17	6.02	0.32	6.17	6.48	0.54
Eu	2.17	2.12	2.05	0.10	2.08	2.04	0.15
Tb	1.05	0.96	0.88	0.03	0.91	0.80	0.09
Yb	1.88	1.81	1.72	0.28	1.77	1.96	0.34
Lu	0.29	0.27	0.26	0.05	0.28	0.28	0.07
Sr/Nd	17.0	19.9	23.0	4.2	23.7	35.6	27.9
Zr/Nb	3.4	3.4	3.5	7.6	3.8	3.6	5.9
Th/Nb	0.09	0.09	0.08	0.08	0.10	0.10	0.19
Zr/Hf	52.5	56.3	61.1	43.5	49.3	36.5	48.3
Ba/Th	168	174	191	35	137	163	87
Ba/Nb	15.0	15.3	15.6	2.8	14.3	16.3	16.6
Sm/Yb	3.51	3.41	3.50	1.11	3.49	3.31	1.58
Ba/La	17.8	19.0	20.5	13.7	14.8	22.7	16.1
Ce/Pb	17.9	21.4	13.8	0.6	11.7	13.0	8.3
(La/Yb) _N	16.8	16.6	16.9	0.7	16.5	12.5	6.6

than the alkali basalt (0.704950–0.705133) and tholeiite (0.704663, Table 3). A positive correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and $1/\text{Sr}$ in some trachytes (Xie *et al.*, 1988) indicating that some of the trachytes may have been contaminated by the crustal materials (e.g., Davidson and Wilson, 1989) during magmatic evolution.

Using the AFC model of DePaolo (1981) and the partition coefficients suggested by Dunn and Sen (1994) and Henderson (1982), and assuming fractional crystallization of 39% plagioclase, 8% olivine, 9% clinopyroxene and 5.9% Fe-Ti oxides we found the D values for Rb and Nb are 0.04152 and 0.162562 respectively. Assuming the primary

Fig. 3. Major elements vs. $100 \times (\text{MgO}/\text{MgO} + \Sigma\text{FeO})$ plots for volcanic rocks from Kirin Province.

magma is tholeiitic and has the following trace element compositions: Rb = 18 ppm, Y = 14 ppm, Nb = 15 ppm, we obtained a r value (the ratio of mass assimilated vs. mass crystallized) of 0.5, which is consistent with variations observed on plots of Nb/Y vs. Rb/Y for the trachytes (Fig. 12).

In a tectonic environment discrimination diagram (Nb-Zr-Y) (Fig. 13), all of the volcanic rocks from Kirin Province fall in the within-plate basalt field defined by Pearce and Norry (1979).

The D-type spinel lherzolite has lower Ba, LREE and Sr than the continental lithospheric

Fig. 4. Ni, Cr, Co, V, Rb, Ba, Li, and Sr vs. $100 \times (\text{MgO}/\text{MgO} + \Sigma\text{FeO})$ plots for volcanic rocks from Kirin Province. Symbols same as in Fig. 3.

mantle (Fig. 11) (Weaver, 1991). The D-type spinel lherzolite may represent ancient depleted continental lithospheric mantle that has undergone previous partial melting. The occurrence of interstitial phlogopite and amphibole in spinel lherzolites from Kirin Province (Ou and Chao,

1987) indicates that these two minerals were formed at a later stage (Zhang *et al.*, 1991) by metasomatic processes. The incompatible element enrichments in E-type spinel-lherzolite (Fig. 11) may also be due to mantle metasomatism with these rocks defining spidergrams similar to that

Fig. 5. Nb, Y, Zr, Sc, Th, Hf, La and Lu vs. $100 \times (\text{MgO}/\text{MgO} + \Sigma\text{FeO})$ plots for volcanic rocks from Kirin Province. Symbols same as in Fig. 3.

of continental lithospheric mantle (Weaver, 1991).

Based on Sr, Nd isotopic ratios and geobarometric data derived from geobarometer recommended by Mercier (1980) (Hsu, unpublished data) we conclude that the upper layer of

the upper mantle in Kirin Province is composed of D-type spinel lherzolite ($^{87}\text{Sr}/^{86}\text{Sr} \approx 0.70381$), whereas the lower layer of the upper mantle is composed of the E-type spinel-lherzolite ($^{87}\text{Sr}/^{86}\text{Sr} \approx 0.70623$). The tholeiite, alkali basalt and

Fig. 6. Chondrite-normalized REE patterns for volcanic rocks from Kirin Province. The normalizing values are from Sun and McDonough (1989).

