Geochemical and Sr–Nd–Pb isotopic compositions of mafic dikes from the Jiaodong Peninsula, China: evidence for vein-plus-peridotite melting in the lithospheric mantle

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Abstract

Major and trace elements and Sr–Nd–Pb isotope data are reported for Cretaceous mafic dikes from the Jiaodong Peninsula, eastern China. These dikes range from medium-K and high-K calc-alkaline to shoshonitic or ultrapotassic rocks, which are characterized by high MgO ($Mg^\# = 71–53$) and Cr (177–1012 ppm) and low TiO_2 (0.55–0.90 wt.%), total Fe_2O_3 (5.12–9.48 wt.%) and CaO (4.99–9.94 wt.%). Overall, they are enriched in the large ion lithophile elements (LILE, e.g., Rb, Ba, Sr) and light rare earth elements (LREE), depleted in the high field strength elements (HFSE, e.g., Nb, Ti, P), and possess uniform initial $^{87}Sr/^{86}Sr$ (0.7094–0.7114) but relatively wide ranges of Nd [$\epsilon_{Nd}(T) = -10.1–-17.0$] and Pb ($^{206}Pb/^{204}Pb = 16.75–18.03$) isotopic ratios, implying a magma origin from enriched but heterogeneous mantle sources. These geochemical and isotopic characteristics can be explained by the vein-plus-peridotite melting model, with amphibole- or phlogopite-bearing pyroxenite veins that reside in refractory lithospheric mantle beneath the North China Block. Such a vein-enriched mantle source formed by multiple metasomatic events, which we infer to have resulted from subduction-related processes that may have occurred in the Late Archean and Mesoproterozoic. The mafic dikes constitute a member of the widespread Mesozoic magmas emplaced in the North China Block as a result of regional lithospheric extension.

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1. Introduction

The North and South China Blocks are generally believed to have collided in Triassic time as man-

ifested by the exhumation of ultrahigh-pressure metamorphic (UHPM) rocks within the Qinling–Dabie–Sulu orogenic belt, the largest expanse of UHPM rocks in the world (cf. Cong, 1996). Studies of mantle xenoliths captured by Ordovician kimberlites and Cenozoic alkaline basalts suggested that beneath the North China Block (NCB) a large part of the ancient, refractory lithospheric mantle (>120 km) has been

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removed and replaced by young and more fertile mantle materials (Menzies et al., 1993; Menzies and Xu, 1998; Griffin et al., 1998; Xu, 2001; Gao et al., 2002), via regional postcollisional tectonomagmatic event(s) that occurred most likely in the Mesozoic (Li et al., 1998; Jahn et al., 1999; Fan et al., 2001).

Mafic dike swarms are a common expression of mantle-derived magma generation that is associated with extensional tectonics postdating continental collisions (e.g., Rock, 1991). The mafic dikes, in this circumstance, provide important information for understanding not only magmatic genesis from the mantle but also tectonic evolution in the orogenic belts. In the Jiaodong Peninsula, which is located in the southeastern margin of the NCB (Fig. 1), mafic dikes are widespread and marked by extensive Early Cretaceous gold mineralization (e.g., Wang et al., 1998; Yang and Zhou, 2001; Zhang et al., 2003). In this paper, we report new results of K–Ar age, major and trace elements, and Sr–Nd–Pb isotope compositions for the Jiaodong mafic dikes (JMD) in the hope: (1) to document the geochemical characteristics of these rocks, (2) to address their magma source(s) and petrogenesis, (3) to discuss the evolution of lithospheric mantle domains beneath North China, and (4) to explore implications for postcollisional tectonic history in the region.

2. Geological background

The Jiaodong Peninsula (Fig. 1) is located to the east of the Tanlu fault and made of two different terrains bounded by the Wulian–Mishan fault (Zhai et al., 2000), namely, the Jiaobei terrain and Sulu orogenic belt. The Sulu region represents an exhumed UHPM complex of the Yangtze Block (YB) (Ernst and Liou, 1995; Hacker et al., 1996, 1998; Li et al., 1999), which had been underthrust northward beneath the NCB to as deep as >200 km (Xu et al., 1992; Ye et al., 2000). The identification of coesite- and diamond-bearing eclogites within the Sulu region (Jahn et al., 1996; Ye et al., 2000) led many workers to propose that the Tanlu Fault displaced left-laterally in the Cretaceous and transferred the Sulu region from Qinling–Dabie region for ~ 500 km (e.g., Xu et al., 1987; Okay and Sengör, 1992). The Jiaobei terrain consists of Precambrian basement rocks (Zhai et al., 2000), in which Mesozoic granites (Wang et al., 1998), bimodal volcanic rocks (Fan et al., 2001) and mafic dikes are exposed. The Mesozoic magmas are associated with the largest gold deposit in China (Wang et al., 1998; Yang and Zhou, 2001; Qiu et al., 2002).

