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ScienceDirect
Lithos 96 (2007) 151 – 169
LITHOS
www.elsevier.com/locate/lithos

Recycling of deeply subducted continental crust in the Dabie Mountains, central China

Fang Huang [a,b,*], Shuguang Li [a,*], Feng Dong [a], Qiuli Li [c],
Fukun Chen [c], Ying Wang [a], Wei Yang [a]

[a] CAS Key Laboratory of Crust-Mantle Materials and Environments, Department of Earth and Space Sciences,
University of Science and Technology of China, Hefei, Anhui 230026, China
[b] Department of Geology, University of Illinois at Urbana-Champaign, 245 NHB, 1301 W. Green St., IL 61801, USA
[c] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

Received 5 November 2005; received in revised form 11 April 2006; accepted 5 September 2006
Available online 3 January 2007

Abstract

Post-collisional mafic–ultramafic intrusive rocks from the North Dabie zone show evidence for derivation from a mantle source that was overprinted by partial melts derived from subducted crust of the South China Block. All the samples are characterized by enrichment of large ion lithophile elements (LILE, e.g., Ba, Th) and depletion of high field strength elements (HFSE, e.g., Nb, Ti). The Zhujiapu intrusion developed in the North Dabie zone has moderately enriched $^{87}Sr/^{86}Sr_i$ (0.70605–0.70827), negative $\varepsilon_{Nd}(T)$ values (−2.3 to −18.8), and unradiogenic Pb isotopes. Such typical “continental” geochemical features do not result from crustal contamination or magma mixing, but reflect the properties of the mantle source. Because the trace element and Sr–Nd isotopic compositions of the post-collisional mafic–ultramafic intrusive rocks from the North Dabie zone are similar to those of the Mesozoic mantle-derived rocks and lower crust granulites and xenoliths from the North China Block, it is unclear whether the “continental” features are due to the contribution of lithospheric mantle and lower crust from the North China Block or deeply subducted materials from the South China Block. However, for a given $^{206}Pb/^{204}Pb_i$ or Δ7/4, the $^{208}Pb/^{204}Pb_i$ or Δ8/4 (159–180) of the post-collisional mafic–ultramafic intrusive rocks from the North Dabie zone is close to the Mesozoic granitoids, eclogites, and gray gneisses from the Dabie–Sulu orogen, but significantly higher than the Mesozoic mantle-derived rocks and lower crust granulites and xenoliths from the North China Block ($\Delta 8/4 < 160$). This indicates that the subducted slabs of the South China Block experienced a higher time-integrated Th/U but similar U/Pb as the deep lithosphere of the North China Block. We therefore propose that the mantle source of the post-collisional mafic–ultramafic intrusive rocks from the Dabie–Sulu orogen result from the depleted upper mantle metasomatised by melts from recycled deeply subducted crust. Due to the continent–continent collision between the South China Block and North China Block in the late Triassic, the lithosphere of the Dabie orogen was over-thickened resulting in eclogitic metamorphism in the mafic lower crust, producing a gravitational instability. The subducted eclogitic lower crust foundered and was recycled into the upper mantle beneath the orogen, resulting in mountain root removal, less mafic composition of unusually evolved continental crust, and upper mantle heterogeneity.

Keywords: Dabie–Sulu orogen; Crust/mantle interaction; Post-collisional magmatism

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* Corresponding authors. Huang is to be contacted at Department of Geology, University of Illinois at Urbana-Champaign, 245 NHB, 1301 W. Green St., IL 61801, USA. S.-G. Li is to be contacted at CAS Key Laboratory of Crust-Mantle Materials and Environments, Department of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China.

E-mail addresses: fhuang1@uiuc.edu (F. Huang), lsg@ustc.edu.cn (S. Li).

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doi:10.1016/j.lithos.2006.09.019

1. Introduction

It has been known for more than 20 years that the subducted oceanic crust can be recycled into the mantle and create mantle heterogeneity (e.g., Zindler and Hart, 1986; Hofmann, 1997; Kogiso et al., 1997; Turner et al., 2003). Ultrahigh-pressure metamorphic (UHPM) rocks (mainly eclogites) characterized by the diagnostic minerals (coesite or diamond) have been observed in many orogenic belt, such as the Western Alps, Western Gneiss Region of Norway, Dabie–Sulu orogen, and Kokchetav massif (Chopin, 1984; Smith, 1984; Okay et al., 1989; Wang et al., 1989; Sobolev and Shatsky, 1990; Xu et al., 1992; Ye et al., 2000). Although it is widely accepted that the continental crust can be subducted to depths of more than 200 km, and then exhumed to the surface very quickly, whether or not this continental material can be recycled into the mantle and to what extent it may contribute to mantle heterogeneity remain poorly understood. Moreover, it has been long suggested that the recycling of mafic continental lower crust into the upper mantle can explain the unusually evolved intermediate composition of Earth's continental crust (e.g., Rudnick, 1995 and references therein). Although it has been suggested that the foundering of eclogitic lower continental crust in the thickened lithosphere could be one means of recycling (Kay and Kay, 1991, 1993; Gao et al., 2004; Lustrino, 2005), recycling of deeply subducted mafic lower continental crust (another important recycling mechanism) has never been proved.

The Dabie–Sulu orogen, one of the largest UHPM terranes in the world, was formed by continent–continent collision between the South China Block and North China Block at ~230 Ma (e.g., Li et al., 2000 and references therein) (Fig. 1A). The exposed UHPM rocks in the Dabie orogen might have experienced two stages of rapid uplift and cooling at 226–219 Ma and 180–175 Ma, respectively; the rocks were then exhumed to the surface in the middle Jurassic (Li et al., 2000; Wand et al., 2002). The exhumed UHPM rocks are mainly felsic gneisses, metapelites, and marbles with a few eclogite lenses or blobs. Extremely low $\delta^{18}O$ values observed in UHPM rocks (e.g., −10 to −9 ‰ in Qinglongshan eclogites) indicate that they experienced interaction with ancient meteoric water before subduction (Zheng et al., 1998). The rock assemblages and their Pb isotopic compositions also suggest that the exhumed UHPM rocks were from subducted upper or lower felsic continental crust (Li et al., 2003). The high-pressure metamorphic and UHPM rocks from subducted mafic lower crust have not yet been observed in the orogenic zone. The subducted slab may have descended to the uppermost mantle as suggested by seismic tomographic data (Xu et al., 2001). It is reasonable to speculate that the voluminous subducted mafic lower crust could be recycled into the mantle because of its relatively high density after eclogitic metamorphism (e.g., Li et al., 1997; Jahn et al., 1999). It is important to search for geochemical evidence for the recycling of deeply subducted crust material and understand its influence on mantle heterogeneity and the compositional evolution of the continental crust.

Voluminous mafic and ultramafic igneous rocks emplaced in the early Cretaceous (~130 Ma) in the Dabie–Sulu Orogen, North China Block, and South China Block, providing a good opportunity to understand the geochemical properties of the uppermost mantle beneath Eastern China during the Mesozoic. These post-collisional mafic–ultramafic intrusive rocks in the Dabie–Sulu orogen are known for their typical "continental" features, such as low ε_{Nd}, enrichment of LILE, and depletion of HFSE. These features have been interpreted to reflect the involvement of subducted crustal materials in their mantle source (Li et al., 1997, 1998b; Ma et al., 1998; Jahn et al., 1999; Fan et al., 2001, 2004;Wang et al., 2005; Yang et al., 2005a; Zhao et al., 2005). However, because sub-continental lithospheric mantle of the overthrust North China Block is characterized by such "continental" features as shown by Mesozoic mantle-derived rocks (see Zhang et al., 2004a for a recent review), and because lower crustal xenoliths and granulites from the North China craton have low ε_{Nd} and unradiogenic Pb isotopes (Liu et al., 2004a), the deep lithosphere of the North China Block can also be a possible contributor to the mantle source of the post-collisional mafic–ultramafic intrusive rocks of the Dabie–Sulu orogen. Whether or not the subducted continental crust of the South China Block can be recycled into the uppermost mantle of the Dabie–Sulu orogen remains an open question given the current evidence. More geochemical data are needed to determine the role that the subducted slab plays in the continent–continent collision.

Because Pb isotopes generally have distinctive features between the upper/lower crust and the mantle components (e.g., Doe and Zartman, 1981; Zindler and Hart, 1986) and Pb is much more enriched in crustal materials than in the mantle, Pb isotopes are sensitive to the contribution of crustal material to mantle-derived rocks. In this study, we present Pb isotopic data and trace element compositions of the Zhujiapu pyroxenite–gabbros from the Dabie orogen, as well as major element and Sr–Nd isotopic data previously published in Chinese journals (Li et al., 1998a,b). The purpose of this study is to determine whether materials from subducted continental crust (South China Block) contributed to the source of the Mesozoic mantle-derived rocks from the