Fig. 7. Chondrite-normalized REE patterns for ilherzolite xenoliths and clinopyroxene megacryst (Hsu, unpublished data) from Kirin Province. The normalizing values are from Sun and McDonough (1989).

Table 3. Sr, Nd and Pb isotopic data of basalts, trachytes and spinel-lherzolite xenoliths from Kirin Province, NE China

Sample	Rock type	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{(4)}\epsilon_{\text{Nd}}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{(5)}\Delta 7/4$
⁽¹⁾ Cw-19	Tholeiite	0.704663 ± 15	0.512744 ± 20	2.1				
⁽²⁾ LG-06	Alkali Basalt	0.704319 ± 15	0.512805 ± 24	3.3				
⁽²⁾ LG-07	Basanite	0.704478 ± 16	0.512712 ± 20	1.4				
⁽²⁾ LG-03	Lherzolite	0.703768 ± 15	0.513012 ± 20	7.3				
⁽²⁾ LG-04	Lherzolite	0.703860 ± 15	0.513074 ± 20	8.5				
⁽²⁾ LG-11	Lherzolite	0.706077 ± 16	0.512631 ± 16	-0.1				
⁽²⁾ LG-15	Lherzolite	0.706187 ± 14	0.512680 ± 20	0.8				
⁽²⁾ LG-16	Lherzolite	0.706440 ± 13	0.512696 ± 21	1.1				
⁽³⁾ X-1	Trachyte	0.70514	0.51263		17.473	15.471	37.681	9
⁽³⁾ K-1	Trachyte	0.7054	0.51259		17.422	15.451	38.2902	8
⁽³⁾ X-17	Trachyte	0.70754	0.51258		17.707	15.510	37.935	10
⁽³⁾ X-24	Trachyte	0.70513	0.51264		17.470	15.486	37.761	10
⁽³⁾ X-39	Tholeiite	0.7052	0.51257		17.47	15.542	37.664	15
⁽³⁾ X-42	Alkali Basalt	0.70513	0.51256		17.486	15.459	37.578	7
⁽³⁾ X-40	Alkali Basalt	0.70495	0.51250		17.534	15.460	37.704	7
⁽³⁾ X-34	Alkali Basalt	0.70495	0.51277		18.082	15.438	37.954	-1
⁽³⁾ X-15	Alkali Basalt				17.459	15.447	37.681	9

Remarks: ⁽¹⁾Tholeiite from Changpaishan area analyzed by the present study. ⁽²⁾Alkali basalt, basanite and spinel-lherzolite xenoliths from Lungkang area analyzed by the present study. ⁽³⁾From Xie *et al.* (1988). ⁽⁴⁾ $\epsilon_{\text{Nd}} = ((^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}} / (^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} - 1) \times 100$; $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} = 0.512638$ (DePaolo and Wasserburg, 1976). ⁽⁵⁾ $\Delta 7/4 = ((^{207}\text{Pb}/^{204}\text{Pb})_{\text{DS}} - (^{207}\text{Pb}/^{204}\text{Pb})_{\text{NHRL}}) \times 100$; $(^{207}\text{Pb}/^{204}\text{Pb})_{\text{NHRL}} = 0.1084(^{206}\text{Pb}/^{204}\text{Pb}) + 13.491$ (Hart, 1984). ⁽⁶⁾ $\Delta 8/4 = ((^{208}\text{Pb}/^{204}\text{Pb})_{\text{DS}} - (^{208}\text{Pb}/^{204}\text{Pb})_{\text{NHRL}}) \times 100$; $(^{208}\text{Pb}/^{204}\text{Pb})_{\text{NHRL}} = 1.209(^{206}\text{Pb}/^{204}\text{Pb}) + 15.627$ (Hart, 1984).

Fig. 8. $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for volcanic rocks, spinel lherzolite xenoliths and clinopyroxene and garnet megacrysts from Kirin Province and Liaoning Province of NE China. The data points for Wutalienshih alkali basalts (W) are from Wang and Xie (1992). The data for Liaoning basalts and megacrysts are from Liu *et al.* (1992). DMM, HIMU, EM-I, EM-II and MORB fields from Hart (1988).