The Precambrian basement is mainly composed of the late Archean Jiaodong Group, which contains volcanic and sedimentary sequences that have been

Fig. 1. Simplified geologic map of the Jiaodong Peninsula showing the sample localities and gold deposits. Inset shows regional tectonic environment of the North China Block and the location of the Jiaodong Peninsula.

metamorphosed into amphibolite to granulite facies. SHRIMP U–Pb dating of zircon indicates that the protolith of the amphibolite was formed at 2530 ± 17 Ma and underwent metamorphism at 1852 ± 37 Ma. (Zhang et al., 2003). The Mesozoic plutonic rocks, which intruded the basement, have been divided based on petrography, geochemistry and isotopic composition into three major suites, namely, Linglong, Guojialing and Kunyushan (Qiu et al., 2002). The Linglong and Kunyushan suites consist of medium-grained met-aluminous to slightly peraluminous biotite–granite, and the Guojialing suite of porphyritic hornblende-biotite granodiorite with large K-feldspar phenocrysts. Their emplacement ages are 160–156 Ma for the Linglong suit (Wang et al., 1998; Zhang et al., 2003), 135–130 Ma for the Kunyushan suit (Zhang et al., 1995) and 130–126 Ma for the Guojialing suit (Wang et al., 1998; Zhang et al., 2003). Contemporaneous volcanism occurred along the Sulu UHP metamorphic belt, mainly in the Laiyang basin (Fig. 1), marked by bimodal compositions (Fan et al., 2001). Fan et al. (2001) proposed that the postcollisional bimodal volcanism was derived from an enriched lithospheric mantle, which might have undergone a fluid-related metasomatism by the subducted YB continent in the Triassic. The thickness of the volcanic sequences varies from several thousands to tens of meters, decreasing from the center to margin of the Basin, whose formation has been interpreted as related to extensional tectonism (Xu et al., 1987; Wang et al., 1998). Thus, the magma generation and associated gold mineralization are ascribed to thermal perturbation affiliated with lithospheric extension owing to large-scale displacement along the Tanlu fault system during late Mesozoic time.

Two main phases of deformation that took place during the Mesozoic are identified in the Jiaodong Peninsula (Wang et al., 1998). The first phase was characterized by northwest–southeast compression that is manifested by prominent northeast-trending brittle–ductile shear zones showing sinistral slip movements. The second phase involved the development of NNE- and NE-trending extensional brittle structures, accompanied by widespread intrusions of dikes and hydrothermal gold mineralization (e.g., Wang et al., 1998; Yang and Zhou, 2001; Zhang et al., 2003). Most of the mafic dikes occur as swarms that strike NE $20\text{--}40^\circ$ and NNE $60\text{--}80^\circ$ with steep dip angles (about E or

W $60\text{--}80^\circ$), and range from 0.2×70 to 1×1500 m² in dimension. They are generally undeformed and show little sign of metamorphism.

3. Samples and petrography

Samples for this study, comprising dolerite, hornblende dolerite and lamprophyre (minette), were collected from mine shafts near the Xincheng, Linglong and Mouping areas. All samples were collected far away from the gold lodes to avoid the effect of later hydrothermal activity. They show holocrystalline, ophitic and/or porphyritic-seriate textures, with phenocryst contents of 10–30%. The phenocrysts consist dominantly of clinopyroxene with subordinate plagioclase in the dolerites and phlogopite with minor orthopyroxene in the minettes. Olivine, hornblende, biotite and Ti-magnetite appear in the matrix of the dolerites and are always subordinate to plagioclase and clinopyroxene. In contrast, opaque minerals are rare in more basic dikes. Sporadic orthopyroxene, as a microphe-nocryst phase, is present. The mineral assemblage of the groundmass is similar to that of the phenocrysts but has a higher population of opaque minerals. Petro-graphic examinations show that even highly porphy-ritic rocks do not have cumulate textures, so that the samples can be used to reflect magma compositions.

Some of the dolerites contain visible carbonate veins and display alteration features such as chloritization along the rims of primary phenocrysts. Olivine and orthopyroxene are often partially replaced by green or brown phyllosilicates. Plagioclase is usually slightly sericitized but totally replaced by sericite, saussurite and chlorite in seriously altered dikes, the latter were excluded from this study. Clinopyroxene that is generally fresh is replaced by chlorite in some altered

Table 1
Whole rock K–Ar dates for mafic dikes from the Jiaodong Peninsula

Sample no.	K (%)	⁴⁰ Ar _{rad} (mol/g)	⁴⁰ Ar _{rad} (%)	Age (Ma)	1σ (Ma)
XC-M02	1.91	4.391e–10	97.19	127.9	2.4
JQ-M02	1.82	4.003e–10	93.43	122.6	2.4
LL-M06	2.01	4.469e–10	92.17	123.9	2.5
DK-M04	1.18	2.815e–10	93.14	132.5	2.6
MP-M06	3.02	6.496e–10	97.81	120.0	1.1

Table 2

Major (wt.%) and trace (ppm) element, and Sr–Nd–Pb isotopic data of mafic dikes from Jiaodong Peninsula, eastern China

