Int J Earth Sci (Geol Rundsch) (2006) 95: 68–79
DOI 10.1007/s00531-005-0509-9

ORIGINAL PAPER

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The geochemical variations of mid-Cretaceous lavas across western Shandong Province, China and their tectonic implications

Received: 3 June 2003 / Accepted: 19 April 2005 / Published online: 22 June 2005

Abstract Major and trace element as well as Sr–Nd isotopic compositions of mid-Cretaceous lavas across western Shandong Province, China have been studied. These lavas can be generally divided into southern Shandong group (including Pingyi and Mengyin) and northern Shandong group (including Laiwu and Zouping) based on their geochemistry. The southern group lavas are characterized by extreme enrichment in LREE, large ion lithophile elements (LILE), and depletion in HFSE along with EMII-like Sr–Nd isotopic compositions, suggesting that the crustal involvements play a significant role in their petrogenesis. Comparing studies with Fangcheng basalts reveal that the Triassic continent–continent collision between the Yangtze craton (YC) and the North China craton (NCC), and subsequent extensive modification of the sub-continental lithospheric mantle (SCLM) beneath the south part of the NCC by silicic melts released from the subducted Yangtze lower crust, formed an enriched lithospheric mantle which was the source of the southern Shandong group lavas. In contrast, the northern Shandong group lavas are mildly enriched in LREE and LILE relative to those of the southern group lavas. The isotope compositions are also distinctive in that the Sr isotopic ratios are very low. Available geochemical evidence and comparing studies with spatially closed related mafic intrusions suggest that the SCLM feeding the northern group lavas seems to be linked to carbonatitic metasomatism and changed modal proportion of phlogopite and clinopyroxene in the mantle rather than subduction-related modifications. The contrasting geochemical characters of the mid-Cretaceous lavas across western Shangdong suggest that the SCLM of the NCC is spatially heterogeneous in Mesozoic.

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Keywords China · Shandong Province · Geochemistry · Mid-Cretaceous · Lavas

Introduction

The outcrops of mantle xenoliths bearing Paleozoic kimberlites and Cenozoic basalts in the North China craton (NCC) provide very useful tools for deciphering the compositional and temporal evolution of the sub-continental lithospheric mantle (SCLM) beneath the NCC during the Phanerozoic. Detailed studies on Ordovician diamondiferous kimberlites and their mantle-derived xenoliths (Chi et al. 1992) and diamond inclusions (Wang et al. 1998) revealed the existence of an old, cold (cratonic geotherm) and thick (ca. 200 km) Archean lithospheric keel beneath the NCC in the early Paleozoic (Griffin et al. 1992, 1998). In contrast, the investigations of the Cenozoic basalts and entrained mantle xenoliths in the east NCC suggest that the SCLM underneath NCC is younger, hotter (oceanic geotherm), and thinner (<80 km) in the Cenozoic (Menzies et al. 1993), this means that at least 120 km of old lithospheric mantle was removed and replaced by newly accreted lithospheric mantle (Menzies et al. 1993; Fan et al. 2000). Besides the above-mentioned catastrophic thinning of the SCLM of the NCC, another tremendous geological event, i.e. the Triassic continent–continent collision of the Yangtze craton (YC) with the NCC took place at the southern margin of the NCC. Such collision on the one hand gave rise to the formation of the Dabie–Sulu ultrahigh-pressure metamorphic belt (Hacker et al. 1996; Cong 1996), on the other hand introduced a great amount of crustal materials from the YC into the mantle of the NCC through deep subduction processes(Zhang and Sun 2002a).

Concomitant with and later than the above two major geologic events, extensive Mesozoic volcanic rocks erupted in Shandong Province, which covers the southeast part of the NCC. Although a lot of studies had been carried out on volcanics in Shandong Province (Wu 1984; Wang et al. 1998), few systematic geochemical investigations were done on the lavas distributed in western Shandong Province. Interestingly, systematic changes of geochemical features have been observed in these coeval volcanics from south to north (Ying 2002). It has been widely accepted that the plate tectonic and volcanic activities are closely related and the volcanism character can reflect the geodynamic context (Condie 1989; Wilson 1989). Thus the geochemical studies on these volcanic rocks may provide us some important information about the geodynamics of the study areas. In this paper, we reported the results of comprehensive geochemical and isotopic studies on Mesozoic volcanic rocks from western Shandong Province in attempts to explain their source characteristics and petrogenesis, and try to understand the geodynamic context and mantle processes which are responsible for the volcanic activities in the Mesozoic.

Geological settings and petrography

The NCC is the largest and oldest craton in China with the presence of Archean terranes of 2.5–3.8 Ga and early Proterozoic basement (Jahn and Zhang 1984; Jahn and Ernst 1990; Liu et al. 1992). The Triassic Dabie–Sulu ultra-high pressure (UHP) metamorphic belt, which resulted from the collision of the NCC with the YC integrated the YC with the NCC along its southeast margin forming a large, united continent in eastern China.

Shandong Province, which is located in the southeast part of the NCC can be generally divided into two parts by the Tanlu fault, a wrench fault which is believed to have been active in the Cretaceous (Xu 1993; Xu and Zhu 1994). The western part is called Luxi, and the eastern the Jiaodong (Fig. 1). The basement in Shandong Province consists of Archean to early Proterozoic amphibolite to granulite facies gneisses. Volcanism has been active since the Paleozoic, the presence of Ordovician diamondiferous kimberlite (ca. 460 Ma) in Mengyin of Luxi area (Lu et al. 1995) implied the existence of a thick cratonic lithosphere in the early Paleozoic. In the Jiaodong region, mid-Cretaceous lavas mainly outcropped in NE-trending fault-rifting basins and demonstrated bimodal characteristics (Fan et al. 2001), the geochemical and isotopic studies suggested that the basaltic rocks originated from enriched lithospheric mantle which had undergone metasomatism by the deeply subducted Yangtze lower/middle crust, whereas the felsic group was generated by anatexis of the lower/middle crust in response to basaltic magma underplating. Differing from the lavas in Jiaodong, those in Luxi area are distributed in a series of NW-trending extensional basins and no systematic investigations had been carried out on them yet.

Within the study areas, a series of coeval, isolated Mesozoic NW-trending extensional basins developed. These are, from south to north, Pingyi basin, Mengyin basin, Laiwu basin and Zouping basin (Fig. 1). Mesozoic volcanic rock samples, for which we reported new geochemical data, were collected from these four basins.