Fig. 9. $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ plots for Kirin basalts (dotted circles) and Kirin trachyte (open circles). DMM, HIMU, EM-I, EM-II, Lower Crust and MORB fields from Hart (1988). SE China basalts from Peng *et al.* (1986), Tu *et al.* (1991, 1992) and Lan *et al.* (1994), and Japan Sea basalts from Okamura *et al.* (1998).

basanite may be derived from an isotopically similar source as suggested by Sr and Nd isotopic data (Table 3) through differing degrees of partial melting of the mantle lherzolite.

From geophysical data it is evident that the Songliao basin in NE China is currently rifting. The thickness of the lithosphere in the center of the basin is around 80 km or about 40 km thinner than at the margins (Ma, 1987). In addition, the crustal thickness in the center of the basin is 23 km, which is 10–20 km thinner than in the marginal portion (Hsu, 1987). Furthermore, the heat flow in the center of the basin is around 95 mw/m^2 decreasing to 44 mw/m^2 at the margins (Wu

and Xie, 1985).

The upwelling of the asthenosphere and thinning of EM-I type lithospheric mantle in Cenozoic time caused rifting, thermal erosion and decompressional melting (Mutter *et al.*, 1988) which also created the possibility of mixing of asthenospheric material with EM-I lithospheric mantle components. The basanites which occur near the margins, may have formed through 5 to 8% partial melting of spinel lherzolite, at relatively deep level, that had been metasomatized, and hence enriched in incompatible elements. By contrast, the alkali basalts and tholeiites may have formed at different levels (shallower than basanite)

Table 4. Chemical compositions of spinel lherzolite xenoliths from Wangching area in Kirin Province as compared with those of primitive mantle and continental lithospheric spinel lherzolite and garnet lherzolite

Sample	⁽¹⁾ Kirin area D-type spinel lherzolite	⁽²⁾ Kirin area E-type spinel lherzolite	⁽³⁾ Continental lithospheric spinel lherzolite	⁽⁴⁾ Primitive mantle	⁽⁵⁾ Continental lithospheric garnet lherzolite
SiO ₂ (%)	43.89	46.05	44.00	44.80	44.90
TiO ₂	0.13	0.25	0.09	0.21	0.06
Al ₂ O ₃	2.16	1.73	2.27	4.45	1.40
ΣFeO	9.78	7.75	8.43	8.40	7.89
MnO	0.14	0.13	0.14	0.14	0.11
MgO	41.01	42.23	41.40	37.20	42.60
CaO	2.35	1.72	2.15	3.60	0.82
Na ₂ O	0.42	0.33	0.24	0.34	0.11
K ₂ O	0.07	0.12	0.05	0.03	0.04
P ₂ O ₅	0.03	0.06	0.06	0.02	0.01
Mg value	88.20	90.62	89.80	88.80	98.60
Rb (ppm)	3.5	4	1.9	0.635	—
Sr	5	34.5	49	21.1	—
Ba	4	27	33	6.989	—
Li	4.65	6.7	1.5	1.6	—
Sc	7.5	8	12.2	—	—
V	38.5	42.5	56	—	—
Cr	2672	3484	2690	2942	—
Ni	2105	2003	2160	1886	—
Co	102.25	98.15	112	—	—
Zn	42.5	47	65	—	—
Cu	23	18	11	—	—
Y	1.75	2.75	4.4	4.55	—
Zr	11	14.5	21	11.2	—
Hf	0.305	0.25	0.27	0.309	—
Nb	1.3	2.3	4.8	0.713	—
Ta	0.065	0.2	0.4	0.041	—
Pb	1.45	0.6	0.16	0.185	—
Cd	0.065	0.055	0.04	—	—
Th	0.09	0.615	0.71	0.085	—
U	0.02	0.06	0.12	0.021	—
La	0.2	3.1	2.6	0.687	—
Ce	1.45	7.05	6.29	1.775	—
Nd	1.15	2.6	2.67	1.354	—
Sm	0.32	0.515	0.47	0.444	—
Eu	0.095	0.14	0.16	0.168	—
Tb	0.04	0.07	0.07	0.108	—
Yb	0.28	0.3	0.26	0.493	—
Lu	0.05	0.055	0.043	0.074	—

Remarks:

^{(1),(2)}Present study; D = Depleted; E = Enriched; ⁽³⁾McDonough (1990); ⁽⁴⁾Sun (1982), Sun and McDonough (1989); ⁽⁵⁾Maaloe and Aoki (1977).

by different degrees of partial melting of the upper mantle material.