	XC-M01	XC-M02	XC-M04	XC-M09	DK-M04	DK-M07	JQ-M02	JQ-M03	LL-M02	LL-M06
Rock type	Qz dolerite	Qz dolerite	Qz dolerite	Qz dolerite	Dolerite	Dolerite	Dolerite	Dolerite	Hb dolerite	Dolerite
Locality	Xincheng	Xincheng	Xincheng	Xincheng	Linglong	Linglong	Linglong	Linglong	Linglong	Linglong
SiO ₂	56.59	57.85	58.50	57.33	44.08	51.75	48.15	49.15	53.17	46.26
TiO ₂	0.63	0.65	0.62	0.66	0.76	0.82	0.86	0.90	0.77	0.80
Al ₂ O ₃	12.47	12.58	14.78	13.30	13.28	14.92	14.14	15.36	14.81	13.52
Fe ₂ O ₃	6.96	6.92	5.12	6.63	8.10	6.83	9.32	9.48	5.72	8.19
MnO	0.18	0.20	0.10	0.15	0.24	0.12	0.17	0.16	0.12	0.18
MgO	8.51	8.19	4.33	8.69	9.35	6.50	10.23	7.33	4.42	8.85
CaO	5.89	5.32	4.99	5.66	8.86	6.80	8.84	8.78	5.19	8.26
Na ₂ O	2.95	2.73	3.69	2.80	1.72	2.84	1.71	2.50	4.01	1.95
K ₂ O	2.20	2.40	2.97	2.22	1.20	2.18	1.36	1.53	2.75	2.53
P ₂ O ₅	0.19	0.18	0.25	0.18	0.35	0.29	0.15	0.15	0.34	0.37
LOI	3.49	2.96	4.43	2.21	12.03	7.01	5.31	4.34	9.38	9.24
SUM	100.06	99.98	99.78	99.83	99.97	100.06	100.24	99.68	100.48	100.15
Mg# ^a	70.97	70.29	62.85	72.39	69.76	65.55	68.71	60.73	60.72	68.35
Cr	771	855	302	1012	358	265	556	201	177	486
Co	41	42	28	41	48	28	37	48	23	37
Rb	138	165	88	82	44	50	42	56	82	66
Sr	1071	1044	1517	1097	880	958	781	1023	1070	1079
Y	18	17	17	20	17	17	17	20	15	20
Zr	212	201	301	200	140	143	137	140	212	167
Nb	16	16	12	17	7.1	10	6.2	5.8	13	10
Cs	5.6	6.1	3.1	3.1	1.4	0.6	2.0	3.5	2.2	2.4
Ba	762	767	4381	1381	1479	1486	893	1094	2601	1866
La	26.3	29.9	74.6	37.7	57.7	44.6	24.1	35.7	82.5	48.7
Ce	50.2	51.5	143	76.2	118	93.6	51.3	76.0	157	99.8
Pr	5.87	5.59	16.2	8.55	13.7	10.8	5.84	8.92	16.7	11.5
Nd	23.5	23.9	58.6	31.7	49.9	38.7	23.2	35.8	57.4	45.6
Sm	5.05	4.46	8.74	6.01	8.03	6.87	3.93	6.56	8.27	7.84
Eu	1.49	1.59	3.22	2.24	2.66	2.42	1.62	2.16	2.77	2.73
Gd	5.26	5.02	7.41	6.36	7.32	6.39	4.37	6.09	7.38	7.10
Tb	0.61	0.59	0.78	0.76	0.78	0.81	0.60	0.80	0.68	0.83
Dy	3.31	3.26	3.45	4.12	3.64	3.70	2.88	4.29	3.26	3.85
Ho	0.65	0.64	0.65	0.76	0.68	0.72	0.73	0.84	0.55	0.74
Er	1.91	1.97	1.82	2.14	1.84	1.80	1.85	2.30	1.48	2.05
Tm	0.24	0.31	0.26	0.28	0.24	0.32	0.27	0.32	0.19	0.27
Yb	1.66	1.75	1.42	2.01	1.56	1.44	1.53	1.56	1.26	1.90
Lu	0.26	0.25	0.21	0.27	0.23	0.25	0.23	0.27	0.18	0.27
Hf	5.55	5.00	7.16	5.61	3.05	3.50	3.58	3.14	4.76	3.99
Ta	2.91	1.25	1.68	3.38	2.32	1.88	2.31	2.38	1.72	4.74
Pb	1.6	1.9	23.7	24.2	19.0	–	–	1.8	85.7	4.2

Th	9.1	9.4	13.6	12.5	7.0	6.2	3.5	3.9	13.5	7.5
U	3.1	2.6	3.0	3.2	1.3	1.1	0.7	0.8	3.0	1.4
²⁰⁶ Pb/ ²⁰⁴ Pb	18.026	17.735	17.483	18.001	17.367	17.176	17.300	17.281	17.063	17.439
²⁰⁷ Pb/ ²⁰⁴ Pb	15.531	15.300	15.444	15.372	15.534	15.443	15.489	15.472	15.287	15.496
²⁰⁸ Pb/ ²⁰⁴ Pb	38.402	37.734	37.989	37.845	37.991	37.717	37.971	37.847	37.297	37.953
⁸⁷ Rb/ ⁸⁶ Sr	0.3635	0.4563	0.1741	0.2186	0.2128	0.1428	0.1453	0.1452	0.2217	0.1590
⁸⁷ Sr/ ⁸⁶ Sr	0.710825	0.710885	0.710419	0.710288	0.710397	0.709839	0.710165	0.710110	0.711076	0.709572
2σ (× 10 ^{−6})	19	17	12	20	14	17	31	14	29	18
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.1046	0.1055	0.0980	0.1010	0.0993	0.0972	0.1100	0.1212	0.0910	0.1029
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512006	0.512006	0.512041	0.511984	0.511806	0.511680	0.511790	0.511807	0.511684	0.511788
2σ (× 10 ^{−6})	11	9	8	15	9	11	16	9	7	10
I _{Sr} (125 Ma)	0.71018	0.71007	0.71011	0.70990	0.71002	0.70959	0.70991	0.70985	0.71068	0.70929
e _{Nd} (125 Ma) ^b	−10.9	−10.9	−10.1	−11.2	−14.7	−17.1	−15.2	−15.0	−16.9	−15.1
T _{DM} (Ga) ^b	1.60	1.61	1.46	1.57	1.79	1.92	1.99	2.20	1.82	1.87
f _{Sm/Nd}	−0.47	−0.46	−0.50	−0.49	−0.50	−0.51	−0.44	−0.38	−0.54	−0.48