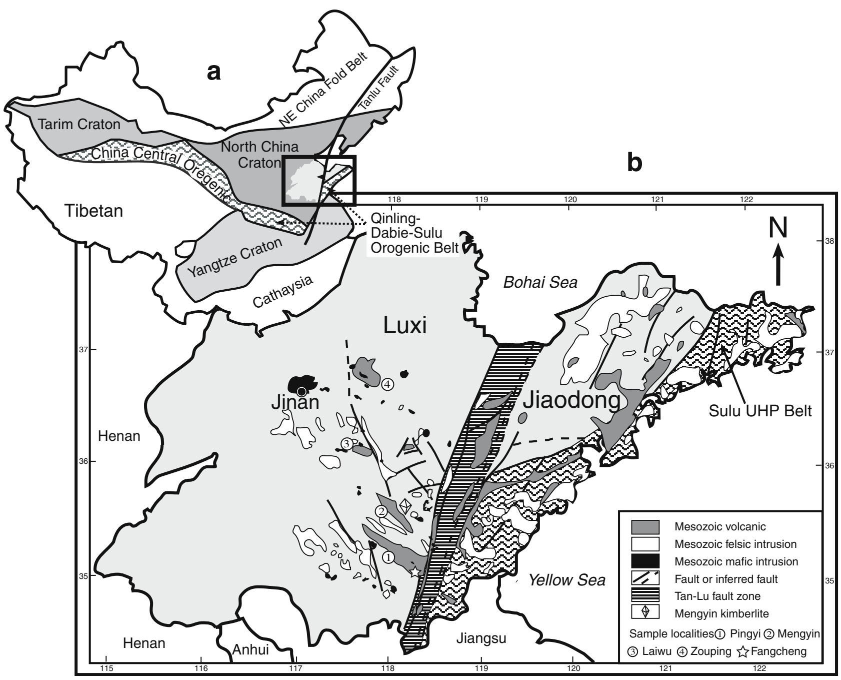

Fig. 1 **a** Simplified *tectonic map* showing major tectonic units in China and the position of Shandong Province in China. **b** The *geological map* of Shandong Province showing distributions of mid-Cretaceous lavas and intrusions and Paleozoic Mengyin diamondiferous kimberlites, with emphases on volcanic rocks in western Shandong Province (after Zhang and Sun 2002a)

Pingyi lavas outcrop in the Pingyi basin which is situated in the southernmost of Shandong Province, erupted at 120 Ma (K–Ar age) (Bureau of Geology and Mineral Resources of Shandong Province, China (BGMRS) 1991). The rocks are mainly composed of basaltic trachyandesite and trachyandesite. A recent discovered Mesozoic Fangcheng basalts (125 Ma) also outcrops in Pingyi basin (Zhang et al. 2002b), The Fangcheng volcanism occurs as a central-type volcano, and belong to the lower part of the Qingshan Formations stratigraphically (Zhang et al. 2002b). In the Mengyin basin, the lavas mainly consist of basaltic trachyandesite (Qiu et al. 1997, 2002), Rb–Sr measurement and ^{40}Ar–^{39}Ar determination gave ages of 119 Ma and 115–124 Ma for Mengyin lavas, respectively (Qiu et al. 1997, 2002). The basaltic andesites at Mengyin and Pingyi are dark green and dark gray, with porphyritic texture and massive structure, and consist of plagioclase, clinopyroxene and sparse amphibole phenocrysts. The phenocrysts are generally 0.5–1 mm in size. The matrix is made up of clinopyroxene, plagioclase and some opaque minerals.

Laiwu lavas outcropping in the Laiwu basin erupted at 119 Ma according to K–Ar dating (BGMRS 1991). These lavas are mainly composed of basaltic andesite and andesite. The rocks are dark gray with porphytic texture and massive structure, and exhibit alteration to moderate extent. The rocks are characterized by plagioclase, clinopyroxene and rare amphibole phenocrysts in a groundmass of plagioclase, clinopyroxene and magnesite. Zouping lavas within the Zouping basin consist of basaltic andesite, and were dated 127 Ma by K–Ar technique (BGMRS 1991). The basaltic andesite samples of the Zouping lavas are very fresh, dark gray, and exhibit aphanitic to weakly porphyritic texture. The phenocrysts are predominantly plagioclase and clinopyroxene with minor amphibole, the grain size is about 1 mm. The groundmass is mainly composed of fine-grained clinopyroxene and plagioclase and a few opaque oxides such as magnetite and ilmentite.

Stratigraphically, all these lavas of the four basins belong to the Qingshan Formation, which is overlaid by late Cretaceous Wangshi Formation and underlaid late Jurassic sandy shale, mudstone and pelitic siltstone (BGMRS 1991).

Analytical procedures

All samples selected for bulk rock major, trace element and isotopic analyses were first trimmed to remove altered surfaces and then crushed with a ceramic jaw crusher and powdered using an agate mill. Major element compositions were analyzed by X-ray fluorescence spectrometry (XRF) with a Philips PW1400 spectrometer at the Institute of Geology and Geophysics (IGG), Chinese Academy of Sciences. Fused glass disks were used and the analytical uncertainties are generally better than 5% for all elements. Loss on ignition (LOI) was determined by routine procedures. Trace elements were measured by inductively coupled plasma mass spectrometry (ICP-MS) at IGG using a Finnigan MAT Element spectrometer, which has a good stability range within ~5%.

Acid-leaching techniques were applied to samples prior to Sr and Nd isotope analyses. The whole rock powders (~100 mg) were leached with 6 M sub-boiled HCl for 1 h at 150°C and dissolved in distilled HF–HNO_3 in Savilles screwtop capsules for 5 days. The Sr and Nd were separated by traditional cation exchange procedures described by Zhou et al. (2002), and isotopic ratios were determined on a Finnigan MAT262 multi-collector mass spectrometer at IGG using static multi-collection. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ data are normalized within run to $^{86}Sr/^{88}Sr$ = 0.1194 and $^{146}Nd/^{144}Nd$ = 0.7219, respectively. Repeated measurement of La Jolla Nd standard and NBS987 Sr standard during the measurement period yield $^{143}Nd/^{144}Nd$ = 0.511861 ± 9 (2σ, n = 12) and $^{87}Sr/^{86}Sr = 0.710255 \pm 9$ (2σ, n = 12), respectively. Total procedural blanks are $\sim10^{-9}$ g for Sr and $\sim10^{-11}$ g for Nd.

Results

Major elements

Based on their geochemical similarities and increasing distance from the YC–NCC margin, the Pingyi and Mengyin lavas are treated as southern Shandong group, and the Laiwu and Zouping lavas are merged as northern Shandong group. The major element data are presented in Tables 1, 2, and 3. The SiO_2 contents of the southern Shandong group lavas range from 51 to 60%, with wider dispersion for the Mengyin lavas. According to the nomenclature of Le Maitre (1989), the southern Shandong group lavas fall in the region of basaltic trachyandesite and trachyandesite (not shown). Some samples from the southern Shandong group, especially those of Mengyin were affected by alteration as seen from the elevated LOI. In order to minimize the alteration effect, a discrimination diagram based on immobile elements is used for classifying the rock samples. The southern Shandong group lavas mainly classified as trachyandesite (Fig. 2) (Winchester and Floyd 1976). The SiO_2 contents of the northern Shandong group lavas range from 50 to 59%. The Zouping lavas within the northern Shandong group are more homogeneous than Laiwu. The northern Shandong group lavas are andesite/basalts in the classification of Winchester and Floyd (1976) (Fig. 2).