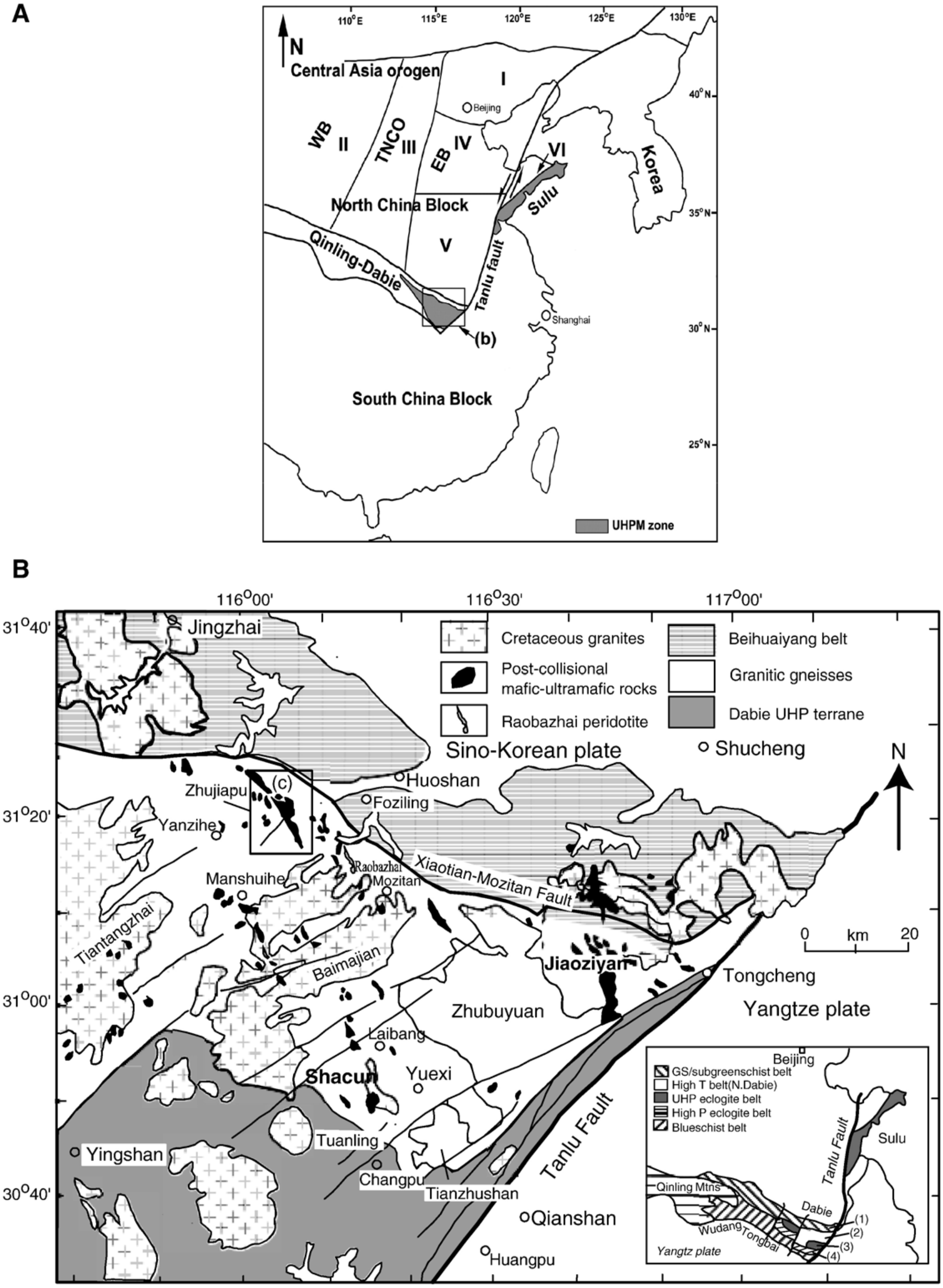

Fig. 1. (A) Simplified tectonic map of Eastern China. WB, TNCO, and EB denote the Western block, Trans-North China orogen, and Eastern block of the North China Craton, respectively. The subdivisions of the North China Craton follow Zhang et al. (2004a): I, Liaoning; II, Erdos; III, Taihang; IV, Luzhong; V-Luxi; VI, Jiaodong. (B) Sketched map for the post-collisional mafic–ultramafic intrusion (PCMI) in the Dabie orogen modified slightly from Jahn et al. (1999) and Zhao et al. (2005). (C) Geological map for the Zhujiapu intrusion.

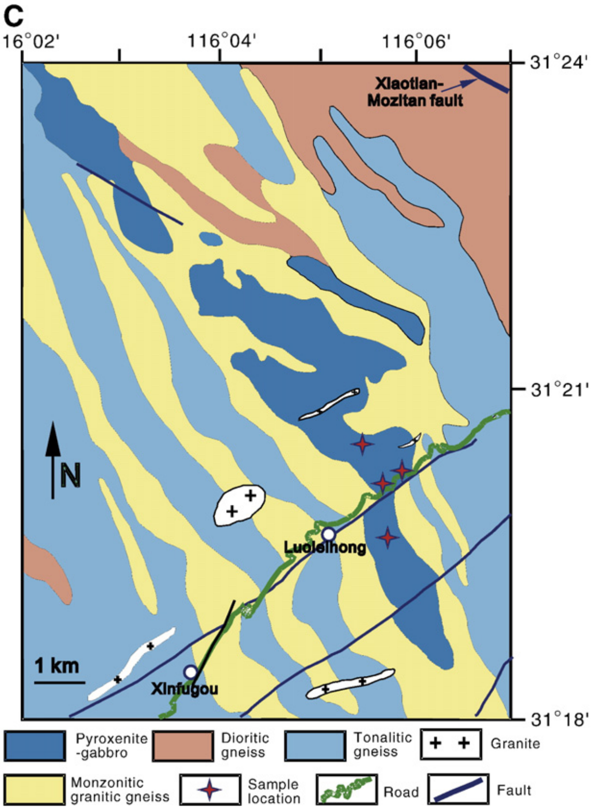

Fig. 1 (*continued*).

Dabie orogen. The resemblance between the Pb isotopic compositions of the post-collisional mafic–ultramafic intrusive rocks and that inferred for the subducted South China Block suggests that lower continental crust has been recycled into the underlying upper mantle.

2. Geological background and petrographic description of samples

The general geological background of the Dabie orogen has been discussed widely (e.g., Hacker et al., 1998; Jahn, 1998; Jahn et al., 1999; Li et al., 2000, 2001a; Fan et al., 2001, 2004). Briefly, the Dabie orogen is divided into four major petro-tectonic units from north to south (Fig. 1B inset): (1) the North Huaiyang greenschist–amphibolite facies zone; (2) the Northern Dabie high P/T metamorphic zone, which contains high temperature diamond-bearing eclogite (Liu et al., 2005; Xu et al., 2005); (3) the Southern Dabie UHPM zone, which contains coesite and diamond-bearing eclogite; and (4) the Hong'an-Susong high-pressure metamorphic zone, which contains "cold" eclogite and blueschist (Li et al., 2001a). It is suggested that zones 2, 3 and 4 are exhumed continental crust of the South China Block that had been subducted to mantle depths (Xu et al., 2000; Li et al., 2001a). In addition, the Paleozoic island arc volcanic rocks and eclogites formed by oceanic subduction are observed on the south side of the North Huaiyang greenschist–amphibolite facies zone in the western Dabie orogen (Li et al., 2001a; Sun et al., 2002). The surface suture between the North China Block and South China Block is located north of the North Dabie zone within the eastern Dabie orogen and along the south margin of the North Huaiyang zone within the western Dabie orogen (Li et al., 2001a). Because the foreland belt lies south of the Dabie orogen and the metamorphic pressure of the rocks in the South Dabie UHPM zone and Hong'an–Susong high-pressure metamorphic zone increases from south to north, it is also commonly believed that the continental crust of the South China Block was subducted northward underneath the North China Block during the continental collision. The Tan-Lu fault transferred the Sulu region northward by ~500 km.

There are two types of mafic–ultramafic rocks in the North Dabie zone. The first is Alpine type peridotite, such as the Raobazhai massif, consisting of dunite and harzburgite (Fig. 1B). These rocks are considered to be fragments of lithospheric mantle that were tectonically emplaced in their present position during the Triassic

Table 1
Major element compositions (%) of the post-collisional mafic–ultramafic rocks from the Zhujiapu intrusion*

Sample no.	Dikes				Cumulates						
	DZh88-1	DZh88-4	DZh-1	DZh-2	DZh88-5	Zh89-1	DZh-3	DZh-4**	DZh-5	DZh-6**	DZh-7**
Rocks type	Pyroxene diorite	Biotite diorite	Pyroxene diorite	Pyroxene diorite	Hornblende pyroxenite	Hornblende pyroxenite	Hornblende pyroxenite	Pyroxene hornblendite	Hornblende pyroxenite	Pyroxene hornblendite	Hornblende pyroxenite
SiO_2	44.26	46.24	45.03	50.77	47.85	47.53	47.16	44.89	50.36	50.85	51.24
Al_2O_3	12.15	18.59	13.58	15.01	3.99	3.82	3.79	2.97	4.48	5.39	5.43
Fe_2O_3	4.07	3.94	5.14	2.60	2.90	3.29	5.63	2.74	2.40	2.27	1.78
FeO	8.39	7.14	7.90	7.33	7.39	5.60	11.05	5.56	6.32	7.26	8.31
MnO	0.23	0.15	0.18	0.19	0.21	0.18	0.34	0.12	0.17	0.18	0.15
MgO	11.19	4.53	9.85	8.58	20.09	19.65	15.14	28.96	17.86	15.66	16.63
CaO	12.26	7.78	10.72	10.99	13.49	15.06	13.83	7.79	14.56	14.35	12.89
Na_2O	1.96	3.93	2.04	2.48	0.61	0.66	0.50	0.45	0.53	0.94	0.80
K_2O	0.92	2.21	0.94	0.50	0.25	0.21	0.10	0.18	0.33	0.53	0.38
TiO_2	1.66	2.34	1.65	0.62	0.46	0.37	0.91	0.32	0.55	0.41	0.50
P_2O_5	0.47	0.97	0.42	0.43	0.39	0.05	0.04	0.04	0.04	0.06	0.05
H_2O^+	1.72	1.31	2.05	0.57	1.37	1.39	0.81	4.40	1.55	0.82	0.91
CO_2	0.42	0.09	0.38	0.07	1.25	1.93	0.35	0.84	0.66	0.53	0.33
Total	99.70	99.22	99.88	100.14	99.74	100.14	99.65	99.26	99.81	99.25	99.40
Mg#	62	43	58	61	80	61	63	87	79	75	75

*: Major element data are from Li et al. (1998a). Samples with ** (DZh-4, DZh-6, and DZh-7) were analyzed at the Geological team No. 313 of the Anhui Province using wet chemical technique. The rest samples were analyzed by X-ray fluorescence and wet chemical method in the Institute of Geophysical and Geochemical Prospecting, Chinese Academy of Geological Sciences. Mg#= molecular proportion of $MgO/(MgO+FeO_T)$, where $FeO_T=FeO+0.9\ Fe_2O_3$.