	LL-M08	MP-M01	MP-M02	MP-M04	MP-M05	MP-M06	MP-M07	MP-M08	MP-M09
Rock type	Dolerite	Dolerite	Dolerite	Dolerite	Dolerite	Minette	Minette	Minette	Minette
Locality	Linglong	Mouping	Mouping	Mouping	Mouping	Mouping	Mouping	Mouping	Mouping
SiO ₂	46.61	47.35	46.49	47.34	50.64	47.84	48.31	49.01	49.21
TiO ₂	0.79	0.83	0.83	0.79	0.61	0.59	0.65	0.55	0.63
Al ₂ O ₃	12.62	14.50	14.50	13.39	14.84	14.51	14.66	13.34	14.67
Fe ₂ O ₃	7.42	7.09	7.82	7.42	5.53	5.53	7.89	8.25	7.14
MnO	0.16	0.11	0.18	0.21	0.10	0.14	0.13	0.17	0.16
MgO	8.49	7.75	5.99	8.49	4.67	5.01	5.32	4.72	4.85
CaO	7.51	7.78	9.94	8.97	5.93	6.69	5.98	6.89	6.37
Na ₂ O	2.22	1.83	2.67	2.27	1.57	0.41	—	—	—
K ₂ O	2.10	2.18	1.63	1.94	3.51	4.13	3.50	2.81	3.59
P ₂ O ₅	0.34	0.37	0.39	0.32	0.29	0.28	0.31	0.26	0.33
LOI	11.49	10.69	9.69	9.15	12.30	14.81	13.51	14.25	13.52
SUM	99.75	100.13	100.13	100.29	99.99	99.94	100.26	100.25	100.47
Mg#	69.58	64.66	60.52	69.59	62.80	64.46	57.42	53.35	57.59
Cr	444	306	329	499	276	242	363	209	225
Co	44	38	43	47	30	26	23	36	33
Rb	58	50	34	40	89	96	128	62	77
Sr	1023	1494	1760	1084	803	1162	314	317	244
Y	19	19	21	18	15	10	18	10	11
Zr	176	167	212	184	160	100	223	104	94
Nb	10.2	11.0	13.8	9.9	9.3	7.1	10.0	6.6	8.1
Cs	1.1	1.6	0.60	0.7	1.5	3.8	4.8	3.3	3.2
Ba	3205	1087	1255	1169	1119	1588	985	410	1074
La	65.1	26.1	35.6	31.4	30.7	39.5	47.5	43.9	44.6
Ce	127	53.8	66.3	60.0	60.5	75.4	98.0	81.4	78.5

(continued on next page)

Table 2 (continued)

	LL-M08	MP-M01	MP-M02	MP-M04	MP-M05	MP-M06	MP-M07	MP-M08	MP-M09
Rock type	Dolerite	Dolerite	Dolerite	Dolerite	Dolerite	Minette	Minette	Minette	Minette
Locality	Linglong	Mouping	Mouping	Mouping	Mouping	Mouping	Mouping	Mouping	Mouping
Pr	14.0	6.19	7.66	6.98	6.91	8.18	11.2	8.72	8.43
Nd	50.8	24.3	30.7	28.8	26.9	28.3	40.3	31.2	29.8
Sm	8.32	5.14	5.77	4.39	4.39	4.67	6.23	4.83	4.43
Eu	2.93	1.57	2.28	1.76	1.60	1.69	2.19	1.35	1.72
Gd	7.62	5.11	6.45	5.12	4.94	4.05	6.41	4.24	4.19
Tb	0.77	0.64	0.74	0.65	0.58	0.44	0.69	0.42	0.48
Dy	3.89	3.42	3.99	3.59	2.33	2.05	3.82	2.17	2.25
Ho	0.75	0.69	0.81	0.73	0.58	0.37	0.73	0.39	0.45
Er	2.01	1.69	2.27	1.77	1.48	1.04	1.80	1.04	1.04
Tm	0.26	0.26	0.34	0.27	0.24	0.15	0.25	0.16	0.21
Yb	1.52	1.70	1.97	2.14	1.42	1.10	1.61	1.29	1.16
Lu	0.24	0.23	0.29	0.29	0.24	0.17	0.29	0.14	0.18
Hf	3.98	4.45	5.13	4.41	4.12	3.15	5.60	2.79	2.82
Ta	1.04	2.14	5.05	2.70	1.40	3.89	5.19	1.18	3.92
Pb	19.4	—	0.8	—	14.2	21.2	32.5	17.8	21.8
Th	8.2	3.0	4.0	5.2	4.5	5.2	6.8	4.6	5.0
U	1.4	0.7	0.8	0.9	1.7	0.9	1.8	1.5	1.2
²⁰⁶ Pb/ ²⁰⁴ Pb	17.117	17.208	17.129	17.093	16.987	16.811	16.745	16.940	16.968
²⁰⁷ Pb/ ²⁰⁴ Pb	15.414	15.415	15.405	15.376	15.437	15.298	15.243	15.383	15.424
²⁰⁸ Pb/ ²⁰⁴ Pb	37.485	37.445	37.367	37.352	37.349	36.920	36.755	37.167	37.433
⁸⁷ Rb/ ⁸⁶ Sr	0.1536	0.0963	—	0.1073	0.3336	0.2382	1.2462	0.5897	0.9451
⁸⁷ Sr/ ⁸⁶ Sr	0.709357	0.709421	—	0.709502	0.709495	0.709727	0.711431	0.710512	0.711075
2σ (× 10 ^{−6})	10	16	—	23	25	20	20	18	23
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.1005	0.1050	—	0.1016	0.0904	0.0920	0.0935	0.0880	0.0927
¹⁴³ Nd/ ¹⁴⁴ Nd	0.511838	0.511926	—	0.511731	0.511690	0.511711	0.511696	0.511698	0.511694
2σ (× 10 ^{−6})	10	11	—	8	7	9	11	6	12
<i>I</i> _{Sr} (125 Ma)	0.70908	0.70925	—	0.70931	0.70890	0.70930	0.70922	0.70946	0.70940
<i>ε</i> _{Nd} (125 Ma)	−14.1	−12.4	—	−16.2	−16.8	−16.4	−16.7	−16.6	−16.8
<i>T</i> _{DM} (Ga)	1.76	1.71	—	1.92	1.80	1.80	1.84	1.76	1.83
<i>f</i> _{Sm/Nd}	−0.49	−0.47	—	−0.48	−0.54	−0.53	−0.52	−0.55	−0.53