There is a marked decrease of CaO and Cr with decreasing MgO for both southern and northern Shandong group lavas, suggesting that the clinopyroxene is the major fractionated phase during the magma evolution. The positive correlations of Co and Ni with MgO imply the removal of olivine during the fractional crystallization. The negative correlation between Al_2O_3

Table 1 Major-element (wt.%) and trace element (ppm) data for mid-Cretaceous lavas from Shandong Province, China

Locality (sample)	Southern Shandong group							
	Pingyi				Mengyin			
	PY-1	PY-2	PY-3	PY-4	M04-1*	My-1*	My-1	My-3
SiO_2	54.9	54.4	53.4	57.0	51.3	54.5	60.3	51.3
TiO_2	0.98	0.91	1.02	0.81	1.15	1.28	0.62	1.08
Al_2O_3	16.5	14.8	14.7	16.9	15.0	16.6	12.8	15.5
Fe_2O_3	7.11	6.23	8.00	6.42	8.38	7.28	4.97	7.90
MnO	0.11	0.10	0.16	0.05	0.08	0.08	0.10	0.15
MgO	3.98	5.46	5.18	3.46	5.78	3.90	3.15	6.14
CaO	5.55	7.90	7.66	4.80	9.24	6.11	7.32	7.99
Na_2O	3.75	3.63	3.28	3.92	2.69	3.99	3.10	3.13
K_2O	4.23	3.45	3.64	4.03	2.47	3.04	3.95	3.23
P_2O_5	0.80	0.72	0.85	0.42	0.86	0.78	0.31	0.86
LOI	1.97	2.13	1.60	2.06			3.26	2.32
Total	99.80	99.68	99.50	99.86	96.93	97.79	99.81	99.53
Cr	287	122	198	242	292	122	197	212
Co	23.0	18.0	21.1	16.1	28.6	20.3	18.1	31.6
Ni	103	61.0	76.5	81.8	114	126	104	96.9
V	112	117	122	83.7	220	142	67.9	133
Rb	58.1	103	82.3	94.6		61.7	164	57.7
Sr	1181	1099	1175	1114	1100	1436	790	1392
Y	17.6	20.0	21.9	12.5			12.7	21.9
Zr	224	293	267	238		287	214	289.2
Nb	22.2	23.9	22.1	17.0	6.7	15.9	9.59	29.6
Cs	0.33	1.36	0.71	1.24			0.67	0.73
Ba	1475	1733	1491	1202	1400	1191	1162	3234
La	103	133	119	66.5	81.9	101.3	62.3	119
Ce	195	234	239	117	187	177	117	227
Pr	23.5	26.6	27.5	14.2	22.4	20.6	12.9	27.1
Nd	88.4	99.3	102.2	51.2	85.8	71.9	47.7	101.9
Sm	13.4	14.4	15.2	7.5	14.0	9.9	7.7	15.2
Eu	3.51	3.96	4.14	2.05	3.10	2.41	1.98	4.15
Gd	9.85	10.57	11.24	5.54	8.10	6.54	5.45	11.29
Tb	1.02	1.04	1.11	0.61	0.96	0.79	0.61	1.14
Dy	4.54	4.71	5.16	2.80	4.90	3.69	2.88	5.30
Ho	0.71	0.79	0.84	0.48	0.83	0.70	0.50	0.89
Er	1.94	2.13	2.30	1.29	2.00	1.49	1.38	2.35
Tm	0.24	0.28	0.28	0.17	0.27	0.22	0.19	0.30
Yb	1.47	1.66	1.67	1.07	1.60	1.16	1.13	1.88
Lu	0.21	0.25	0.25	0.15	0.25	0.17	0.17	0.28
Hf	6.34	7.71	7.30	6.18			5.67	7.67
Ta	0.67	0.72	0.65	0.58			0.55	0.87
Th	13.6	18.2	14.9	10.1		8.30	9.95	13.4
U	2.49	2.41	1.99	2.07			2.00	2.46
Pb	18.6	22.0	19.4	24.6			16.2	16.4
$(La/Yb)_N$	48.5	55.4	49.3	42.9	35.4	60.4	38.3	44.0
Eu/Eu*	0.93	0.97	0.96	0.97	0.88	0.91	0.93	0.96

and MgO and little change in Sr with decreasing MgO preclude the fractionation of plagioclase.

Trace elements

Trace element and rare earth element data are listed in Tables 1, 2, and 3. The southern Shandong group lavas possess much higher REE contents ($\sum$REE = 260–530 ppm) than those of northern group lavas ($\sum$REE = 82–140 ppm). In the chondrite-normalized REE pattern diagrams, both groups exhibit LREE enrichment. The southern group lavas are characterized by much higher LREE/HREE ratios ($(La/Yb)_N$ = 35–82) compared with the northern group lavas ($(La/Yb)_N$ = 8–10). Both the southern and northern group lavas display a poorly developed Eu anomaly with Eu/Eu^* ($Eu/Eu^* = Eu_N / \sqrt{[(Sm_N)\times(Gd_N)]}$) ranging from 0.84 to 0.97 for the southern and 0.91–1.18 for the northern. The REE patterns of the southern group are comparable to those of the Fangcheng basalts, whereas the REE patterns of the northern group are substantially different from those of Fangcheng basalts (Fig. 3).

In the Primitive mantle normalized diagrams (Fig. 4), both the southern and northern Shandong group lavas are enriched in large ion lithophile elements (LILE) such as Ba, Rb, K, and Pb coupled with depletion of high field strength elements (HSFE) especially for Nb, Ta, and Ti. These features are usually interpreted to characterize subduction- related rocks or collision-related rocks (Bri-

Table 2 Major element (wt.%) and trace element (ppm) data for mid-Cretaceous lavas from Shandong Province, China