Table 2

Trace element compositions (ppm) of the post-collisional mafic–ultramafic intrusive rocks from the Zhujiapu intrusion

Method	Standard						Dikes							Cumulates						
	BHVO (n=3)		BCR-2 (n=3)		G-2		Dzh88-1	Dzh88-4		DZh-1		DZh-2		Dzh88-3	Dzh88-5	Dzh89-1	DZh-3	DZh-5		DZh-6
	1	Ref.	1	Ref.	1	Ref.	2	1	2	1	2	1	2	1	2	2	2	1	2	2
Sc	32.6(1.7)	32.0	32.5(1.6)	33.0	3.64	3.50		14.8		37.1		28.9		46.7				52.0		
V	325(6)	317	406(15)	416	36.7	36.0	299	202	213	325	322	196	181	141	186	163	345	162		191
Cr	272(11)	280	18.5(1.5)	18.0	12.6	8.70	389	19.0	28	147	161	152	168	950	1016	1344	448	970		967
Co	45.34(82)	45.0	36.8(1.3)	37.0	4.45	4.60		32.0		63.1		69.1		73.2				74.8		
Ni	119.8(2.3)	119	12.91(18)	13.0	2.89	5.00	109	18.9	18.9	82.8	84	53.6	52	230	280	246	106	228		287
Rb	9.56 (16)	9.80	48.97(64)	48.0	164	170	19.1	55.2	55	17.6	17	9.10	10	5.6	5	2	1	5.9		13
Sr	394.4(9.1)	389	340.8(4.9)	346	467	478	111	1434	1414	664	630	946	965	103	110	111	75	103		142
Y	26.48 (31)	26.0	36.15(22)	37.0	9.98	11.0	27.7	28.2	27	31.5	27	18.3	19	12.0	17	16	27	16.3		21
Zr	174.5(1.9)	172	183.3(5.8)	188	327	309	65	257	395	49.1	49	41.2	49	30.8	26	25	49	38.9		43
Nb	19.23 (22)	18.0	13.08(14)	14.0	12.9	12.0	9.4	18.6	17	4.55	9	2.0	5	0.85	5	6	7	2.14		8
Cs	0.11 (0)	0.13	1.26(1)	1.10	1.49	1.34		0.54		0.22		0.39		0.37				0.44		
Ba	132.8(4.8)	130	667.3(6.8)	683	1735	1882	461	1591	1500	475	437	306	284	86.4	89	101	50	100		196
La	15.13(28)	15.0	24.59(33)	25.0	85.8	89.0	18.70	47.7	52.7	14.5	15.9	15.7	16.6	4.6	5.4	6.2	7.7	6.5	6.9	
Ce	38.23 (49)	38.0	53.30(89)	53.0	151	160	51.3	107	115.3	39.8	41.3	36.9	37.4	11.8	13.2	16.0	26.0	18.7	25.4	
Pr	5.58 (4)	5.70	7.04(7)	6.80	17.7	18.0	8.1	14.2	14.84	6.31	6.74	5.15	5.24	1.76	2.18	3.14	4.54	2.92	3.18	
Nd	24.76 (33)	25.0	28.50(30)	28.0	53.7	55.0	39.83	55.5	60.53	29.8	31.71	22.0	22.49	8.23	9.77	10.55	22.58	13.6	14.19	
Sm	6.30 (12)	6.20	6.68(10)	6.70	7.36	7.20	9.16	10.5	10.56	7.53	7.49	4.97	4.72	2.28	2.53	2.77	5.7	3.53	3.42	
Eu	2.06 (5)	2.06	1.99(3)	2.00	1.52	1.40	2.23	2.92	2.7	2.11	1.97	1.44	1.29	0.65	0.68	0.68	1.33	0.91	0.87	
Gd	5.71 (11)	6.30	6.24(9)	6.80	5.36	4.30	8.29	8.47	8.16	6.55	7.01	4.23	4.09	2.11	2.45	2.41	5.29	3.04	3.23	
Tb	0.93 (0)	0.90	1.04(1)	1.07	0.53	0.48	1.21	1.09	1.06	1.02	1.01	0.63	0.57	0.35	0.38	0.38	0.82	0.50	0.48	
Dy	5.28 (9)	5.20	6.20(11)	6.34	2.34	2.40	6.86	5.42	5.66	5.64	5.78	3.43	3.38	2.05	2.29	2.2	4.95	2.87	2.86	
Ho	1.04 (2)	1.04	1.33(1)	1.33	0.37	0.40	1.24	0.98	1	1.14	1.09	0.69	0.62	0.43	0.42	0.4	0.91	0.59	0.53	
Er	2.51 (5)	2.40	3.48(3)	3.63	0.97	0.92	3.15	2.39	2.45	2.76	2.8	1.73	1.61	1.07	1.10	1.05	2.43	1.49	1.4	
Tm	0.34 (1)	0.33	0.52 (1)	0.54	0.12	0.18	0.44	0.31	0.35	0.38	0.43	0.24	0.25	0.15	0.17	0.16	0.39	0.21	0.22	
Yb	2.06 (4)	2.00	3.35(5)	3.50	0.73	0.80	2.32	1.84	1.89	2.29	2.2	1.54	1.34	0.95	0.85	0.83	2.14	1.33	1.14	
Lu	0.29 (1)	0.28	0.50(0)	0.51	0.10	0.11	0.33	0.26	0.29	0.31	0.33	0.22	0.2	0.13	0.13	0.12	0.33	0.19	0.17	
Hf	4.30 (10)	4.10	4.60(2)	4.80	7.83	7.90		4.34		1.52		1.18		0.78				1.10		
Ta	1.34 (2)	1.40	0.85 (1)	0.81	0.88	0.88		0.69		0.67		1.08		0.060				0.65		
Pb	2.22 (12)	2.60	12.72 (54)	11.0	38.9	30.0		8.54		4.58		5.10		2.31				2.24		
Th	1.26 (3)	1.20	5.87 (13)	6.20	24.2	24.7		1.08		0.90		0.97		0.56				0.48		
U	0.43 (1)	0.42	1.66 (3)	1.69	1.72	2.07		0.23		0.16		0.18		0.097				0.086		
ΣREE							153.1	258.6	277.4	120.1		98.9		36.5	41.52	46.87	85.0	56.4		
Eu/Eu*							0.78	0.95	0.89	0.92		0.96		0.91	0.84	0.80	0.74	0.85		
$(La/Yb)_N$							5.78	18.60	19.99	4.54		7.31		3.46	4.51	5.33	2.56	3.50		
$(Gd/Yb)_N$							2.96	3.81	3.57	2.37		2.27		1.84	2.38	2.40	2.04	1.89		

Reference values of BHVO, BCR-2, and G-2 are from Govindaraju (1994); 32.6(1.7) is read as 32.6±1.7 $Eu/Eu^* = Eu_N/\sqrt{Sm_N \times Nd_N}$. Analysis methods: 1, ICP-MS; 2, REE by ICP-OES method and other trace elements by XRF.

(244–230Ma) (Li et al., 1989, 1993; Liu et al., 2000). The second type is the pyroxenite−gabbro intrusions (e.g., the Zhujiapu intrusion), which are distributed in the North Dabie zone much more widely than the first type. Zircon U–Pb (Li et al., 1999; Wang et al., 2005; Zhao et al., 2005) and whole rock Ar–Ar (Li et al., 1999; Wang et al., 2005; Zhao et al., 2005) geochronology suggests that these pyroxenite–gabbro intrusions were formed in the early Cretaceous (~130 Ma). These rocks intruded into neo-Proterozoic gneisses but were intruded by granite dikes with ages of 125–110 Ma (Li et al., 2001a) (Fig. 1B,C).

The samples in this study were collected from the Zhujiapu pyroxenite–gabbro intrusion, which is one of the largest mafic–ultramafic intrusions in the North Dabie zone (Fig. 1C). The sample locations are distributed along a northwest to southeast transect across the whole intrusion. It is mainly composed of pyroxenite and hornblende pyroxenite cumulate, which is not deformed or metamorphosed. The mineral assemblage of the pyroxenite is clinopyroxene+orthopyroxene+hornblende±plagioclase±biotite. Petrographic observation shows that pyroxenite and plagioclase are coexisting minerals, while hornblende partly replaces pyroxene and biotite partly replaces hornblende. Consequently, the crystallization sequence of these minerals is orthopyroxene+plagioclase+clinopyroxene→hornblende→biotite. Four mafic samples (DZh-1, DZh-2, DZh88-1, DZh88-4) were collected from pyroxene diorite and biotite diorite dikes which intruded the coarse-grainewd pyroxenites. A zircon U–Pb age for a gabbro dike is 130.2±1.4 Ma (Li et al., 1999), establishing that the gabbros are part of the same magmatic event. The country rocks of this intrusion are mainly banded plagioclase–hornblende (so-called “gray gneiss”) and hornblende gneisses. SHRIMP zircon U–Pb ages from the gray gneisses in the North Dabie zone show that the age of the protolith is neo-Proterozoic (700–800 Ma) with metamorphic ages of ~220 Ma and ~130 Ma (Hacker et al., 1998; Liu et al., 2000). These ages suggest that the banded gneisses also experienced Triassic metamorphism and were influenced by the early Cretaceous magmatic event. Pb isotope compositions of the gray gneisses from the North Dabie zone indicate that their protoliths were probably derived from the middle–lower crust due to rifting at the north margin of the South China Block during the neo-Proterozoic (Li et al., 2003).

3. Analytical methods

The samples were prepared by slicing rock chunks using a diamond saw with the iron trace on the cut surface removed using silicon carbide sandpaper in water. The rock slices were then wrapped in cloth and crushed to ~1 cm using a plastic-coated hammer and only fresh chips without any gray gneiss xenoliths or veins were handpicked. The samples were washed with distilled water, then ground in a tungsten-carbide shatter box at the Massachusetts Institute of Technology (MIT) or in an agate mortar at the Institute of Geophysical and Geochemical Prospecting Techniques (IGGPT), the Ministry of Geology and Mineral Resource, China. Major and trace elements (except rare earth elements) were first analyzed by X-ray fluorescence (XRF) spectrometer at the IGGPT (Tables 1 and 2). FeO content was determined by wet chemistry. CO_2 and H_2O were determined by nonaqueous titration and gravimetric methods at the IGGPT, respectively (Li et al., 1998a). Rare earth element (REE) concentrations were obtained by ICP-OES at the Wuhan Analytical Center, the Bureau of Land and Mineral Resources of Hubei Province, China. Trace element contents of DZh-1, DZh-2, DZh-5, Dzh88-3, and Dzh88-4 were re-analyzed by ICP-MS in the Key Laboratory of Continental Dynamics in the Department of Geology of the Northwest University, Xi’an China. As shown in Table 2, trace element compositions measured by ICP-MS agrees well with the data using ICP-OES and XRF methods. The Rb, Sr, Sm, and Nd data were measured by isotope dilution method (Li et al., 1998b) (Table 3) at MIT (samples DZh-1, 2, 3, 4, 5, 6, and 7) or at the Geological Institute of the Chinese Academy of Geological Sciences. Rb and Sr contents by XRF and Sm and Nd by ICP-OES of most samples are generally consistent with the results from isotope dilution methods. However, significant difference between isotope dilution and other methods does exist in a few samples. The reason for this is not clear but calculated initial Sr or Nd isotopic ratios do not show substantial differences using the different methods. The Pb isotope data of six samples were analyzed in the Laboratory for Radiogenic Isotope Geochemistry in the Institute of Geology and Geophysics, Chinese Academy of Science using a MAT-262 mass spectrometer (Table 3). Pb was purified by the conventional anion-exchange method (AG1-X8, 200-400 resin) using HBr as an eluant. The total procedural blank is 50 to 100 pg. Fractionation of Pb isotopes during TIMS analyzes were calibrated against standard NBS981. The average NBS981 measured during the course of this study is $^{206}Pb/^{204}Pb = 16.9376 \pm 0.0015$ (2σ), $^{207}Pb/^{204}Pb = 15.4939 \pm 0.0014$ (2σ), and $^{208}Pb/^{204}Pb = 36.7219 \pm 0.0033$ (2σ).