The eruption of lavas with EM-I characteristics during the Miocene-Holocene has important

implications for our understanding of the longevity of their distinct isotopic mantle material. Notably, several authors have argued that EM-I lithospheric mantle was developed in Archean

Fig. 10. The incompatible elements ratios vs. Th plot for tholeiites, alkali basalts, basanites and spinel lherzolite xenoliths from Kirin Province.

time (Fraser *et al.*, 1985; Dudas *et al.*, 1987; Menzies and Hawkesworth, 1987). However in Kirin Province, the basement age is estimated to be 1.7–1.8Ga (Zhang *et al.*, 1984) or even younger

(700–800 Ma, Wang, 1982) indicating that formation of an EM-I lithospheric mantle may be extended to post Archean time.

Fig. 11. Primitive mantle-normalized incompatible element patterns for volcanic rocks and D-type and E-type spinel lherzolite xenoliths from Kirin Province as compared with continental lithospheric mantle (CLM; Weaver, 1991). Normalizing values and OIB pattern from Sun and McDonough (1989).

Fig. 12. Nb/Y vs. Rb/Y for volcanic rocks from Kirin Province.

Fig. 13. Zr/4-2Nb-Y discrimination diagram for Kirin volcanic rocks. Variation fields after Pearce and Norry (1979). Symbols same as in Fig. 3.

Acknowledgments—We are grateful to Prof. Shan-wen Chiu of Chang-chun Institute of Geography, Academia Sinica, and Mr. Shi-Kuei Wang of the Department of Geology, Chang-chun College of Geology for their assistance during field work in Kirin Province. We thank Dr. C. H. Chen of Academia Sinica (Taipei) for performing the Sr and Nd isotopic analyses of the basalts. We would like to thank Drs. R. J. Arculus and C. J. Bryant for their critical review of the manuscript. This study was supported by the National Science Council of the Republic of China.