Southern Shandong group		Northern Shandong group						
Locality (sample)	Mengyin	Laiwu		Zouping				
	My-8	My-9	ZWZ09	GJL03	GJL05	ZWZ08	WNS-1	WNS-2
SiO_2	55.9	58.4	57.5	56.7	59.5	50.9	53.6	53.5
TiO_2	1.09	0.73	0.63	0.56	0.69	0.66	0.89	0.71
Al_2O_3	15.2	15.6	16.4	14.4	16.1	16.6	15.7	13.9
Fe_2O_3	6.07	4.38	7.13	7.73	6.84	9.05	9.51	9.55
MnO	0.07	0.19	0.14	0.16	0.21	0.18	0.11	0.12
MgO	5.26	4.63	3.29	5.94	2.33	5.12	5.98	8.26
CaO	6.75	5.47	3.93	5.65	3.72	5.84	8.36	8.50
Na_2O	3.31	3.89	4.85	3.13	4.10	5.31	2.90	2.49
K_2O	3.32	3.96	2.83	2.37	3.44	0.90	1.53	1.69
P_2O_5	0.63	0.51	0.22	0.20	0.27	0.25	0.51	0.26
LOI	1.92	2.07	2.71	3.58	2.36	5.46	1.23	1.42
Total	99.54	99.82	99.62	100.0	99.63	100.3	99.92	99.90
Cr	252	207	57.8	291	26.8	47.8	155	368
Co	31.6	19.3	18.3	27.4	16.8	25.6	29.1	37.8
Ni	126	117	30.7	114	20.6	38.5	44.6	80.6
V	90.6	70.5	135	145	187	159	156	149
Rb	46.5	73.9	61.3	54.8	75.9	23.3	33.3	40
Sr	946	1103	562	510	541	548	682	452
Y	15.8	12.6	14.3	13.1	15.1	15.0	16.9	13.0
Zr	264	271	118	92.6	111	100	84.7	73.7
Nb	22.9	20.1	4.33	3.82	4.57	3.60	3.92	3.63
Cs	0.39	0.58	2.56	0.65	1.19	5.18	1.64	1.97
Ba	1071	1497	987	907	1137	444	847	591
La	101	90.8	24.2	21.2	25.2	24.6	20.3	12.1
Ce	181	157	44.4	40.1	49.6	46.0	43.2	25.5
Pr	21.7	19.3	5.60	4.90	6.30	5.90	5.60	3.30
Nd	78.4	70.4	23.1	21.1	26.4	24.7	26.6	15.7
Sm	11.4	10.2	3.90	3.80	4.60	4.20	5.10	3.40
Eu	2.95	2.67	1.31	1.16	1.40	1.54	1.56	0.99
Gd	8.47	7.43	3.41	3.30	3.78	3.69	4.44	3.22
Tb	0.87	0.73	0.50	0.48	0.54	0.55	0.60	0.45
Dy	3.82	3.11	2.78	2.62	3.01	2.98	3.28	2.61
Ho	0.66	0.50	0.52	0.49	0.55	0.56	0.66	0.54
Er	1.71	1.30	1.56	1.49	1.68	1.62	1.84	1.53
Tm	0.21	0.16	0.26	0.24	0.30	0.28	0.24	0.21
Yb	1.29	0.98	1.64	1.48	1.72	1.70	1.64	1.39
Lu	0.18	0.13	0.26	0.22	0.26	0.28	0.24	0.21
Hf	7.45	7.60	3.33	2.74	3.38	3.00	2.86	2.43
Ta	0.71	0.63	0.30	0.26	0.30	0.30	0.42	0.29
Th	13.2	14.5	4.16	4.61	5.41	6.42	2.10	1.93
U	2.24	2.09	0.98	1.15	1.42	0.99	0.62	0.61
Pb	17.8	23.7	22.7	19.5	26.2	24.2	4.96	3.62
$(La/Yb)_N$	54.2	64.4	10.2	9.9	10.2	10.0	8.6	6.0
Eu/Eu*	0.91	0.93	1.09	0.99	1.01	1.18	0.99	0.91

queu et al. 1984; Ringwood 1990; Schmidberger and Hegner 1999). Th and U are generally depleted in the northern group lavas but enriched in the southern group (Fig. 4). Like the REE patterns, the spidergrams of the southern group lavas are roughly coincident with those of Fangcheng basalts except for the prominent depletion of Rb and the generally higher heavy REE contents in the latter, and the northern group lavas present striking contrasts to the Fangcheng basalts.

Radiogenic isotopes

Sr–Nd isotope analyses are listed in Table 4 and plotted in Figure 5. The initial $^{143}Nd/^{144}Nd$ ratios of the southern Shandong group lavas are relatively uniform, whereas their Sr isotopes are heterogeneous. The lavas are characterized by extremely high Sr and low Nd isotope ratios ($^{143}Nd/^{144}Nd$ = 0.51164–0.51192; $^{87}Sr/^{86}Sr$ = 0.70891–0.71025). The northern Shandong group lavas also show uniform Nd and heterogeneous Sr isotope compositions and can be divided into two groups in terms of Sr isotopic ratios. The Zouping lavas have the lowest Sr and Nd isotopic ratios and the Laiwu have relatively higher $^{87}Sr/^{86}Sr$ ratios at given ε_{Nd} relative to Zouping. The leaching experiment indicates that there is little variation in isotopic ratios between leached and unleached samples (see Table 4), thus the secondary effect of alteration or weathering on isotopic compositions of samples can be ruled out.

Table 3 Major element (wt.%) and trace element (ppm) data for mid-Cretaceous lavas from Shandong Province, China

Locality (sample)	Northern Shandong group								
	Zouping								
	WNS-3	WNS-4	WNS-5	WNS-7	WNS-8	WNS-9	YQS-1	YQS-2	YQS-4
SiO_2	55.1	54.5	55.8	54.4	55.0	54.6	53.6	53.7	53.9
TiO_2	0.75	0.74	0.89	0.93	0.89	0.90	1.02	1.01	0.80
Al_2O_3	14.4	14.3	15.0	14.7	14.7	14.6	15.4	15.2	14.0
Fe_2O_3	8.90	9.87	8.08	9.17	8.28	8.56	9.77	9.79	9.14
MnO	0.12	0.11	0.08	0.11	0.11	0.12	0.12	0.11	0.11
MgO	6.99	6.79	5.92	6.34	6.50	6.67	5.54	5.58	7.49
CaO	8.12	8.03	7.38	7.40	7.43	7.22	7.81	7.43	8.40
Na_2O	2.78	2.55	3.20	2.95	2.92	3.01	3.24	2.77	2.66
K_2O	1.33	1.30	1.73	2.15	2.47	2.75	1.92	2.10	2.00
P_2O_5	0.31	0.27	0.46	0.48	0.43	0.43	0.50	0.48	0.38
LOI	1.32	1.98	1.73	1.76	1.05	1.58	1.29	1.86	1.47
Total	99.63	99.99	99.9	99.81	99.80	100.04	99.82	99.59	99.83
Cr	306	441	270	275	285	292	160	165	348
Co	27.6	37.9	25.0	37.9	28.7	29.9	29.8	29.2	32.7
Ni	89.6	89.4	71.9	75.5	80.9	88.0	38.9	38.2	84.2
V	143	143	125	148	137	149	159	154	140
Rb	28.1	30.4	33.2	49.2	47.0	54.1	26.9	35.9	45.1
Sr	535	531	574	603	552	548	654	601	611
Y	14.4	14.6	17.7	18.6	16.7	18.1	17.9	17.9	15.7
Zr	95.7	86.1	130	130	115	120	76.1	64.5	64.4
Nb	4.27	4.28	6.88	6.45	5.66	6.14	5.91	5.58	4.82
Cs	1.76	1.42	0.80	1.86	12.8	1.45	0.69	1.27	1.08
Ba	556	515	683	776	950	988	891	805	665
La	16.3	16.2	23.4	26.1	23.1	25.0	24.6	24.6	21.1
Ce	32.3	33.9	54.0	54.6	48.0	51.3	52.8	51.5	42.9
Pr	4.20	4.30	7.20	7.00	6.10	6.50	6.80	6.50	5.60
Nd	19.6	19.7	33.3	31.5	27.3	29.4	30.8	30.1	25.0
Sm	3.90	4.00	6.30	6.10	5.30	5.60	6.10	5.80	4.90
Eu	1.18	1.29	2.07	1.72	1.55	1.66	1.82	1.77	1.41
Gd	3.52	3.60	5.39	5.30	4.64	5.00	5.24	5.12	4.36
Tb	0.49	0.49	0.71	0.69	0.60	0.65	0.69	0.65	0.57
Dy	2.81	2.78	3.95	3.80	3.39	3.63	3.77	3.67	3.16
Ho	0.56	0.58	0.75	0.76	0.66	0.71	0.74	0.71	0.64
Er	1.64	1.67	2.10	2.10	1.89	2.04	2.06	2.01	1.72
Tm	0.21	0.21	0.27	0.27	0.24	0.25	0.27	0.25	0.23
Yb	1.49	1.46	1.77	1.83	1.59	1.73	1.71	1.68	1.55
Lu	0.21	0.22	0.25	0.28	0.24	0.26	0.26	0.25	0.23
Hf	3.07	2.74	4.07	4.05	3.63	3.84	2.54	2.19	2.20
Ta	0.27	0.29	0.36	0.34	0.34	0.38	0.30	0.29	0.27
Th	2.15	2.56	2.64	2.59	2.65	2.84	2.24	2.28	2.33
U	0.68	0.76	1.01	0.81	0.76	0.82	0.72	0.71	0.70
Pb	6.46	13.5	1.64	2.35	3.52	3.38	4.27	4.60	7.52
$(La/Yb)_N$	7.6	7.7	9.2	9.9	10.1	10.0	10.0	10.1	9.4
Eu/Eu*	0.97	1.03	1.07	0.92	0.95	0.95	0.98	0.99	0.93