^a Mg[#] = atomic 100 (Mg/Mg + Fe²⁺), in which FeO = 0.9Fe₂O₃.

^b The ¹⁴³Nd/¹⁴⁴Nd and ¹⁴⁷Sm/¹⁴⁴Nd of chondrite and depleted mantle at present day are 0.512638 and 0.1967, 0.51315 and 0.222, respectively. —: Not determined and/or below detecting limit (—).

Fig. 2. Plots of (a) Total alkali vs. SiO_2 , and (b) K_2O vs. SiO_2 for mafic dikes from the Jiaodong Peninsula. The nomenclature fields are from Le Maitre et al. (1989).

samples. The four minette samples analyzed do not show apparent alteration features but contain tiny pellets and/or veins of igneous carbonates, which have been measured for stable isotope (C, H, O) ratios suggestive of upper mantle origin (Sun et al., 2001). Emplacement of such carbonatite-bearing minettes is interpreted to be the result of “comagmatic metasomatism” owing to high volatile contents, i.e., a process coined as gas phase metasomatism (cf. Rock, 1991), which may largely account for the high loss on ignition (LOI) concentrations observed in these rocks (see below).

4. Analytical methods

Conventional whole-rock K–Ar age determinations were carried out at the Institute of Geology, Chinese State Seismological Bureau. The analytical procedures

are similar to those described by Chen and Chen (1997).

Major and trace elements and Sr–Nd–Pb isotope data were obtained at the Institute of Geology and Geophysics, Chinese Academy of Sciences. Major elements were analyzed by X-ray Fluorescence (XRF) method combining with wet chemical method (MgO , Na_2O , P_2O_5 and LOI). Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was used to analyze trace element contents. Analyzed uncertainties are ± 3 –5% for major elements and better than 5–8% for trace elements (Ren, 1995).

Samples for isotopic analysis were dissolved in Teflon bombs after being spiked with ^{84}Sr , ^{87}Rb , ^{150}Nd and ^{147}Sm tracers prior to $\text{HF} + \text{HNO}_3$ (with a

Fig. 3. Chondrite-normalized REE patterns for mafic dikes from the Jiaodong Peninsula.

ratio of 2:1) dissolution. Rb, Sr, Sm and Nd were separated using conventional ion exchange procedures and measured using a VG-354 multicollector mass spectrometer (Qiao, 1988). Procedural blanks were <100 pg for Sm and Nd and <500 pg for Rb and Sr. $^{143}\text{Nd}/^{144}\text{Nd}$ were corrected for mass fractionation by normalization to $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$, and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios normalized to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$. Typical within-run precision (2σ) for Sr and Nd was estimated to be ± 0.00002 and ± 0.000015 , respectively. The measured values for the La Jolla Nd standard and NBS-607 Sr standard were $^{143}\text{Nd}/^{144}\text{Nd}=0.511853 \pm 7$ (2σ , $n=12$) and $^{87}\text{Sr}/^{86}\text{Sr}=1.20042 \pm 2$ (2σ , $n=12$), respectively, during the period of data acquisition. Pb isotope data were corrected by reference to the analyses of NBS981 Pb standard that indicate a mass fractionation averaging -0.1% per amu. (Yang, 2000).

5. Analytical results

5.1. K–Ar dating result

Our K–Ar data (Table 1) yielded a magmatic duration of 132.5–120.0 Ma for mafic dikes from the Xincheng, Linglong and Mouping areas. The emplacement of the dikes took place synchronously with formations of the Guojialing granodioritic suite (130–126 Ma, Wang et al., 1998; Zhang et al., 2003) and gold mineralization in the Jiaobei terrain (Wang et al., 1998; Yang and Zhou, 2001; Zhang et al., 2003). This is consistent with the K–Ar results reported by Li and Yang (1993) and Sun et al. (1995) and zircon SHRIMP U–Pb ages reported by Zhang et al. (2003) and confirms previous notion that the dike swarm occurred in the early Cretaceous.

5.2. Major and trace element data

Results of major and trace element analyses are listed in the Table 2 and plotted in Figs. 2–4. Whole-

Fig. 4. Primitive mantle (PM)-normalized trace element variation patterns for mafic dikes from the (a) Xincheng, (b) Linglong and (c) Mouping areas, respectively. (d) Plots of averaged values of the dikes in comparison with the (upper) continental crust (Rudnick and Fountain, 1995). Normalizing data of the PM are from Sun and McDonough (1989).

rock silica contents (SiO_2) range from 56.59 to 58.50 wt.% in the Xincheng, 44.08–53.17 wt.% in the Linglong and 46.49–50.64 wt.% in the Mouping areas (Table 2), which overall range from basalt to andesite with minor trachyandesites according to the nomenclature of Le Maitre et al. (1989). All dikes belong to subalkaline rocks based on the alkali vs. silica plot (Fig. 2a). They are characterized by low