REFERENCES

- Chen, C. H. (1988) Estimation of the degree of partial melting by $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ and $\text{Al}_2\text{O}_3/\text{SiO}_2$ of basic magmas. *Chem. Geol.* **71**, 355–364.
- Davidson, J. P. and Wilson, I. R. (1989) Evolution of an alkali basalt-trachyte suite from Jebel Marra volcano, Sudan, through assimilation and fractional crystallization. *Earth Planet. Sci. Lett.* **95**, 141–160.
- DePaolo, D. J. (1981) Trace element and isotopic effects of combined wall rock assimilation and fractional crystallization. *Earth Planet. Sci. Lett.* **53**, 189–202.
- DePaolo, D. J. and Wasserberg, G. J. (1976) Nd isotopic variations and petrogenetic models. *Geophys. Res. Lett.* **3**, 249–252.
- Dudas, F. O., Carlson, R. W. and Eggler, D. H. (1987) Regional middle Proterozoic enrichment of the sub-continental mantle source of igneous rocks from central Montana. *Geology* **15**, 22–25.
- Dunn, T. and Sen, C. (1994) Mineral/matrix partition coefficients for orthopyroxene, plagioclase and olivine in basaltic to andesitic systems: A combined analytical and experimental study. *Geochim. Cosmochim. Acta* **58**, No. 2, 717–733.
- Dupré, B. and Allègre, C. J. (1983) Pb-Sr isotopic variations in Indian Ocean basalts and mixing phenomena. *Nature* **303**, 142–146.
- Fan, W. and Menzies, M. A. (1994) Geochemistry of volcanic rocks and ultramafic xenoliths from eastern China: implications for the structure of the lower lithosphere.
- Fraser, K. J., Hawkesworth, C. J., Erland, A. J. R., Mitchell, H. and Scott-Smith, B. H. (1985) Sr, Nd and Pb isotope and minor element geochemistry of lamproites and kimberlites. *Earth Planet. Sci. Lett.* **76**, 57–70.
- Hart, S. R. (1984) A large-scale isotope anomaly in the southern hemisphere. *Nature* **309**, 753–757.
- Hart, S. R. (1988) Heterogeneous mantle domains: signatures, genesis, and mixing chronologies. *Earth Planet. Sci. Lett.* **90**, 273–296.
- Hart, S. R. and Allègre, C. J. (1980) Trace-elements constraints on magma genesis. *Physics of Magmatic Processes* (Hargraves, R. B., ed), 121–159, Princeton University Press, Princeton.
- Hart, S. R. and Dunn, T. (1993) Experimental clinopyroxene/melt partitioning of 24 trace elements. *Contrib. Mineral. Petrol.* **113**, 1–8.
- Henderson, P. (1982) *Inorganic Geochemistry*. Pergamon Press, 353 pp.
- Hsu, K. J. (1987) Origin of sedimentary basins of China. Chinese sedimentary basins. *Sedimentary Basins of the World, 1* (Zhu, X., ed.), 207–227, Elsevier, Amsterdam.
- Jaques, A. L. and Green, D. H. (1980) Anhydrous melting of peridotite at 0–15 kb pressure and the genesis of tholeiitic basalts. *Contrib. Mineral. Petrol.* **73**, 287–310.
- Kelemen, P. B., Shimizu, N. and Dunn, T. (1993) Relative depletion of niobium in some arc magmas and the continental crust: partitioning of K, Nb, La and Ce during melt/rock reaction in the upper mantle. *Earth Planet. Sci. Lett.* **120**, 111–134.
- Lan, C. Y., Chung, S. L., Mertzman, S. A. and Hsu, W. Y. (1994) Petrology, geochemistry and Nd-Sr isotope of late Miocene basalts in Liehyu and Chinmen, Fujian. *J. Geol. Soc. China* **37**, No. 3, 309–334.
- Le Bas, M. J. (1986) A chemical classification of volcanic. *J. Petrol.* **27**, Part 3, 745–750.
- Liu, C. C. (1988) Cenozoic volcanic phases in NE China. *Acta Petrologica Sinica* **88-1**, 1–10.
- Liu, C. Q., Masuda, A. and Xie, G. H. (1992) Isotope and trace-element geochemistry of alkali basalts and associated megacrysts from the Huangyishan volcano, Kuandian, Liaoning, NE China. *Chem. Geology* **97**, 219–231.
- Liu, S. and Wang, S. K. (1987) Volcanic base surge deposits in Kirin Province. *Geol. Rev.* **33**, No. 3, 577–581 (in Chinese).
- Ma, X. Y. (1987) Lithospheric dynamics map of China and adjacent seas (1:4,000,000) and explanatory notes. Publishing House of Geology, Beijing, 52 pp.
- Maaloe, S. (1994) Estimation of the degree of partial melting using concentration ratios. *Geochim. Cosmochim. Acta* **58**, No. 11, 2519–2525.
- Maaloe, S. and Aoki, K. (1977) The major element composition of the upper mantle estimated from the composition of lherzolite. *Contrib. Mineral. Petrol.* **63**, 161–173.
- McDonough, W. F. (1990) Constraints on the composition of the continental lithospheric mantle. *Earth Planet. Sci. Lett.* **101**, 1–18.
- McKay, G. (1985) Crystal/liquid partitioning of REE in basaltic systems: Extreme fractionation of REE in olivine. *Geochim. Cosmochim. Acta* **50**, 69–79.