All Fe expressed as Fe_2O_3, *LOI* loss on ignition *Refer to the data of Qiu et al. (1997)

Discussion

Crustal contamination

It is essential to test the influence by any crustal contamination during the magma ascent since the lavas were formed in continental settings. The extent of wall rock contamination in continental basalts is controversial and difficult to identify unless chemical compositions of both contaminant and magmatic source are independently known (Carlson and Hart 1988). Generally, the addition of crustal material to magmas is expected to result in a negative covariance of $^{87}Sr/^{86}Sr$ with parameters such as MgO and positive correlations with Rb/Sr and K_2O/P_2O_5(Carlson and Hart 1988), though these relationship may be complicated by assimilation–fractional crystallization and partial melting effects (DePaolao 1981).

Figure 6a and b shows that $(^{87}Sr/^{86}Sr)_i$ values of the Mengyin lavas of the southern Shandong group increase with decreasing MgO and increasing Rb/Sr ratios, suggesting that assimilation–fractional crystallization processes (AFC) is involved in the evolution of Mengyin lavas. In contrast, $(^{87}Sr/^{86}Sr)_i$ values of Pingyi lavas of the southern Shandong group and the northern Shandong group lavas vary only slightly over the range of MgO and Rb/Sr, precluding significant crustal contamination.

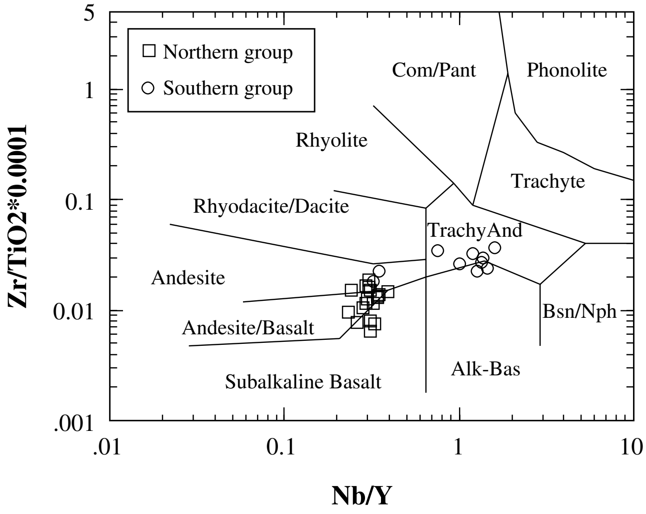

Fig. 2 Classification of mid-Cretaceous lavas of western Shandong based on immobile elements (according to Winchester and Floyd 1976)

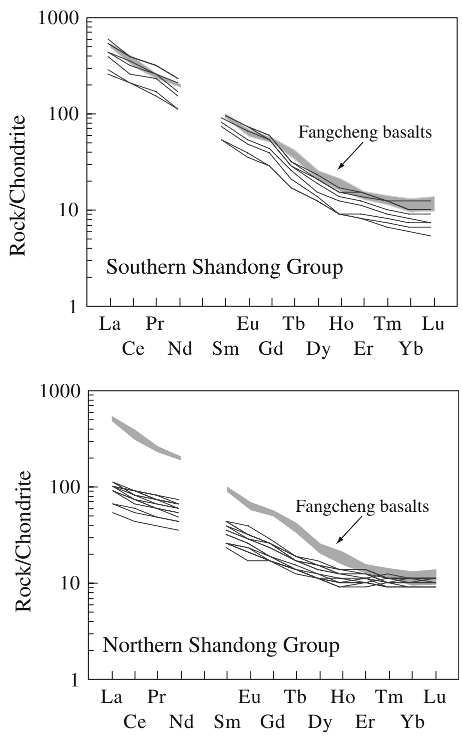

Fig. 3 Chondrite-normalized REE patterns of mid-Cretaceous lavas from western Shandong Province. The *shaded field* shows the REE pattern of Mesozoic Fangcheng basalts (Zhang et al. 2002b), Chondrite values are from Anders and Grevesse (1989)

It can also be observed from Fig. 6 that the least evolved sample (My-3) of the Mengyin lavas has an isotopic composition almost similar to those of Pingyin, thus it is reasonable to assume that the sample of Mengyin with the highest MgO content experienced the minimal contamination and preserved the original isotopic signatures.

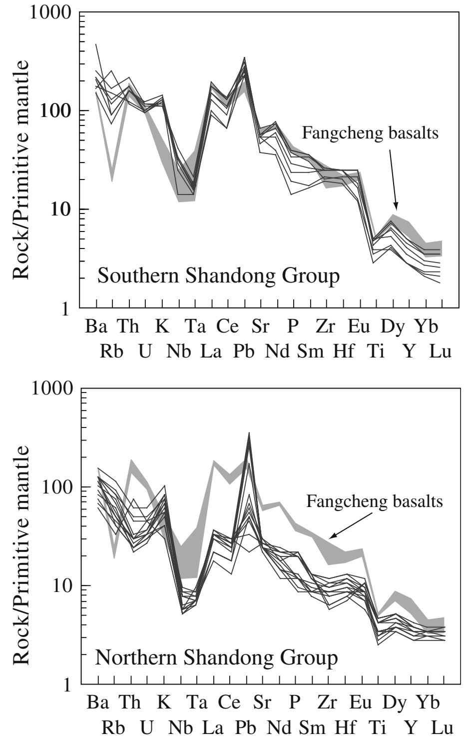

Fig. 4 Primitive mantle normalized trace element diagrams for mid-Cretaceous lavas from western Shandong Province. The *shaded field* shows the spidergram of Mesozoic Fangcheng basalts (Zhang et al. 2002b). The primitive mantle values are from Sun and McDonough (1989)

Southern Shandong group

A remarkable feature of the southern Shandong group lavas is that all of them show highly LILE and LREE enrichment and significant depletion of HFSE as well as EMII-like Sr–Nd isotopic compositions, almost the same as the Mesozoic Fangcheng basalts (Zhang et al. 2002b). As discussed above, most samples of the southern Shandong group except some of Mengyin escaped crustal contamination during ascent, thus their geochemical and isotopic features were inherited from their source region.

It is generally accepted that the depletion of Nb, Ta, and Ti and enrichment of LILE are common features of lavas of active continental margin and suggest that the mantle source had been contaminated by continental crust (Briqueu et al. 1984; Ringwood 1990). The Ba/Nb ratio of active continental margin magmatism is usually greater than 28 (Fitton et al. 1988), the high Ba/Nb ratios of the southern Shandong group lavas ranging between 45 and 120, well exceed 28, also suggesting that the southern Shandong group lavas are products of subduction related magmatism.