TiO_2 (0.55–0.90 wt.%), total Fe_2O_3 (5.12–9.48 wt.%) and CaO (4.99–9.94 wt.%), and high Mg numbers [$\text{Mg number} = \text{Mg}/(\text{Mg} + 0.9\text{Fe}_T) = 53\text{--}71$] and Cr contents (177–1012 ppm, with most >200 ppm). Using K_2O vs. SiO_2 nomenclature of Le Maitre et al. (1989), these dikes are classified as medium-K, high-K calc-alkaline to shoshonitic rocks (Fig. 2b). The four minette samples from the Mouping area

Fig. 5. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\epsilon_{\text{Nd}}(T)$ diagram of mafic dikes (b), compared with volcanic rocks, granites and Cenozoic basalts (a) in the Jiaodong Peninsula. Data sources include: (1) the NCB lower and upper crusts and the YB lower crust from Jahn et al. (1999), (2) the Jiaodong volcanic rocks from Fan et al. (2001), granites from Yang (2000), and kimberlites from Zheng et al. (1998), (3) Cenozoic basalts from Peng et al. (1986), Basu et al. (1991), Tatsumoto et al. (1992) and Chung (1999).

possess $K_2O > 3$ wt.% and $K_2O/Na_2O > 2$ wt.%, together with $MgO > 3$ wt.% and high Cr (> 200 ppm), belonging to the ultrapotassic rocks defined by Foley et al. (1987) and thus similar to the composition of potassic rocks from Central Italy (Peccerillo, 1990). Note that these samples have low Na_2O (< 0.4 wt.%), similar to certain minettes from Peru, the eastern Andean Cordillera (Carlier et al., 1997) and eastern Antarctica (Hoch et al., 2001).

Chondrite-normalized REE patterns for the dikes are marked by (1) an enrichment in the LREE, (2) less variation in the heavy REE (HREE), and (3) minor or absent positive Eu anomalies (Fig. 3). Overall speaking, these samples display a large variation in REE abundance levels (total REE = 122–340 ppm), with variable (La_N/Sm_N) ratios (3.3–6.5) and (La_N/Yb_N) ratios (10.5–46.8). In the primitive mantle (PM) normalized trace element variation diagram (Fig. 4), all dikes show very distinctive negative anomalies in the HFSE (Nb and Ti), coupled with enrichments in the LILE relative to LREEs (e.g., $Ba/La = 9$ –59) and HFSE (e.g., $Ba/Nb = 47$ –367, $La/Nb = 1.6$ –8.1). A significant feature to note is that the abundance levels of LREE and LILE of shoshonitic and high-K calc-alkaline rocks are apparently higher than those of medium-K magmas from the same area (Figs. 3 and 4).

5.3. Sr–Nd–Pb isotope data

Initial $^{87}Sr/^{86}Sr$ ratios of the JMD are relatively uniform (0.70890–0.71017; Table 2), whereas their Nd isotopes are heterogeneous among samples from three localities. The ϵ_{Nd} (125 Ma) values are -10.1 – -11.2 , -14.1 – -17.1 and -12.5 – -16.8 for samples from the Xincheng, Linglong and Mouping areas, respectively (Table 2). In the Sr–Nd isotopic correlation diagram (Fig. 5b), the Xincheng samples exhibit higher initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios that plot away from samples from the other two areas. Pb isotopic ratios of the JMD are also distinctive, with $^{206}Pb/^{204}Pb$ ratios of the Xincheng, Linglong and Mouping samples ranging from 17.48 to 18.03, 17.06–17.44 and 16.75–17.21, respectively (Table 2 and Fig. 6). Note that the Pb isotope compositions of Xincheng samples plot close to or within the field of Cenozoic alkaline basalts from the same region, which represent within plate magmas derived mainly from

Fig. 6. Plots of $^{206}Pb/^{204}Pb$ vs. (a) $^{207}Pb/^{204}Pb$ and (b) $^{208}Pb/^{204}Pb$ ratios of mafic dikes from the Jiaodong Peninsula. The NHRL is from Hart (1984). Data sources for Cenozoic basalts are same as Fig. 5.

the asthenospheric mantle (Peng et al., 1986; Basu et al., 1991; Chung, 1999). All samples except two from the Xincheng area (XC-M04 and XC-M02) plot above the Northern Hemisphere Reference Line (Hart, 1984).

6. Discussion

6.1. Petrogenesis: crustal assimilation vs. source enrichment

The JMD have generally high MgO (max. 10.23 wt.%; $Mg^\# = 71$) and Cr (max. 1012 ppm) contents, indicating a dominant magma source from the upper mantle. However, these dikes are also marked by “crustal-like” trace element and isotopic features, e.g., the enrichments in the LILE and LREE, depletions in the HFSE (Table 2; Fig. 3), and high initial

$^{87}\text{Sr}/^{86}\text{Sr}$ and low ε_{Nd} (T) values (Table 2; Figs. 5 and 6). It is important to note that their overall geochemical characteristics resemble those of postcollisional lavas emplaced in the Tethyan orogenic belts, such as Spanish lamproites (Nelson et al., 1986) and Tibetan shoshonitic rocks (Turner et al., 1996; Miller et al., 1999), which are widely considered to have originated from enriched lithospheric mantle sources.