4. Results

4.1. Major and trace elements

Based on the outcrop relationships and petrographic observations, the Zhujiapu intrusion can be subdivided

Table 3
Sr–Nd–Pb isotopic compositions of the post-collisional mafic–ultramafic rocks from the Zhujiapu intrusion*

Sample no.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr_i$	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma$)
DZh88-1**	18.92	110.4	0.4884	0.708250±17	0.707348	2.446	15.58	0.0950	0.511630±9
DZh88-4**	52.74	1303	0.1172	0.707271±31	0.707054	10.63	58.30	0.1103	0.512028±41
DZh-1**	16.32	639.9	0.0739	0.707775±25	0.707638	7.847	31.37	0.1512	0.511757±19
DZh-2**	8.023	975.4	0.0268	0.707701±28	0.707651	4.982	22.78	0.1322	0.511710±19
DZh88-3	18.26	97.76	0.5408	0.707681±45	0.706682	2.988	10.76	0.1680	0.512136±54
DZh88-5	10.07	118.5	0.2461	0.707897±60	0.707442	2.948	10.83	0.1647	0.512071±44
DZh89-1	3.72	68.51	0.1571	0.707892±17	0.707602	1.626	6.211	0.1584	0.512272±66
DZh-3	2.924	71.20	0.1189	0.707537±30	0.707317	6.181	23.09	0.1618	0.511783±17
DZh-4	1.023	273.0	0.0108	0.706071±30	0.706051	4.985	14.64	0.2058	0.512529±19
DZh-5	5.766	99.41	0.1679	0.707647±27	0.707337	3.634	14.20	0.1547	0.511794±18
DZh-6	14.80	144.9	0.2956	0.708812±28	0.708266	4.178	16.72	0.1510	0.511638±20
DZh-7	17.32	98.69	0.5082	0.708930±29	0.707991	3.837	15.42	0.1503	0.511647±18

*: Sr–Nd isotope data are from Li et al. (1998b). Samples with ** are dikes. Initial isotopic ratios are calculated to 130 Ma. Initial Pb isotopic ratios were calculated using the whole rocks U, Th, Pb contents by ICP-MS. Chondritic uniform reservoir (CHUR): $^{147}Sm/^{144}Nd=0.1967$; $^{143}Nd/^{144}Nd=0.512638$. Depleted mantle (DM): $^{147}Sm/^{144}Nd=0.2137$; $^{143}Nd/^{144}Nd=0.51315$. $\Delta 7/4=(^{207}Pb/^{204}Pb_i–^{207}Pb/^{204}Pb_{NHRL})\times 100$; $\Delta 8/4=(^{208}Pb/^{204}Pb_i–^{208}Pb/^{204}Pb_{NHRL})\times 100$; $^{207}Pb/^{204}Pb_{NHRL}=^{206}Pb/^{204}Pb_i\times 0.1084+13.491$; $^{208}Pb/^{204}Pb_{NHRL}=^{206}Pb/^{204}Pb_i\times 1.209+15.627$ (Hart, 1984). Because U, Th and Pb contents of Dzh89-1 are not available for the initial isotopic ratio calculation, the average $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$ values of other five samples were used for a rough estimate.

into two genetically related rock types. The first type includes ultramafic cumulates, such as pyroxenites, hornblende–pyroxenites, and pyroxene–hornblendites. The second type includes mafic dikes, such as pyroxene–diorites and biotite diorites (which may come from more differentiated magmas based on Mg#) (Fig. 2). The cumulate samples have higher MgO and CaO (greater than 12 and 12.5 wt.%, respectively) but lower TiO_2 (<0.1 wt.%), Al_2O_3 (<5.5 wt.%) and Na_2O (<0.1 wt.%) contents than the dike samples. MgO of the differentiated samples show negative correlations with TiO_2, Al_2O_3, and Na_2O (Fig. 2B, C, and E), but positive correlating with CaO (Fig. 2D), while MgO contents of the cumulate samples show weaker or no such correlations. Mg-numbers (Mg#) of the cumulate samples range from 63 to 87, higher than those of the differentiated magma dikes (43–62). DZh-4 is a cumulate sample with low CaO content and high MgO and H_2O content, consistent with the relatively higher proportion of biotite and hornblende. The Zhujiapu intrusion has high H_2O contents, which is not be due to alteration, but reflects significant amounts of hornblende and biotite in the samples.

4.2. Trace elements

Trace element compositions are given in Table 2. As shown in Fig. 2G, H, and I, the cumulate samples have higher Ni (most >150 ppm) but lower La (<8 ppm) and Sr concentration (<120 ppm) relative to the differentiated magma dike. MgO contents of the differentiated dike samples show positive correlation with compatible elements (e.g., Ni) but negative correlation with incompatible elements (e.g., La, Sr). This indicates that the compositions of dike samples are mainly controlled by the relative proportion of clinopyroxene and plagioclase. MgO contents of the cumulate samples also show positive correlation with Ni but weak or no correlation with La and Sr.

Chondrite-normalized REE patterns are shown in Fig. 3A. Both cumulate and dike samples have moderate to slight negative Eu anomalies with Eu*/Eu from 0.74 to 0.96. Total REE concentrations of the cumulate are from 36.5–85.0 ppm, significantly lower than the dike samples (98.9–277 ppm). All samples are enriched in light rare earth elements (LREE). The $(La/Yb)_N$ (5.33–2.56) and $(Gd/Yb)_N$ (1.89–2.40) of the cumulate samples are smaller than the values of the dikes ($(La/Yb)_N=4.54–20$ and $(Gd/Yb)_N=2.27–3.81$). In the primitive mantle normalized trace element spidergram (Fig. 3B), the trace element abundances of dikes are obviously higher than the cumulate. Both dike and cumulate samples show enrichment in Pb and LILE (e.g., Ba and Th) and depletion in HFSE (e.g., Zr and Ti). Notably, Rb is depleted relative to Ba in these post-collisional mafic–ultramafic intrusive rocks, showing a similarity to trace element pattern of the lower continental crust (Fig. 3B).

4.3. Sr–Nd–Pb isotope data

Whole rock Sr–Nd–Pb isotopic compositions are given in Table 3. Initial isotopic ratios are calculated back at 130 Ma. The $\varepsilon_{Nd}(T)$ values of the Zhujiapu

ε_{Nd}(T)	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	^{206}Pb/^{204}Pbi	^{207}Pb/^{204}Pbi	^{208}Pb/^{204}Pbi	Δ7/4	Δ8/4
−18.0								
−10.5	16.974(2)	15.415(2)	37.740(10)	16.940	15.413	37.688	8.60	158.04
−16.4	16.604(2)	15.349(2)	37.509(6)	16.561	15.347	37.429	6.07	178.04
−17.0	16.922(2)	15.412(2)	37.813(5)	16.878	15.410	37.735	8.93	170.28
−9.3	16.934(6)	15.410(5)	37.730(10)	16.881	15.407	37.631	8.65	159.40
−10.5								
−6.5	17.071(9)	15.441(8)	37.880(20)	*17.027*	*15.439*	*37.801*	*10.22*	*158.85*
−16.1								
−2.3								
−15.8	16.714(8)	15.384(7)	37.630(20)	16.666	15.382	37.543	8.41	176.62
−18.8								
−18.6								

mafic–ultramafic rocks show significant variation from −2.3 to −18.8, with most of them less than −9, roughly overlapping the values of the Mesozoic basaltic rocks (Li and Yang, 2003) and carbonatites (Ying et al., 2004) from the North China Block. In Fig. 4, the Sr–Nd isotopic compositions of the Mesozoic mantle-derived rocks from the North China Block show strong regional variation (Zhang et al., 2004a). ^{87}Sr/^{86}Sr$_i$ of the post-collisional mafic–ultramafic intrusive rocks varies less (0.70605–0.70827) than the Mesozoic mantle-derived rocks from the North China Block (Fig. 4). The Sr–Nd isotopic data in this study, together with previous results for other post-collisional mantle-derived rocks from the Dabie–Sulu orogen, define a trend between the depleted mantle and lower crust (Jahn et al., 1999; Fan et al., 2004; Guo et al., 2004; Wang et al., 2005) (Fig. 4). Apparently, the Sr–Nd isotopic compositions of the post-collisional mafic–ultramafic intrusive rocks from the Dabie orogen are different from those of the Paleozoic kimberlite and peridotite xenoliths from the North China Block (Zhang et al., 2002), the Mesozoic mafic rocks from the South China Block (Li and Yang, 2003), young upper continental crust (Jahn et al., 1999), and the upper crust of the North China Block (Jahn et al., 1999; Xu et al., 2004a). However, they are close to the range of the Mesozoic mantle-derived rocks from the North China Block.