The westward subduction of Izanagi plates beneath eastern Eurasia was widely used to interpret the Mesozoic volcanic activity in eastern China including those from the Shandong Province (Wu 1984). However,

Table 4 Sr and Nd isotope data for mid-Cretaceous lavas from western Shandong Province, China

	Locality	Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$	$(^{87}Sr/^{86}Sr)_i$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm 2\sigma$	$(^{143}Nd/^{144}Nd)_i$	ε Nd(t)	ε Sr(t)
Southern Shandong group	Pingyi	Py-1	0.1545	0.709492 ± 22	0.709229	0.0903	0.511890 ± 9	0.511817	−13.0	69.2
		Py-1[a]	0.0991	0.709589 ± 10	0.709420	0.1175	0.511924 ± 8	0.511831	−12.7	71.9
		Py-2	0.1738	0.709940 ± 9	0.709644	0.0859	0.511767 ± 9	0.511699	−15.3	75.1
		Py-3	0.2107	0.710634 ± 10	0.710275	0.0884	0.511910 ± 13	0.511841	−12.5	84.0
		Py-4	0.2421	0.709324 ± 16	0.708911	0.0883	0.511969 ± 10	0.511900	−11.4	64.7
		Py-4[a]	0.2199	0.709411 ± 9	0.709036	0.1030	0.512009 ± 8	0.511928	−10.8	66.5
	Mengyin	My-1	0.5692	0.712988 ± 9	0.712017	0.0892	0.511740 ± 8	0.511670	−15.9	108.8
		My-1[a]	0.4581	0.712674 ± 9	0.711893	0.1048	0.511726 ± 9	0.511644	−16.4	107.0
		My-3	0.1191	0.710194 ± 14	0.709991	0.0881	0.511811 ± 6	0.511742	−14.5	80.0
		My-3[a]	0.1550	0.710418 ± 10	0.710154	0.1093	0.511844 ± 8	0.511758	−14.2	82.3
		My-8	0.1638	0.710925 ± 17	0.710646	0.0859	0.511774 ± 11	0.511707	−15.2	89.3
		My-8[a]	0.1338	0.710911 ± 10	0.710683	0.1099	0.511778 ± 10	0.511692	−15.5	89.8
		My-9	0.1977	0.711788 ± 15	0.711451	0.0929	0.511766 ± 11	0.511693	−15.4	100.7
		My-9[a]	0.1436	0.711830 ± 10	0.711585	0.0770	0.511724 ± 9	0.511663	−16.0	102.6
Northern Shandong group	Laiwu	GJL05	0.3891	0.708669 ± 8	0.708005	0.1174	0.511809 ± 13	0.511717	−15.0	51.8
		GJL05[a]	0.3543	0.708695 ± 9	0.708091	0.1156	0.511805 ± 10	0.511714	−15.0	53.0
		ZWZ08	0.1265	0.707769 ± 12	0.707553	0.1173	0.511790 ± 14	0.511698	−15.3	45.4
		ZWZ08[a]	0.1101	0.707863 ± 9	0.707675	0.1174	0.511754 ± 8	0.511662	−16.0	47.1
		ZWZ09	0.3538	0.708144 ± 7	0.707541	0.1449	0.511866 ± 6	0.511752	−14.3	45.2
		ZWZ09[a]	0.2960	0.708171 ± 8	0.707666	0.1145	0.511836 ± 9	0.511746	−14.4	47.0
	Zouping	WNS-1	0.1374	0.704397 ± 10	0.704163	0.1219	0.511706 ± 10	0.511610	−17.0	−2.7
		WNS-2	0.2500	0.704649 ± 9	0.704223	0.1337	0.511984 ± 18	0.511879	−11.8	−1.9
		WNS-3	0.1459	0.705042 ± 19	0.704793	0.1265	0.511862 ± 8	0.511763	−14.1	6.2
		WNS-4	0.1493	0.704538 ± 8	0.704283	0.1272	0.511982 ± 11	0.511882	−11.7	−1.0
		WNS-5	0.1970	0.704948 ± 11	0.704612	0.1185	0.511754 ± 6	0.511661	−16.1	3.6
		WNS-7	0.2300	0.704704 ± 17	0.704312	0.1206	0.511762 ± 4	0.511667	−15.9	−0.6
		YQS-1	0.1208	0.704181 ± 15	0.703975	0.1210	0.511807 ± 10	0.511712	−15.1	−5.4
		YQS-2	0.1711	0.704444 ± 11	0.704152	0.1205	0.511751 ± 9	0.511656	−16.1	−2.9

Initial ratios are calculated assuming an age of 120 Ma for all lavas. *Epsilon value* are calculated using present-day ratios of $^{147}Sm/^{144}Nd = 0.1967$, $^{143}Nd/^{144}Nd = 0.512638$, $^{87}Rb/^{86}Sr = 0.0847$, and $^{87}Sr/^{86}Sr = 0.7045$ for CHUR [a] Determined after acid leaching

during the early Cretaceous, western Shandong was too far from the subduction zone of the Paleo-Pacific plate (> 1000 km). In addition, geophysical data from paleomagnetic evidence had indicated that the western-dipping subduction of Izanagi plate toward eastern China occurred no earlier than the late Cretaceous (Engebretson et al. 1985), thus the southern Shandong group lavas (mid-Cretaceous) appears to be unrelated to such kind of plate subduction.

Since the southern Shandong group lavas and the Fangcheng basalts share similar geochemical and isotopic features, it is necessary to discuss the Fangcheng basalts firstly. Fangcheng basalts occurred in the same basin as Pingyi lavas, however, Fangcheng basalts is a little older (125 Ma) than the Pingyi lavas (120 Ma) and stratigraphically lower than Pingyi lavas. So the Fangcheng basalts and southern Shandong group lavas belong to different volcanic sequences. Based on detailed studies of the Fangcheng basalts, Zhang et al. (2002b) proposed that Fangcheng basalts originated from the Mesozoic enriched mantle, such enriched Mesozoic lithospheric mantle shows significant contrast with the Paleozoic and Cenozoic lithospheric mantle represented by Paleozoic kimberlites and Cenozoic basalts, respectively. The enriched Mesozoic mantle cannot simply inherit from its Paleozoic counterpart and was evolved from Paleozoic through extensive interaction with melts derived from the lower crust of YC which was subducted beneath NCC during the Triassic continent–continent collision of YC with NCC. Extensive peridotite–melt interaction resulted on the one hand in the LILE, LREE-enriched and HFSE-depleted geochemical and