There are at least three likely processes to account for the JMD geochemistry. These are: (1) crustal assimilation, i.e., mantle-derived melts that assimilated wall rocks during magma ascent; (2) relatively old source metasomatism, i.e., enrichment in the mantle source region via geodynamic processes such as subduction; and (3) binary mixing between mantle- and crustal-derived magmas. Crustal assimilation may produce some trace element and isotopic variations observed in Figs. 3–6. It, however, does not explain the very high concentrations of Ba (max. of 4381 ppm) and Sr (max. of 1760 ppm) of the JMD (Table 2; Fig. 4d), which are much higher than the continental crust values (Ba = 390 ppm; Sr = 325 ppm; Rudnick and Fountain, 1995), and hence these data exclude crustal assimilation to have played a significant role in the petrogenesis. Besides, crustal assimilation coupled with fractional crystallization (AFC) is unlikely as this would result in progressive decreases in Cr, Ni, Co, and Mg numbers with concomitant increase in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and decrease in ε_{Nd} (T) values, features that are not observed in the JMD. The third scenario, i.e., magma mixing, is also not favored because this should generate mixing curves in the isotopic correlation diagrams and in plots between isotopic ratios and certain elements (e.g., MgO or SiO_2), which are not observed either (Figs. 5–7). Two groups of dikes are identified, as shown in Fig. 7a, one with high MgO ($\text{Mg\#} > 68$) and Cr (> 300 ppm) and the other with low MgO ($\text{Mg\#} < 68$) and Cr (< 400 ppm). These rocks do not display mixing curves (Fig. 7a). Moreover, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of each group are rather uniform over a wide range of MgO contents (Fig. 7b).

Therefore, we argue that the geochemical and isotopic characteristics of the JMD are, similar to the Tethyan orogenic lavas (Nelson et al., 1986; Turner et al., 1996; Miller et al., 1999), derived from enriched domains or metasomes (Menzies et al., 1993) in the lithospheric mantle beneath the NCB. Such

Fig. 7. (a) Cr vs. Mg# diagram for mafic dikes from the Jiaodong Peninsula, through which two groups of dikes, one with higher Mg# ($\text{Mg\#} > 68$) and Cr ($\text{Cr} > 300$ ppm) and the other with lower Mg# ($\text{Mg\#} < 68$) and Cr ($\text{Cr} < 400$ ppm), are grouped. (b) Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios vs. MgO diagram.

domains appear to be heterogeneous and are believed to have resulted from multiple metasomatic events (see below).

6.2. Characteristics of the mantle sources

Mafic dikes from the Xincheng have relatively higher ε_{Nd} (T) values (-10 – -11) and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (17.48–18.03) than those of the Linglong and Mouping dikes (Figs. 5 and 6). Distinctions can also be observed in plots of ε_{Nd} (T) values with MgO, K_2O and Sm/Nd ratios (Fig. 8), in which the Xincheng rocks define one magmatic evolution trend whereas the Linglong and Mouping lavas delineate a second. These can not result from a single source but require involvement of multiple mantle components. For each group, there are at least two “end-members”, i.e., a high-Mg,

Fig. 8. Plots of $\epsilon_{\text{Nd}}(T)$ vs. (a) MgO, (b) K_2O , and (c) Sm/Nd indicating two evolution trends of mafic dikes from the Jiaodong Peninsula. See text for detailed discussion.

low-K component and a low-Mg, high-K component (Fig. 8a and b). This observation is consistent with the vein-plus-wall-rock melting model proposed by Foley (1992). Under the framework of that model, melting of the veins (pyroxenite) would form the shoshonitic and high-K calc-alkaline melts with lower MgO contents that are more enriched in incompatible trace elements, whilst partial melting of the wall-rock (peridotite)

produces the high-Mg melts with lower K_2O and less enriched incompatible elements.

The high-Mg ($\text{Mg}\# > 68$) dikes, with high Cr (358–1012 ppm) but low total Fe_2O_3 and CaO (Table 2), are likely to have originated from a refractory mantle source that had experienced previous extraction of basaltic melts. This notion is supported by plots of Fe_2O_3 vs. TiO_2 (Fig. 9a), in which these high-Mg dikes fall in the field defined by the experimental melts from depleted peridotite (Falloon et al., 1988). Such a refractory mantle may be represented by the lithospheric mantle of the NCB.

There are two types of “vein” component, marked by different isotopic compositions (Fig. 8), the low-Mg, high-K characteristics furthermore point to potassium-rich phases (e.g., phlogopite, amphibole) in

Fig. 9. (a) Plots of TiO_2 vs. total Fe_2O_3 for mafic dikes with Mg number > 68 in comparison with fields of the peridotitic melts reported by Falloon et al. (1988). (b) Rb/Sr vs. Ba/Rb diagram for all mafic dikes from the Jiaodong Peninsula.

the vein sources. Melts in equilibrium with phlogopite are expected to have higher Rb/Sr (>0.1) and lower Ba/Rb (<20) ratios than those from amphibole-bearing sources (Furman and Graham, 1999). In Fig. 9b, high-K lavas from the Xincheng and Linglong areas display higher Ba/Rb (>30) and lower Rb/Sr (<0.1), suggesting an amphibole-bearing vein source. In contrast, shoshonitic dikes from the Mouping area exhibit lower Ba/Rb (<20) and higher Rb/Sr (>0.1), implying phlogopite to have been involved in the magma generation. Note that dikes from the Linglong and Mouping areas appear to be derived from “veins” that contain different types of K-rich phases, i.e., amphibole and phlogopite, respectively, although they delineate similar evolution trends in Fig. 8.