The Pb isotopic compositions of the Zhujiapu intrusion are similar to the Mesozoic basaltic dikes from the Dabie orogen recently reported by Wang et al. (2005) (Fig. 5). The ^{206}Pb/^{204}Pb$_i$ of the Zhujiapu intrusions range from 16.561 to 17.027, similar to those of the wall rock gneiss (15.8–17.2) (Li et al., 2003) and Mesozoic mantle-derived rocks from the North China Block (15.7–17.9) (Li and Yang, 2003). However, they are obviously lower than the values of MORB, EMII (Zindler and Hart, 1986), Mesozoic mafic rocks from the South China Block (18.0–19.0) (Li and Yang, 2003), and Paleozoic kimberlite and peridotite–xenolith (19–21) from Eastern China (Zheng and Lu, 1999; Zhang et al., 2002). The ^{206}Pb/^{204}Pb$_i$ and ^{207}Pb/^{204}Pb$_i$ of the post-collisional mafic–ultramafic intrusive rocks are similar to those of basaltic rocks from the Luxi-Jiaodong region of the North China Block (Fig. 5A), while ^{208}Pb/^{204}Pb$_i$ of the post-collisional mafic–ultramafic intrusive rocks are higher than that of any mantle-derived samples and lower crustal granulites and xenoliths (Liu et al., 2004a) from the North China Block, given a similar ^{206}Pb/^{204}Pb$_i$ (Fig. 5B). Notably, Pb isotopic compositions of feldspar from gray gneiss from North Dabie zone (Wang and Li, unpublished data) and omphacites from eclogites and feldspars from gneisses sampled by the Chinese Continental Scientific Drilling project in the Sulu orogenic belt (Dong et al., unpublished data) are in good agreement with the post-collisional mafic–ultramafic intrusive rocks from the Dabie orogen.

5. Discussion

5.1. Crustal contamination or mantle heterogeneity?

Negative anomalies of HFSE and positive anomalies of LILE in mantle-derived rocks are usually considered as typical “continental” signatures (e.g., Jahn et al., 1999). Considering the geologic background of the Dabie orogen, the “continental” signature might be due to:

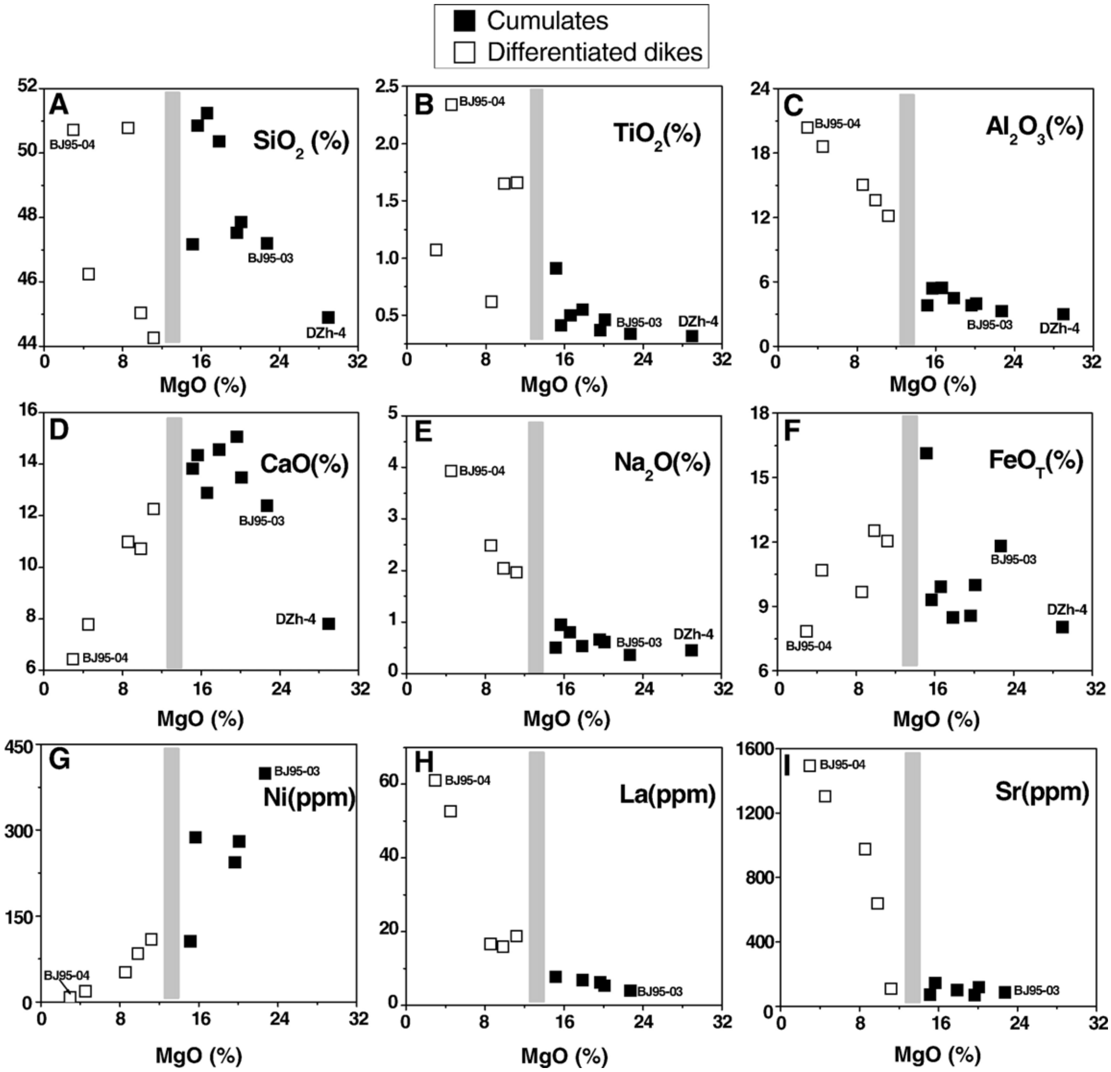

Fig. 2. Plots of MgO versus major (SiO_2, TiO_2, Al_2O_3, CaO, Na_2O, and FeO_T) and trace elements (Ni, La, and Sr) of the Zhujiapu intrusion. Two other samples from the Zhujiapu (BJ95-03 and BJ95-04) are from Jahn et al. (1999). The gray bars represent the compositional gap between the cumulate and differentiated magma dike.

(1) continental crust contamination during intrusion of the mantle-derived melts, or (2) heterogeneity of the uppermost mantle enriched by recycled continental crust. Two lines of evidence rule out the first possibility. First, as suggested by Jahn et al. (1999) and Zhang et al. (2002), assimilation of the crust required to obtain $\varepsilon_{Nd}(T)$ as low as −18.8 will increase the SiO_2 and alkali contents and decrease the MgO contents significantly, which is inconsistent with the low SiO_2 (51.2–44.3 wt.%) and K_2O+Na_2O (most less than 3 wt.%) of the Zhujiapu intrusion. Second, their Sr–Nd–Pb isotopic compositions do not correlate with the geochemical parameters sensitive to crustal contamination such as SiO_2 content (Fig. 6). This indicates that it is highly unlikely that the Sr–Nd–Pb isotope characteristics of post-collisional mantle-derived magmas in the Dabie–Sulu orogen were significantly changed by assimilation and fractional crystallization (AFC) processes in the shallow crust. Zhao et al. (2005) also show that there is no correlation between $\delta^{18}O$ (1.1–6.6‰) and SiO_2 in the Shacun post-collisional mafic–ultramafic intrusion. Therefore, the trace element and isotope characteristics of the Zhujiapu intrusion does not reflect crustal contamination during magma ascent, but likely a heterogeneous uppermost mantle source.

However, a typical Sr–Nd–Pb isotopic signature of the depleted mantle has not been detected in the post-collisional mafic–ultramafic intrusive rocks. Based on variable but low $\delta^{18}O$ values of the UHP metamorphosed ultramafic

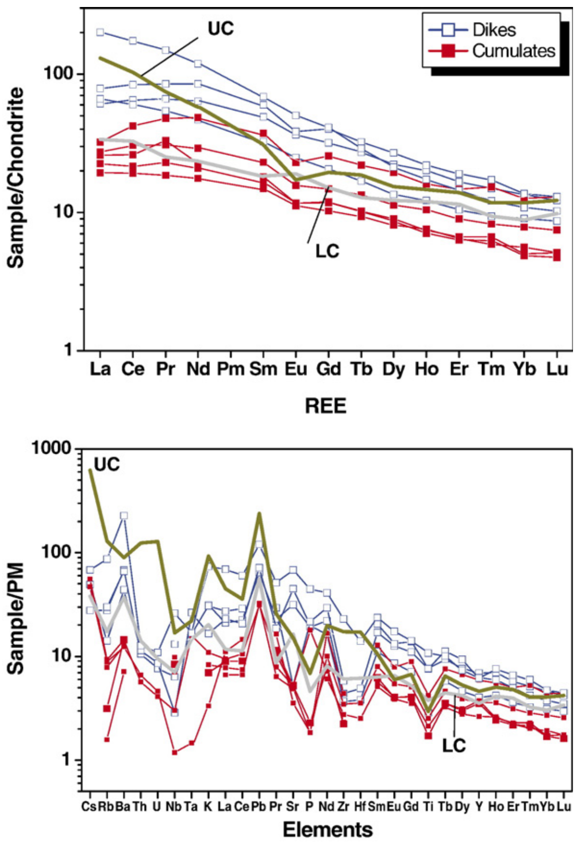

Fig. 3. A. Chondrite-normalized REE patterns for the mafic–ultramafic rocks from the Zhujiapu intrusion; B. Primitive mantle-normalized trace element spidergrams of the mafic–ultramafic rocks. Solid symbols denote the cumulate samples, while open symbols are samples from the differentiated magma. The Zhujiapu intrusion is characterized by enrichments of LILE and depletions of HFSE. UC, MC, and LC denote the upper, middle, and lower crust from Rudnick and Gao (2003). Chondrite and primitive mantle data are from Sun and McDonough (1989).

rocks (peridotites and garnet–pyroxenites) from the Dabie–Sulu orogenic belt, Zhao et al. (2005) argued that they might result from partial melting of peridotites and garnet–pyroxenites in the subducted slabs of the South China Block by the heat from a global "super plume" in the late Mesozoic without involvement of uppermost mantle. However, taking into account of the solidi of the typical mantle peridotite and garnet pyroxenite, which could be up to ~1470 and 1440 °C at 3 GPa (~100 km), respectively (Hirschmann, 2000; Kogiso et al., 2003), the plume would partially melt not only the subducted lithosphere of the South China Block but also the asthenospheric mantle, which is not consistent with the suggestion in Zhao et al. (2005). The UHP metamorphosed ultramafic rocks (garnet–peridotites and garnet pyroxenites) exposed in the Dabie–Sulu orogenic belt are volumetrically too small to be the protolith for the post-collisional mafic–ultramafic intrusive rocks. Furthermore, there is no evidence for the existence of abundant UHP metamorphosed ultramafic rocks in the lower crust in the Dabie–Sulu orogen either. Therefore, the post-collisional mafic–ultramafic intrusive rocks were mainly derived by partial melting of the uppermost mantle, not garnet–peridotites and garnet pyroxenites from the subducted slab.