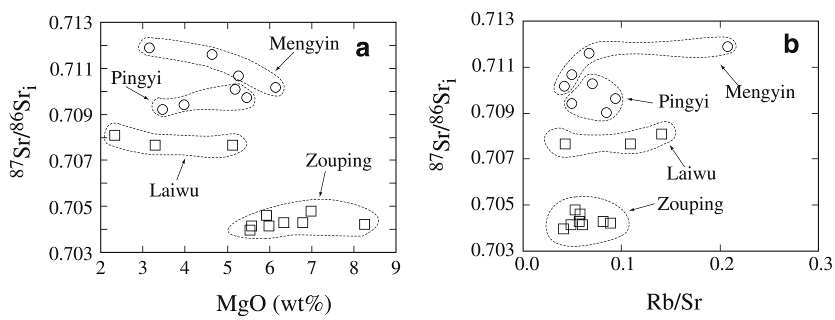

Fig. 5 Plot of wt.% MgO versus $(^{87}Sr/^{86}Sr)_i$ (**a**) and Rb/Sr versus $(^{87}Sr/^{86}Sr)_i$ (**b**) for the studied lavas. Note no significant variation of $(^{87}Sr/^{86}Sr)_i$ values observed for samples except those of Mengyin of southern Shandong group over a range of MgO and Rb/Sr ratios

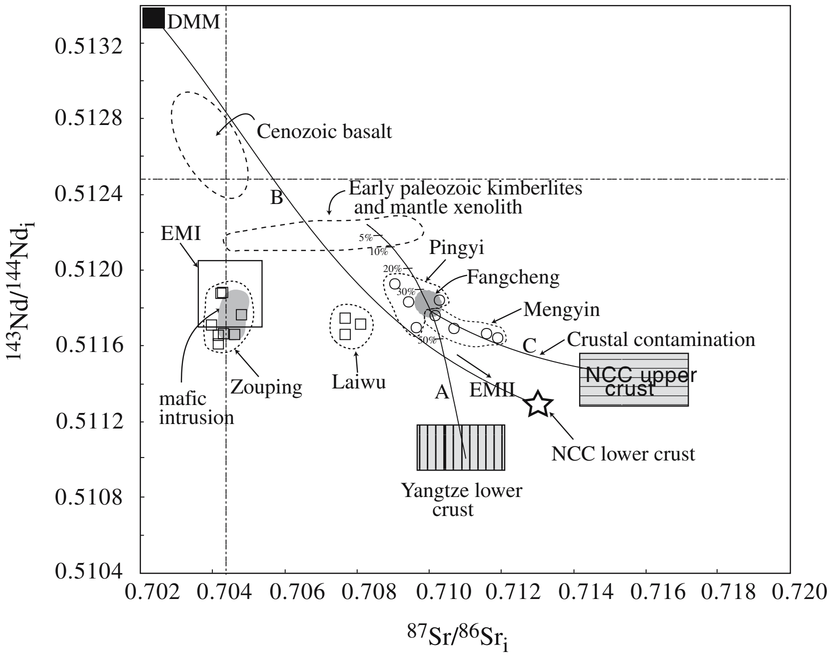

Fig. 6 $(^{87}Sr/^{86}Sr)_i$ versus $(^{143}Nd/^{144}Nd)_i$ diagram of mid-Cretaceous lavas from western Shandong Province. Initial Sr and Nd isotopic ratios were calculated to 120 Ma, also shown are Paleozoic Mengyin kimberlites and their borne mantle peridotites and Cenozoic basalts of eastern China. Initial Sr and Nd isotopic ratios for Mengyin kimberlites were recalculated to 120 Ma. Data of kimberlites and their borne mantle peridotite and Cenzoic basalts are from Zhang et al. (2002b) and references therein. Mesozoic Fangcheng basalts are from Zhang et al. (2002b). Zouping mafic intrusions are from Guo et al. (2001). Yangtze lower crust and NCC upper crust are from Jahn et al. (1999). The *white star* represents the lower crust composition of NCC based on the isotopic data of a granulite from the exposed granulite terrain near Hannuoba (Zhou et al. 2002). *A* refers to the mixing between the Paleozoic lithospheric mantle and subducted Yangtze lower crust. The mixing of the Paleozoic mantle with 30–40% lower crust can produce the southern Shandong group lavas. *B* is the mixing of DMM with NCC lower crust, such kind of mixing cannot account for the formation of the northern Shandong group lavas. *C* is the mixing trend of the southern Shandong group lavas with NCC upper crust, which can explain some of crustal contaminated Mengyin samples. The mixing parameters used are Yangtze lower crust, Sr = 300 ppm, Nd = 20 ppm, $^{87}Sr/^{86}Sr = 0.711$, $^{143}Nd/^{144}Nd = 0.5110$; Kimberlite-borne mantle peridotites, Sr = 95 ppm, Nd = 21 ppm, $^{87}Sr/^{86}Sr = 0.7085$, $^{143}Nd/^{144}Nd = 0.51225$; NCC lower crust, Sr = 477 ppm, Nd = 8 ppm, $^{87}Sr/^{86}Sr = 0.712$, $^{143}Nd/^{144}Nd = 0.511148$. The DMM, EMI and EMII values are from Zindler and Hart (1986)

EMII-like Sr–Nd isotopic features, and on the other hand in the formation of significant amount of pyroxenites veins in the mantle. The abundant pyroxenite xenoliths in the Fangcheng basalts are consistent with such kind of peridotite–melt interaction.

Taking into consideration the strong resemblance of geochemical and isotopic characteristics and the closely spatial and temporal relationship between the southern Shandong group lavas and the Fangcheng basalts, it is reasonable to infer that the mantle source of the southern Shandong group lavas is geochemically similar to that of Fangcheng basalts and may have experienced the same evolutionary processes. A simple mass balance calculation was adopted to model the observed Sr–Nd isotopic features of the southern Shandong group lavas (Fig. 5). The calculation shows that injection of about 30% of Yangtze lower crustal material into the mantle would effectively modify the old lithospheric mantle and produce the extremely high Sr and low Nd isotopic ratios owned by the southern Shandong group lavas. In so far as the crustal contaminated samples of Mengyin during ascent are concerned, the potential contaminant would be the NCC upper crust (Fig. 5).

Northern Shandong group

The northern Shandong group lavas also show LILE, LREE enrichment and HFSE depletion, although the enrichment is mild relative to those of the southern Shandong group. In the Sr–Nd diagram, the northern Shandong group lavas have low Sr and Nd isotopic ratios, showing EMI-like signature rather than the EMII affinity possessed by the southern Shandong group. The fact that Sr isotopic ratios change slightly with MgO indicates that the crustal contamination during ascent is negligible, in addition, the depletion of Th and U in the northern Shandong group lavas was also inconsistent with the contamination of upper crust, thus their geochemical and isotopic characteristics were mainly determined by source characteristics and partial melting processes.