6.3. Multiple mantle metasomatic events

The identification of different types of the vein component implies that there were different types of metasomatism at different times, i.e., multiple metasomatic events, in lithospheric mantle of the NCB. The general similarity in incompatible element patterns between the JMD and upper continental crust (Fig. 4d) tends to support the contention that attributes recycled continental crustal materials to explain the generation of postorogenic potassic lavas (e.g., Nelson, 1992; Peccerillo, 1999). To account for the “crustal-like elemental and isotopic signatures” observed in Cretaceous mafic–ultramafic intrusions from the northern Dabie complex, which are temporally and geochemically comparable with the JMD, Li et al. (1998) and Jahn et al. (1999) envisioned a recycled component composed of the YB lower and/or middle crust to have been subducted via the Triassic continental collision processes and later involved in the magma generation. However, such a Triassic subduction/collision interpretation works only in areas close to the Dabie–Sulu orogenic belt, whereas Cretaceous magmatism is widespread over the NCB, occurring extensively in the Liaoning Province and Western Shandong Province (Chen and Chen, 1997; Guo et al., 2001). We therefore favor a larger-scale and longer-lasting scenario that is multiple continental arc-type magmatic events in the Late Archean and Mesoproterozoic, a mechanism proposed to have caused mafic magma underplating around the crust–mantle boundary in the NCB (Yu et

al., 2003). Such magmatic events took place before/ during the final assemblage of the NCB that occurred at ~ 1.8 Ga in the Late Paleoproterozoic (Zhao et al., 2001). This interpretation is consistent with the observation that mafic granulite and pyroxenite xenoliths have Sr–Nd–Pb isotopic compositions overlapping with those of the JMD and contemporaneous magmas from the NCB (Zhou et al., 2002; Yu et al., 2003).

The “ancient” subduction-related enrichments above-described may have resulted in the amphibole and phlogopite-bearing pyroxenite veins involved in the JMD generation. These veins could have been imparted with the incompatible element features observed in the JMD and, with time, developed the radiogenic isotopic signatures (Foley, 1992; Schmidt et al., 1999). The Xincheng dikes have apparently higher $\epsilon_{\text{Nd}}(T)$ values and Pb isotopic ratios than the Linglong and Mouping ones, leading to the two distinct trends observed in Fig. 8. This may be explained by similar metasomatic events at different times. Relative to dikes from the other two areas that exhibit Nd isotopic model ages (T_{DM}) between 1.7 and 2.2 Ga (Table 2), the Xincheng samples appear to have younger and restricted T_{DM} ages of ~ 1.5 – 1.6 Ga that is consistent with the interpretation of a younger enrichment in the mantle source region.

6.4. Tectonic implications

Magmatism in the Jiaodong Peninsula has been proposed as being produced under an intracontinental extension setting (Fan et al., 2001), in association with the development of rifting basins and major strike-slip movement of the Tanlu fault zone during the late Mesozoic (e.g., Xu et al., 1987). Such intracontinental extensional magmatism marked by subduction geochemical fingerprints is not unusual in modern and ancient orogens (e.g., Turner et al., 1996; Romer et al., 2001). Studies focused on mantle xenoliths from the NCB (Menzies et al., 1993; Menzies and Xu, 1998; Griffin et al., 1998; Xu, 2001; Gao et al., 2002; Zhou et al., 2002) repeatedly indicated that the cratonic lithosphere beneath has been removed for at least 120 km, although the precise timing and mechanism of the removal remain highly debated. The collision between the North China and South China (or Yangtze) Blocks and the subduction of Pacific

Oceanic plate along the East Asia not only resulted in the UHPM rocks exposed in the Qinling–Dabie–Sulu orogenic belt, but also reactivated the eastern part of the NCB cratonic lithosphere as manifested by extensive basin formation and movement of the Tanlu fault since Jurassic time. The reactivation, affiliated most likely with the lithospheric removal and replacement by ascended asthenosphere, led to elevation of the geotherm and thus the widespread magmatic activity. Consequently, the NCB evolved from stable craton through contractional orogen to an extensional tectonic environment that is characterized by development of rifted basins and basaltic eruptions in the Cenozoic history (e.g., Tian et al., 1992; Ren et al., 2002).

7. Concluding remarks

Our K–Ar dates indicate that the dikes from the Jiaodong Peninsula, eastern China occurred in the Early Cretaceous (135–115 Ma), broadly synchronous with the massive emplacement of granitic plutons and gold mineralization in the region. The dikes range in composition from medium-K and high-K calc-alkaline to shoshonitic or ultrapotassic rocks, whose overall geochemical and isotopic characteristics can be explained in terms of the vein-plus-wall-rock melting model (Foley, 1992), in which the veins consist of amphibole- or phlogopite-bearing pyroxenites and the wall-rock peridotite is refractory cratonic lithospheric mantle beneath the North China Block. The enriched mantle source may have resulted from multiple metasomatic events imparted by subduction-related processes that occurred in the Late Archean and Mesoproterozoic before/during the accretion of the North China Block. It became involved in the magma generation when the Triassic continental collision and the subduction of Pacific plate along the East Asia reactivated the stable lithosphere of the North China Block. Therefore, the mafic dikes, analogous to post-collisional lavas from many orogens, represent intra-continental extension-induced magmas derived from the lithospheric mantle that was previously metasomatized by subduction zone processes. In the Jiaodong Peninsula, the mafic dikes are associated with volcanic sequences and felsic plutons showing similar geochemical affinities. Together with contemporaneous lavas from the Dabie–Sulu orogenic belt and other

localities in the North China Block, these rocks constitute the Mesozoic magmatic province whose generation and evolution bear important information about the timing and mechanism of key tectonic events such as the lithospheric removal from below this region. Furthermore, detailed investigations of individual outcrops are hence urgently needed.

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