- Menzies, M. A. and Hawkesworth, C. M. (1987) Upper mantle processes and composition. *Mantle Xenoliths* (Nixon, P. H., ed.), 725–738, Wiley, London.
- Mercier, J. C. C. (1980) Single pyroxene thermobarometry. *Tectonophysics* **70**, 1–37.
- Middlemost, E. A. K. (1989) Iron oxidation ratios, norms and the classification of volcanic rocks. *Chem. Geol.* **77**, 19–26.
- Mutter, J. C., Buck, W. R. and Zehnder, C. M. (1988) Convective partial melting 1. A model for the formation of thick basaltic sequences during the initiation of spreading. *J. Geophys. Res.* **93**, 1031–1048.
- Okamura, S., Arculus, R. J., Martynov, Y. A., Kagami, H., Yoshida, T. and Kawano, Y. (1998) Multiple magma sources involved in marginal-sea formation: Pb, Sr, and Nd isotopic evidence from the Japan Sea region. *Geology* **26**, 619–622.
- Ou, M. and Chao, D. S. (1987) *Cenozoic Basalts and Their Xenoliths in Eastern China*. Sci. Pub. Co., 490 pp. (in Chinese).
- Pearce, J. A. and Norry, M. J. (1979) Petrogenetic implications of Ti, Zr, Y and Nb variation in volcanic rocks. *Contrib. Mineral. Petrol.* **69**, 33–47.
- Peng, Z. C., Zartman, R. E., Futa, K. and Chen, D. G. (1986) Pb, Sr and Nd isotopic systematics and chemical characteristics of Cenozoic basalts, eastern China. *Chem. Geol. (Isot. Geosci. Sect.)* **59**, 3–33.
- Stormer, J. C. and Nicholls, J. (1978) XLFRAC: a program for the interactive testing of magmatic differentiation models. *Computers and Geosciences* **4**, 143–159.
- Sun, S. S. (1982) Chemical composition and the origin of the Earth's primitive mantle. *Geochim. Cosmochim. Acta* **46**, 179–192.
- Sun, S. S. and McDonough, W. F. (1989) Chemical and isotopic systematics of oceanic basalts: implication for mantle composition and processes. *Magmatism in the Ocean Basins* (Saunders, A. D. and Norry, M. J., ed.), Geol. Soc., Sp. Pub., **42**, 313–345.
- Sun, S. S. and Nesbitt, R. W. (1978) Petrogenesis of Archean ultrabasic basic volcanic: evidence from rare earth elements. *Contrib. Mineral. Petrol.* **65**, 301–325.
- Tatsumoto, M., Basu, A. R., Wankang, H., Junwen, W. and Guanghong, X. (1992) Sr, Nd and Pb isotopes of ultramafic xenoliths in volcanic rocks of eastern China: enriched components EMI and EMII in subcontinental lithosphere. *Earth Planet. Sci. Lett.* **113**, 107–128.
- Tu, K., Flower, M. F. J., Carlson, R. W., Zhang, M. and Xie, G. (1991) Sr, Nd and Pb isotopic compositions of Hainan basalts (south China): implications for subcontinental lithosphere Dupal source. *Geology* **19**, 567–569.
- Tu, K., Flower, M. F. J., Carlson, R. W., Xie, G. H., Chen, C. Y. and Zhang, M. (1992) Magmatism in the South China Basin, 1. Isotopic and trace element evidence for an endogenous Dupal mantle component. *Chem. Geol.* **97**, 47–63.
- Wang, H. C. (1982) The main stages of crustal development of China. *Earth Sciences* **7**(1), 155–177 (in Chinese with English abstract).
- Wang, J. W. and Xie, G. H. (1992) Geochemistry of potassic lava from Wutalienshih. *Geochronology and Geochemistry of Cenozoic Volcanic Rocks from China*, 213–227, Seismic Pub. Co. (in Chinese).
- Weaver, B. L. (1991) The origin of oceanic island basalt end member. Compositions: trace element and isotopic constraints. *Earth Planet. Sci. Lett.* **104**, 381–397.
- Wu, Q. F. and Xie, Y. Z. (1985) Heat flow in Songliao Basin. *Seismology and Geology* **7**(2), 59–64 (in Chinese with English abstract).
- Xie, G. H., Wang, J. W., Basu, A. R. and Tatsumoto, M. (1988) Petrochemistry and Sr, Nd, Pb isotopic geochemistry of Cenozoic volcanic rocks; Changpaishan area, NE China. *Acta Petrologica Sinica* **4**, 1–13 (in Chinese).
- Zhang, M., Suddaby, P., Menzies, M. A. and Thirlwall, M. F. (1991) EMI signature from within the post-Archaean subcontinental lithospheric mantle: Isotopic evidence from the potassic volcanic rocks in NE China. *Geochem. J.* **25**, 387–398.
- Zhang, Z. M., Liou, J. G. and Coleman, R. G. (1984) An outline of the plate tectonics of China. *Geol. Soc. Am. Bull.* **95**, 295–312.
- Zhou, X. and Armstrong, R. L. (1982) Cenozoic volcanic rocks of eastern China: secular and geographic trends in chemistry and strontium isotopic composition. *Earth Planet. Sci. Lett.* **58**, 301–329.