5.2. Mantle source for the post-collisional mafic–ultramafic intrusive rocks from the Dabie–Sulu orogen

As mentioned above, although major and trace element contents of the Zhujiapu intrusion samples suggest the post-collisional mafic–ultramafic intrusive rocks result from partial melting of the upper mantle with some involvement of continental material, whether or not the subducted continental crust of the South China Block is recycled into

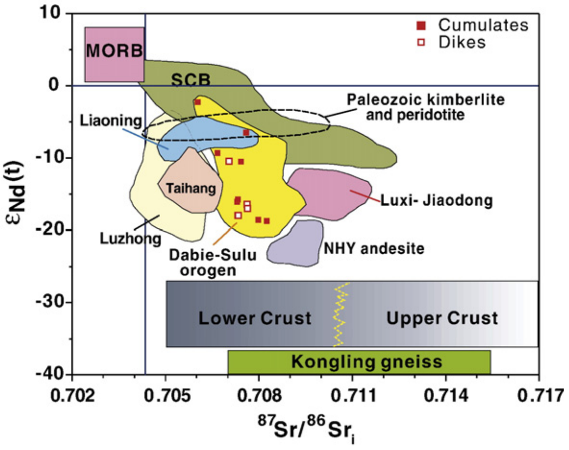

Fig. 4. ε_{Nd}(130 Ma) and initial $^{87}Sr/^{86}Sr$ ratios of the post-collisional mantle-derived rocks in the Dabie–Sulu orogen. The post-collisional mafic–ultramafic intrusive rocks from the Dabie–Sulu orogen show no significant difference from the Mesozoic mantle-derived rocks from the North China Block in terms of the Sr–Nd isotopic composition. Liaoning, Taihang, Luzhong, and Luxi-Jiaodong are referred to the subdivisions of the North China Craton in Fig. 1a. Data source: andesite from the North Huaiyang zone, Fan et al. (2004); mafic igneous rocks from the Dabie–Sulu orogen, this study, Jahn et al. (1999), Fan et al. (2001), Wang et al. (2005), and Yang et al. (2005a,b); lamprophyres from the Sulu orogen, Guo et al. (2004); mafic rocks from the North China Block: Liaoning, Zhang et al. (2003) and Yang et al. (2004); Taihang, Chen et al. (2003), Zhang et al. (2004a), and Wang et al. (2006); Luzhong, Guo et al. (2001a), Xu et al. (2004a), and Zhang et al. (2004a); and Luxi-Jiaodong, Qiou et al. (1997; 2002), Zhang and Sun (2002), Zhang et al. (2002), Liu et al. (2004b), Xu et al. (2004a, b), and Yang et al. (2004); carbonatites from the North China Block, Ying et al. (2004); mafic rocks from the South China Block (SCB), Yu et al. (1993), Liao et al. (1999), Yang et al. (1999), Xu et al. (1999). Guo et al. (2001b), Li et al. (2001b), and Zhou et al. (2001). Other data source: Paleozoic kimberlite and peridotites, Zhang et al. (2000, 2002); Kongling gneiss, Ma et al. (2000); South China Block upper/lower crust, Xu et al. (2004a).

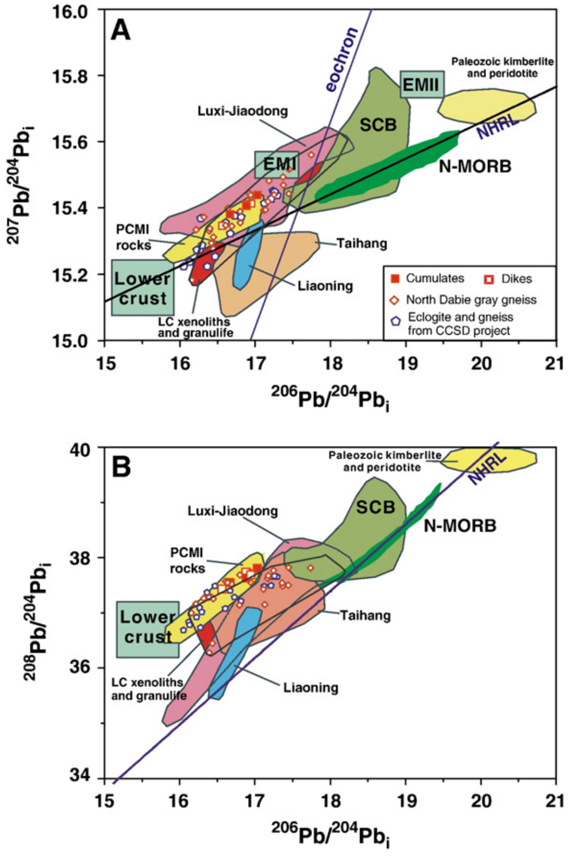

Fig. 5. Initial Pb isotopic compositions of the Zhujiapu intrusion. Data source: The post-collisional mafic–ultramafic intrusive (PCMI) rocks from Dabie, this study and Wang et al. (2005); Liaoning, Zhou et al. (2001) and Zhang et al. (2003); Taihang, Zhang et al. (2004a) and Wang et al. (2006); Luzhong, Xu et al. (2004b); Luxi-Jiaodong, Qiou et al. (1997, 2002), Zhang and Sun (2002), Zhang et al. (2002), Xu et al. (2004b), Liu et al. (2004b), and Yang et al. (2004); South China Block (SCB), Chen et al. (1994), Zhang (1995), and Yan et al. (2003); MORB, EMI, and EMII, Zindler and Hart (1986); Paleozoic kimberlite and peridotite, Zheng and Lu (1999) and Zhang et al. (2002); lower crust (LC) xenolith and granulite from the North China Block, Liu et al. (2004a); eclogite and gneiss from the Chinese Continental Scientific Drilling (CCSD) project (Dong et al., unpublished data); gray gneiss from the North Dabie zone (Wang and Li, unpublished data). $({}^{207}\mathrm{Pb}/{}^{204}\mathrm{Pb})_{\mathrm{NHRL}}=0.1084\times({}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb})_i+13.491$; $({}^{208}\mathrm{Pb}/{}^{204}\mathrm{Pb})_{\mathrm{NHRL}}=1.209\times({}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb})_i+15.627$.

the uppermost mantle remains a question for two reasons. First, the sub-continental lithospheric mantle of the North China Block is highly heterogeneous having a broad range in Sr–Nd isotopic compositions, enrichment in LILE, and depletion in HFSE (Zhang et al., 2004a). Second, the lower crustal xenoliths and granulites from the North China Block also have low $\varepsilon_{\mathrm{Nd}}$ and unradiogenic Pb isotopes (Liu et al., 2004a). Therefore, the origin of the "continental" geochemical features of the post-collisional mafic–ultramafic intrusive rocks from the Dabie–Sulu orogen is not definitive based on these data. Pb isotopes provide important constraints on distinguishing between materials from the subducted continental slab of the South China Block and sub-continental lithospheric mantle and lower crust of the North China Block. This, in turn is crucial for understanding whether the continental crustal materials of the South China Block are recycled to the uppermost mantle during continent–continent collision.

The Pb isotopic composition of the subducting South China Block slab, as reflected by the UHPM rocks, is

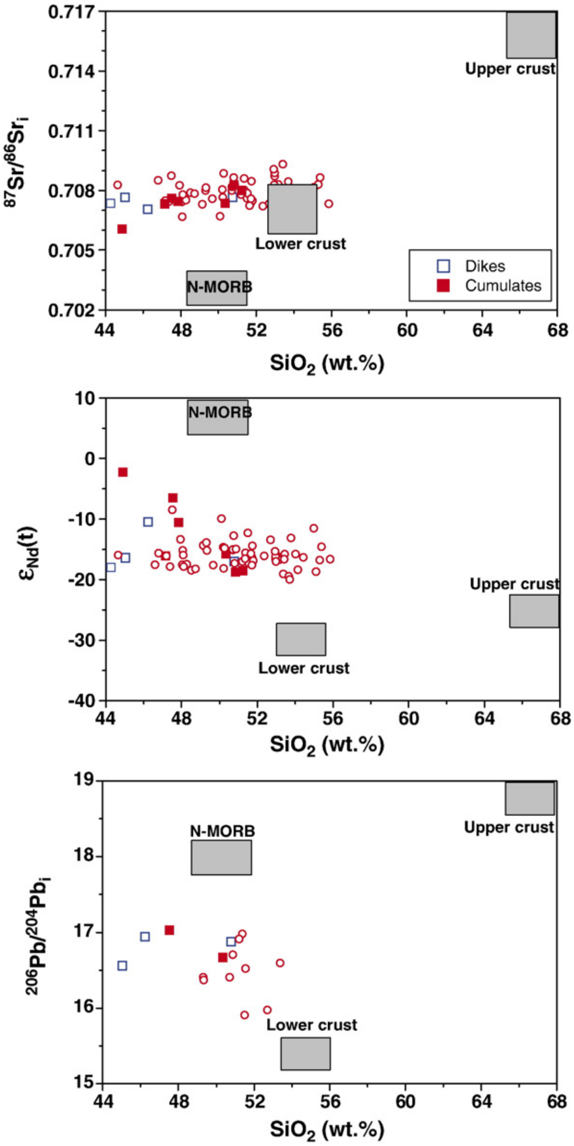

Fig. 6. Plots of initial Sr–Nd–Pb isotopic ratios vs. $\mathrm{SiO_2}$ content of the post-collisional mafic–ultramafic intrusive rocks indicate that assimilation of upper crust is insignificant. See text for more discussion. Data source of other samples (open circles) from the Dabie–Sulu Orogen are same as Fig. 4. Upper and lower crust and N-MORB are from Table 4.