Given the northern Shandong group lavas originated from asthenosphere with depleted Sr–Nd isotopic signatures and the mixing of asthenosphere-derived magmas with lower crust of NCC in the source produced the observed Sr–Nd isotopic ratios of northern Shandong group lavas. The lower crust of the NCC was estimated

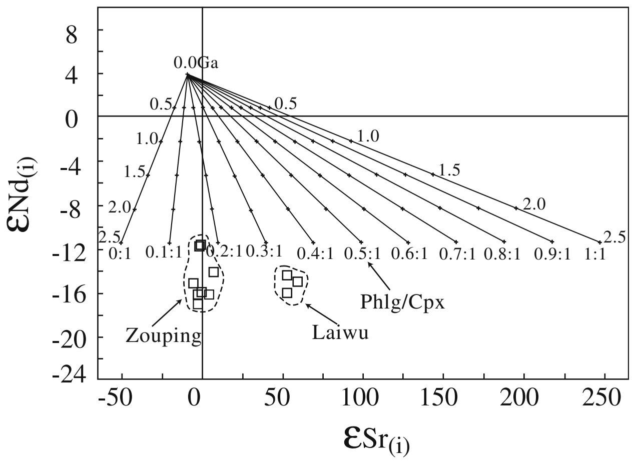

Fig. 7 ε Sr (i) vs. ε Nd (i) as an indicator of Sr and Nd isotopic evolution corresponding to modal proportion of phlogopite and clinopyroxene (according to Schmidt et al. 1999). The mantle source for the northern Shandong group lavas are characterized by low ratios of phlogopite and clinopyroxene

to be highly variable in Sr and Nd isotope through the studies of Archean granulite-faceis rocks, which were considered to stand for the lower crust composition (Jahn and Zhang 1984). Here, we take the Archean granulite terrain of Hannuoba as representative NCC lower crust, which has $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of 0.712 and 0.511148, respectively (Zhou et al. 2002). Obviously, the mixing of asthenosphere-derived magmas with lower crust of NCC cannot produce the north Shandong group lavas (line B in Fig. 5).

Alternatively, if the north Shandong group lavas originated from the Mesozoic lithospheric mantle and the mantle during the Mesozoic was similar to that in the early Paleozoic, then the primitive magma should share the initial Sr and Nd isotopic compositions as the Ordovician kimberlites (Chi et al. 1992). The mixing of such kind of primitive magma with the lower crust of NCC also is unlikely to generate the observed isotopic composition of the northern Shandong group lavas.

The highly negative HFSE anomalies and ε Nd(t) of the north Shandong group lavas required a long-term LREE enrichment relative to HFSE before magma formation. The possible mechanism may be related with carbonatitic metasomatism because the carbonatitic melts are enriched in LREE and depleted in HFSE (Woolley and Kempe 1989; Ionov 1988). The relatively low initial Sr isotopic ratios in north Shandong group lavas are also consistent with carbonatitic metasomatism due to the low Rb/Sr ratio in carbonatitic melts (Bell and Blenkinsop 1989).

In a metasomatized mantle, phlogopite, amphibole and clinopyroxene are thought to control the Sr, Nd isotopic evolution (Schmidt et al. 1999). For example, radiogenic Sr isotope is mainly determined by phlogopite while clinopyroxene is responsible for the evolution of the Nd isotope since the low partition coefficients for Sm and Nd in Phlogopite make its influence negligible (Schmidt et al. 1999). Different modal proportions of phlogopite and clinopyroxene in peridotite would result in distinct ε Sr and ε Nd values after a long-term undisturbed evolution (Fig. 7).

There are some almost coeval mafic intrusive complexes (namely Zouping intrusion and Jinan intrusion) in the same region where the northern Shandong group lavas are distributed (Guo et al. 2001). Based on the investigation of these mafic intrusions, it was deduced that the Mesozoic lithospheric mantle beneath NCC was mainly composed of phlogopite-bearing garnet harzburgites. The partition coefficients of Rb, Sr, Sm, and Nd between the major phases of mantle peridotites such as olivine, orthopyroxene and garnet and melt are very low than those of phlogopite and clinopyroxene (Kennedy et al. 1993). So the contribution of olivine, orthopyroxene and garnet to Sr and Nd in the mantle reservoir can be negligible. The Sr and Nd isotopic compositions imply that the modal proportion of phlogopite/clinopyroxene in the mantle source of north Shandong group lavas range from 0.15:1 for Zhouping to 0.3:1 for Laiwu (Fig. 7).

Tectonic implications

The different geochemical characteristics of the southern Shandong group lavas and the northern Shandong group lavas imply that the Mesozoic lithospheric mantle of NCC is heterogeneous. We propose that such heterogeneous Mesozoic mantle resulted from different tectonic evolutions of the different parts of NCC. The Mesozoic lithosphere was undoubtedly evolved from the Paleozoic lithosphere, thus it should have inherited some Paleozoic lithosphere signatures. The northern Shandong group lavas are characterized by EMI-like Sr and Nd isotopic features, suggesting that their mantle source retained characteristics of the old lithospheric mantle, with some kind of modification. The studies on the northern Shandong group lavas and nearby mafic intrusions suggest that carbonatitic metasomatism and the changing of phlogopite/clinopyroxene modal proportion in mantle source result in the transformation of the mantle from Paleozoic to Mesozoic. In contrast, the southern Shandong group lavas have much higher Sr and lower Nd isotopic composition than those of the Paleozoic mantle, indicating that the Mesozoic mantle beneath the south part of NCC was modified severely by the addition of a significant amount of crust-derived silicic melts, which required an early subduction processes to bring the crust to the mantle. We envisage that the early subduction is the Triassic collision of YC with NCC. The collision of the YC with the NCC at ~220 Ma introduced the Yangtze lithosphere into the mantle beneath the south part of the NCC, the upper crust of the Yangtze lithosphere failed to reach the deeper mantle because of its buoyancy (Ye et al. 2000) and moved upward rapidly with slab break-off, forming the UHP metamorphic belt of Dabie mountain. With the subduction switched to a highly compressional mode (Chemenda et al. 2000), the residual lower crust of the YC began to detached from the lithospheric mantle and underplated beneath the base of the NCC lithosphere due to its buoyancy relative to the surrounding mantle. Subsequently, the silicic melt produced by partial melting of these crustal materials infiltrated the overriding lithosphere and interacted with the mantle peridotites. Extensive interaction would have completely modified the old lithosphere, and generated the Sr–Nd isotopic enriched Mesozoic lithosphere that was the source of the southern Shandong group lavas. Geophysical data by seismological chromatography also revealed the slab-like high-speed anomaly in the mantle beneath the southern part of the NCC, which might be the residue of the partially melted lower crust (Xu et al. 2001).

Conclusions

The widely distributed mid-Cretaceous lavas in western Shandong Province can generally be divided into southern and northern Shandong groups based on their distinctive geochemistry. The southern group is strongly enriched in LREE and LILE, and depleted in HFSE and show EMII-like Sr–Nd isotopic compositions, suggesting they were originated from an enriched Mesozoic lithospheric mantle which was evolved from its Paleozoic counterpart through extensive interaction with crust-derived melts. The melts were generated from partial melting of subducted lower crust of the YC during the continent–continent collision of the NCC with the former. The northern group lavas are enriched in LREE and LILE and mildly depleted in HFSE relative to the southern group. They are quite different from the southern group with their EMI-like Sr and Nd isotopic compositions. Rather than being the product of a subduction-related magmatism, the formation of the northern Shandong group lavas are thought to have originated from a carbonatitic metasomatized mantle with changed modal proportion of phlogopite and clinopyroxene.

Acknowledgements This work was financially supported by Ministry of Science and Technology, China (G199075504) and Chinese Academy of Sciences (KZCX1-07). We are grateful to Liang Bangqi and Du Benming from Shandong Bureau of Geology and Mineral Resources for their help in fieldwork. Li He, Zhu Heping and Li Chaofeng are appreciated for their assistance in arranging geochemical analysis. Constructive reviews by Dr. Worthington TJ and Duggen S are acknowledged.

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