substantially different from the sub-continental lithospheric mantle and lower crust of the North China Block. First, as shown in Fig. 5, the omphacites and feldspars from the high-pressure metamorphic rocks from the North Dabie zone and drilling core from the Chinese Continental Scientific Drilling project in the Sulu region have higher ^{208}Pb/^{204}Pb$_i$ than the mantle-derived rocks and lower crustal xenoliths and granulites from the North China Block at a given ^{206}Pb/^{204}Pb$_i$. This is consistent with the relationship between the $\Delta8/4$ and $\Delta7/4$ (Fig. 7), which shows that the high-pressure metamorphic rocks from Sulu orogen and gray gneiss from the North Dabie zone and have higher $\Delta8/4$ than mantle-derived rocks and lower crustal samples from the North China Block, while the $\Delta7/4$ is similar to samples from the Luxi-Jiaodong region. On the other hand, Sr–Nd–Pb isotope signatures and δ^{18}O values (4.14 to 6.11‰) of zircons of the Mesozoic granitoids in the Dabie–Sulu orogen indicate that they result from partial melting of the lower crust of South China Block (Zhang, 1995; Zhang et al., 2004b; Zhao et al., 2004). The Mesozoic granitoids also have higher $\Delta8/4$ than the deep lithosphere of the North China Block as reflected by the mantle-derived rocks and lower crustal xenoliths and granulites. Therefore, the protolith of some high-pressure metamorphic rocks and the lower crust of the Dabie–Sulu orogen have a history of higher Th/U but similar U/Pb relative to the sub-continental lithospheric mantle of the North China Block. The $\delta7/4+\ \delta8/4$ document that the post-collisional mafic–ultramafic intrusive rocks from the Dabie orogen are closer to the subducted slabs of the South China Block than the sub-continental lithospheric mantle and lower crust of the North China Block (Fig. 7). The relatively low $\Delta8/4$ (or ^{208}Pb/^{204}Pb at a given ^{206}Pb/^{204}Pb) for the sub-continental lithospheric mantle and lower crust of the North China Block indicate that partial melting of old enriched lithosphere cannot produce the Pb isotopic signature of the post-collisional mafic–ultramafic intrusive rocks from the Dabie Orogen. This provides the first direct evidence for the involvement of deeply subducted materials added to the uppermost mantle of the Dabie–Sulu orogen.

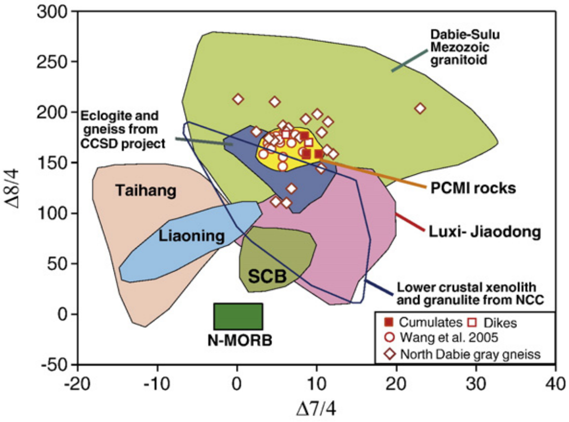

Fig. 7. Delta7/4 versus Delta8/4 of the Mesozoic mantle-derived rocks from Eastern China. The sources of Pb isotopic data are same with Fig. 5 except the granitoids from the Dabie–Sulu orogen from Zhang (1995) and Zhang et al. (2004b). The post-collisional mafic–ultramafic intrusive rocks have similar $\Delta8/4$ to the Mesozoic granitoids, gray gneisses, and high-pressure metamorphic rocks from the Chinese Continental Scientific Drilling (CCSD) project and the North Dabie Zone, but obviously higher than all samples from the different regions and lower crustal granulites and xenoliths in the North China Block. It apparently shows that the high 8/4 of the post-collisional mafic–ultramafic intrusive rocks have a derivation of the upper mantle strongly modified by the recycled subducted continental materials of the South China Block, especially the lower crust. Data sources are same as Fig. 5.

5.3. Petrogenesis of the post-collisional mafic–ultramafic intrusive rocks

Two possible mechanisms can be envisaged to account for the petrogenesis of the post-collisional mafic–ultramafic intrusive rocks in the Dabie Orogen: (1) they result from depleted mantle-derived magmas mixed with felsic magma derived by subducted lower

Table 4
Parameters of isotopic mixing model

	^{87}Sr/^{86}Sr	Sr (ppm)	ε_{Nd}	Nd (ppm)	Ba (ppm)	Rb (ppm)	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	Pb (ppm)
UM[a]	0.703	20	8	1.2	6.989	0.635	18.0	15.6	38.7	0.185
MORB[b]	0.704	150	8	15	6.3	0.56	18.4	15.5	37.6	0.54
Lower crust[c]	0.710	300	−30	24	287	8.4	15.508	15.117	36.818	4.2
Upper crust[d]	0.718	350	−25	26	628	82	19	15.7	39	30

a, b, UM stands for upper mantle peridotite. Sr–Nd data of MORB and UM are from Jahn et al. (1999); Pb, Ba, and Rb data are from Sun and McDonough (1989).

c, Sr–Nd data of lower crust are from Xu et al. (2004a) and Jahn et al. (1999); Pb isotopic composition is from feldspar Pb of Mesozoic granite from the Dabie orogen (Zhang, 1995). Pb concentration is from Rudnick and Fountain (1995). Rb and Ba of the upper crust are from Rudnick and Gao (2003), while Rb and Ba of the lower crust are from the Huilanshan mafic granulite from the Dabie orogen (Hou, 2003).

d, Sr and Nd isotopic compositions of upper crust are modified after Xu et al. (2004a). Pb data are from Wang et al. (2005).

crust, or (2) they are derived from a hybrid upper mantle metasomatised by the melts from subducted continental crust. A simple magma-mixing model between MORB and crust-derived magma with low ε_{Nd} (e.g., lower crust) shows that assimilation of 60 wt.% crustal material is required to decrease the ε_{Nd} of the parental magma from +8 to −18. However, the SiO_2 content of the mixed magma will increase significantly, which is not consistent with the observed composition of the Zhujiapu samples (Table 1). Therefore, partial melting of upper most mantle enriched by melts from subducted lower crust is the only viable process for generating the geochemical features of the Zhujiapu intrusion.

Jahn et al. (1999) proposed that the Sr–Nd isotopic compositions of the post-collisional mafic–ultramafic intrusive rocks result from binary mixing between the mid-lower crust and upper mantle peridotite. However, such binary mixing should result in a positive trend in a $^{206}Pb/^{204}Pb_i$-$\varepsilon_{Nd}(T)$ diagram and negative trend in $^{206}Pb/^{204}Pb_i$–$^{87}Sr/^{86}Sr_i$ diagram, which is inconsistent with observed post-collisional mafic–ultramafic intrusive rocks (see Figs. 8 and 6 in Wang et al., 2005). Three-component mixing models using Sr–Nd–Pb isotopic ratios and Ba/Rb show that addition of a small amount of mafic lower crustal materials (with less than 1% upper crust) to the upper mantle could result in the Sr–Nd–Pb isotopic features of the post-collisional mafic–ultramafic intrusive rocks from the Dabie orogen (Fig. 8). As shown in Fig. 8A, the $^{206}Pb/^{204}Pb_i$ of the post-collisional mafic–ultramafic intrusion in the Dabie orogen and basaltic rocks from the Luxi-Jiaodong region correlate positively with $^{87}Sr/^{86}Sr_i$. Recent discoveries of zoned olivine crystals in mantle xenolith from the Fangcheng basalt in Luxi area (Zhang, 2005) and a composite dunite–orthopyroxenite xenolith in Mesozoic Laiwu high Mg diorite (Chen and Zhou, 2005) indicate that metasomatic reactions occur between mantle peridotite and melt derived from subducted crust in the sub-continental lithospheric mantle beneath the south margin of the North China Block. The less radiogenic Pb and Sr isotopic ratios of the post-collisional mafic–ultramafic intrusive rocks suggests that their mantle source may require more involvement of subducted lower crustal materials than the Luxi-Jiaodong mafic rocks. The results of mixing models using different isotopic ratio pairs and Ba/Rb indicate that less than 15 wt.% crustal materials are required to be added in the uppermost mantle. The deeply subducted crustal material is composed of more than 90% lower crustal plus less than 10% upper crustal material. This would not dramatically change the major element composition but could revise the trace element and isotopic features of the upper mantle peridotite significantly. Because the upper crust is lighter and softer than the lower crust, most of the upper crustal material may

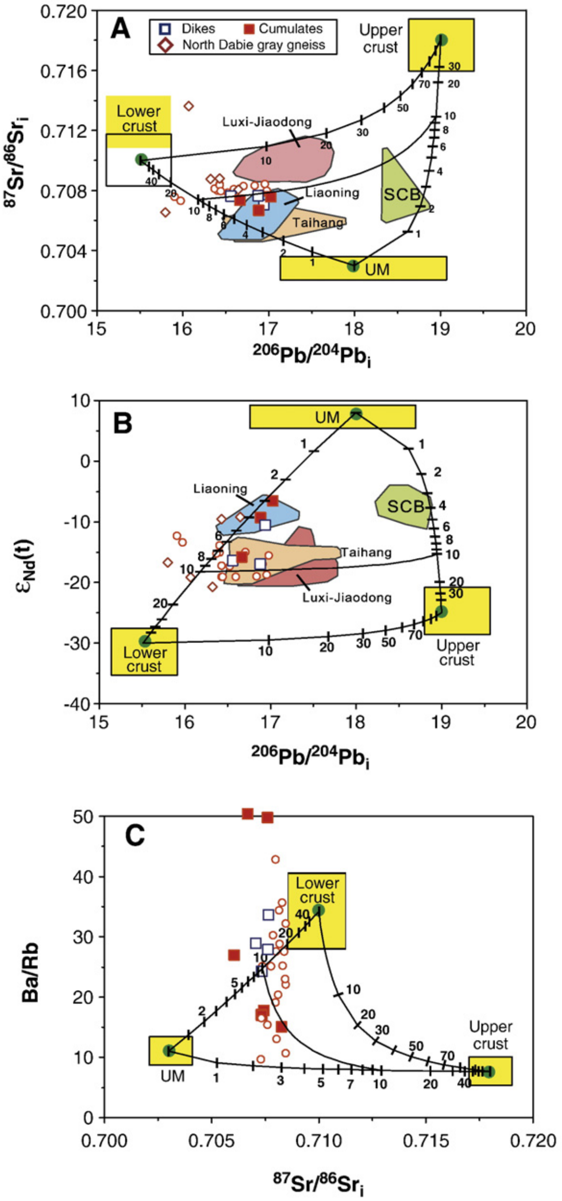

Fig. 8. Sr–Nd–Pb isotope and Ba/Rb diagrams showing mixing between upper/lower crust and upper mantle peridotites. Mass fractions on the mixing curves are given in wt.%. The parameters for the mixing calculation are presented in Table 4. Data sources for Mesozoic mantle-derived rocks from the North China Block are same with Figs. 4 and 5. The Ba/Rb ratio of lower crust is based on mafic granulites from the Dabie orogen in Hou (2003). Mixing calculations show the post-collisional mafic–ultramafic intrusive rocks from the Dabie–Sulu orogen could step from partial melting of the depleted upper mantle hybridized by <15 wt. % of the recycled subducted lower crust with slight involvement of the upper crust (<1%).

have been exhumed during or shortly after the collision from mantle depths. This might be the reason why the contribution of the upper crust is less than 1 wt.%. Mixing between crustal materials and other possible mantle components such as EMI requires even less contribution of continental material because EMI has lower Pb isotope ratios and $\varepsilon_{\mathrm{Nd}}$ than depleted upper mantle (not shown in Fig. 8). We therefore consider that the "continental" signature in the post-collisional mafic–ultramafic intrusive rocks from the Dabie orogen is a result of partial melting of upper mantle peridotite modified by melts from deeply subducted lower crust with low $\varepsilon_{\mathrm{Nd}}$, $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}_i$, $^{207}\mathrm{Pb}/^{204}\mathrm{Pb}_i$, moderate $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}_i$, but high $^{208}\mathrm{Pb}/^{204}\mathrm{Pb}_i$, plus a small contribution of upper crustal materials.

5.4. Delamination of the deeply subducted lower crust

The deeply subducted continental crust could be recycled into the upper mantle by delamination (Lustrino, 2005), which has been proposed to explain the tectonic structure and magmatism in several orogens, including the Tibeten Plateau (England, 1993), Andean Puna Altiplano (Kay and Kay, 1993), and Sierra Nevada (Lee et al., 2000). The tectonic scenario from early Triassic to early Cretaceous around the Dabie–Sulu orogen can be illustrated in Fig. 9. The subduction of the South China Block continental crust occurred in the early Triassic (Li et al., 1993) (Fig. 9A), followed by slab break-off and the initial uplift of UHPM rocks from mantle depths to mid-crustal levels (Li et al., 2000; Sun et al., 2002) (Fig. 9B). Paleomagnetic studies suggest that the convergence between the North China Block and South China Block continued after break-off of the subducted plate (Lin et al., 1985; Zhao and Coe, 1987). The continuous convergence between the North China Block and South China Block created an over-thickened lithosphere in the Dabie–Sulu orogen and southern margin of the North China Block (Fig. 9C). The appearance of garnet and loss of plagioclase in the deeply subducted mafic lower crust or lower part of thickened mafic lower crust resulted in a gravitational instability and negative buoyancy in the keel of the thickened lithosphere. The mafic lower continental

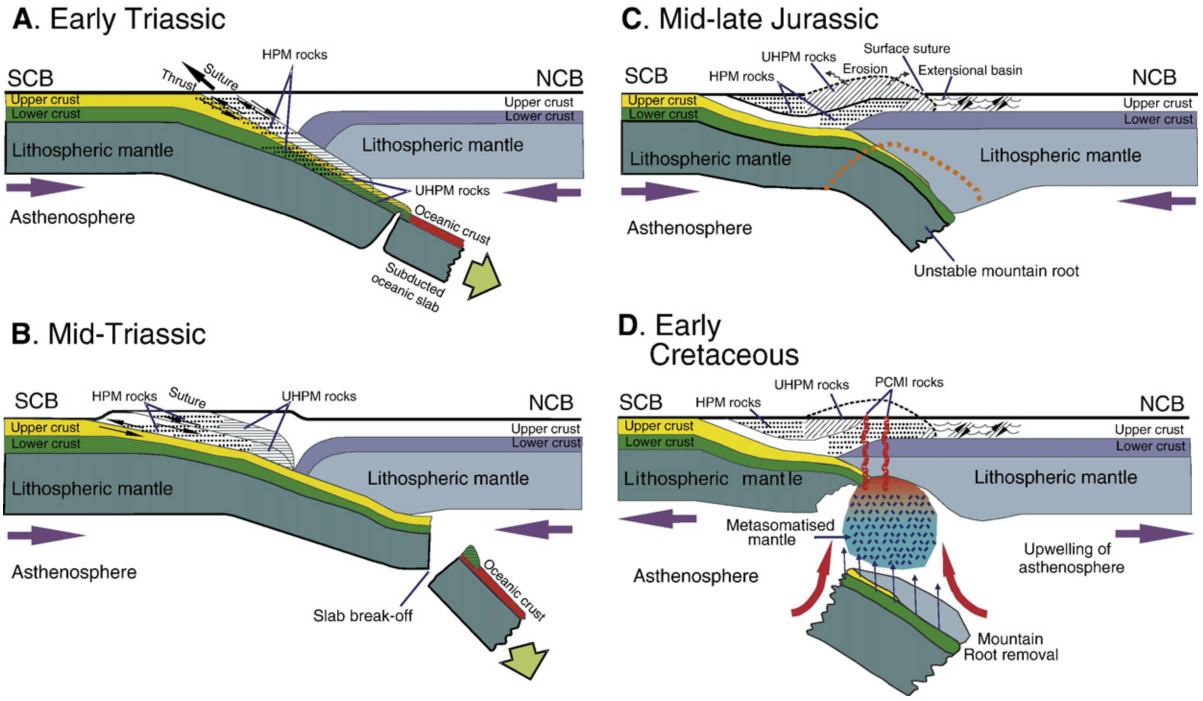

Fig. 9. Tectonic cartoons showing the continent–continent collision, lithospheric delamination, recycling of subducted crustal materials, and post-collisional mafic magmatism. (A) Continental collision between the North China Block (NCB) and South China Block (SCB) occurred at ~230 Ma with thrust fault developed. (B) After break-off of the subducted oceanic slab, the continental slab will bounce upward and continuously be flat subducted. (C) Continuous subduction of the South China Block created over-thickened lithosphere in the mid-Jurassic, which is gravitationally unstable. (D) Subducted lower crust and lithospheric mantle foundered into asthenosphere in the early Cretaceous. Partial melts from the deeply subducted lower crust metasomatised asthenosphere. During lithospheric extension and thinning, the metasomatised asthenosphere was partially melted, producing the post-collisional basaltic magma with "continental" signatures. HPM rocks stand for high-pressure metamorphic rocks.

(eclogitic) crust and lithospheric mantle of the South China Block (with a density up to 3.8 g/cm^3) would detach and founder into the upper mantle (Fig. 9D). Because of the correspondence between the fast uplift of the Dabie orogen and an intense post-collisional magmatism and because no Jurassic igneous rocks have been observed in the Dabie orogen, the delamination or mountain root removal in the Dabie orogen may have occurred in the early Cretaceous (Hou et al., 2005). The asthenosphere upwelled to replace the volume previously occupied by the delaminated lithosphere (Lustrino, 2005). This asthenosphere was metasomatised by SiO_2-rich melt derived from the foundering subducted crustal materials (mainly mafic lower crust). Under the extensional environment in the early Cretaceous, the upwelling metasomatised mantle was partially melted due to decompression to produce the parental magma of the post-collisional mafic–ultramafic intrusive rocks (Fig. 9D).

6. Conclusions

The post-collisional mafic–ultramafic intrusive rocks from the Dabie orogen clearly show "continental" signatures, such as enrichments in LILE and Pb, depletions in HFSE, moderate $^{87}Sr/^{86}Sr_i$, low ε_{Nd}, and unradiogenic Pb isotopes. Rb depletion relative to Ba suggests the involvement of the lower continental crust as the main source of the "continental" signatures. These "continental" signatures reflect the properties of the mantle source and do not result from crustal contamination during magma ascent or mixing between crustal and mantle-derived magmas. There is no obvious difference between the trace element and Sr–Nd isotopic composition of the post-collisional mafic–ultramafic intrusive rocks and the Mesozoic mantle-derived rocks from the North China Block; however, the Pb isotopic signatures are distinctive. For a given initial $^{206}Pb/^{204}Pb$ or $\Delta 7/4$, the $^{208}Pb/^{204}Pb$ or $\Delta 8/4$ of the post-collisional mafic–ultramafic intrusive rocks is significantly higher than the deep lithosphere of the North China Block including the sub-continental lithospheric mantle as reflected by Mesozoic mantle-derived rocks and the ancient lower crust by granulites and xenoliths from the North China Block. In contrast, this high $^{208}Pb/^{204}Pb$ is observed in Mesozoic granitoids, gray gneisses, and eclogites from the Dabie–Sulu orogen. This strongly indicates that the mantle source of the post-collisional mafic–ultramafic intrusive rocks contained deeply subducted continental materials from the South China Block. The "continental" signatures of the post-collisional mafic–ultramafic intrusive rock result from a hybrid mantle metasomatised by recycled crustal material. Therefore, we conclude that the deeply subducted continental crust, especially its lower mafic crust, could be recycled into the upper mantle and create mantle heterogeneity. The granulite to eclogite facies transformation (reflecting the over-thickening of lithosphere) creates a gravitational instability in the subducted mafic lower continental crust, providing the driving force for the lithospheric delamination. Foundering and recycling of deeply subducted lower mafic continental crust could result in mountain root removal, mantle heterogeneity, and a more intermediate composition of the bulk crust.

Acknowledgement

This work was funded by the Natural Science Foundation of China (Grant. No.40373009) and the Major State Basic Research development program (Grant. No. G1999075503). We thank Bin Chen for revising the geology map and Zhenhui Hou for providing the unpublished Ba and Rb data of mafic granulites from the Dabie Orogen. Constructive reviews by Yaoling Niu, Roberta Rudnick, and Suzanne Kay have allowed significant improvement of the paper. We thank Emily Berna and Dr. Craig Lundstrom for help with polishing the English. This contribution benefited from S. R. Hart who provided training in Sr–Nd isotope analysis when Shuguang Li was visiting MIT.

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