Geological Society, London, Special Publications

Contributions of the lower crust to Mesozoic mantle-derived mafic rocks from the North China Craton: implications for lithospheric thinning

F. Huang, S.-G. Li and W. Yang

Geological Society, London, Special Publications 2007, v.280; p55-75.
doi: 10.1144/SP280.3

Contributions of the lower crust to Mesozoic mantle-derived mafic rocks from the North China Craton: implications for lithospheric thinning

F. HUANG[1,2], S.-G. LI[1,*] & W. YANG[1]

[1]*CAS Key Laboratory of Crust–Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China (*Corresponding author e-mail: lsg@ustc.edu.cn)*

[2]*Department of Geology, University of Illinois at Urbana–Champaign, 1301 W. Green Street, IL 61801, USA*

Abstract: The lithospheric mantle underneath the North China Craton changed completely from the Palaeozoic to the Cenozoic. This study reviews geochemical data from Mesozoic mantle-derived mafic rocks from the North China Craton to investigate the role of mafic lower continental crust in lithosphere replacement. Samples from the North China Craton have typical 'continental' geochemical signatures, including depletion of high field strength elements, enrichment of large ion lithophile elements and Pb, unradiogenic Pb isotopes, and enriched Sr–Nd isotopic ratios. Positive correlation between initial $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$, low Ce/Pb and Nb/U, high Ba/Nb and La/Nb, and unradiogenic Pb isotopes of Mesozoic mafic rocks cannot simply be explained by derivation from a lithospheric mantle enriched by ancient (Archaean or Mesoproterozoic) fluid or melt metasomatism. Instead, they more probably result from a lithospheric mantle or upwelling asthenosphere underneath the North China Craton that was modified by the lower continental crust in the Mesozoic. Because oceanic plate subduction zones surrounded the North China Craton during the late Palaeozoic, the lithospheric mantle underneath the North China Craton was weakened by fluids derived from subducted slabs, and thus shortened and thickened by continent–continent collisions of the North China Block with the South China Block and the Siberian plate. Metamorphic reactions occurred in the mafic lower continental crust beneath the North China Craton, creating garnet-bearing assemblages (eclogite and garnet pyroxenite) with densities of up to 3.8 g cm^{-3}, which led to negative buoyancy in the over-thickened lithosphere. The unstable lithosphere was delaminated and subsided into the uppermost mantle. The delaminated lower crust partially melted, producing SiO_2-rich melts that metasomatized surrounding asthenospheric mantle, which upwelled and replaced the volume formerly occupied by the delaminated lithospheric mantle, resulting in the 'continental' geochemical signatures widely observed in Mesozoic mantle-derived mafic rocks from the North China Craton. The 'continental' geochemical signatures of Mesozoic mantle-derived mafic rocks suggest that lithospheric delamination could have occurred by the time of volcanic eruption in the northern margin of the North China Craton in the mid-Jurassic and later in the southern margin and Dabie–Sulu Orogen in the early Cretaceous.

The lithospheric thinning of the North China Craton during the Mesozoic has attracted considerable attention over the last two decades (e.g. Griffin *et al.* 1998; Guo F. *et al.* 2001; Zhang *et al.* 2002, 2003, 2004; Chen B. *et al.* 2003; Xu Y. *et al.* 2004*a*; Zhang 2005). Diamond-bearing kimberlites and mantle xenoliths demonstrate that a thick (*c.* 200 km) cold (*c.* 40 mW m^{-2}) lithosphere existed in the North China Craton in the Palaeozoic, but a thin (*c.* 80 km) and hot (*c.* 60 mW m^{-2}) lithosphere was present in the Cenozoic in the eastern part of the North China Craton (Eastern Block in Fig. 1; Griffin *et al.* 1998; Zheng *et al.* 2003). This indicates that about 120 km of lithosphere has been removed since the early Palaeozoic. Also, the geochemical characteristics of the Palaeozoic and Cenozoic lithosphere mantle are very different (Table 1). The Palaeozoic lithospheric mantle underneath the North China Craton is characterized by EMII features, such as high $^{206}Pb/^{204}Pb$ (*c.* 20.2), a significant variation of $^{87}Sr/^{86}Sr$, and negative ε_{Nd} (*c.* −5) (Zheng & Lu 1999; Zhang *et al.* 2002), distinct from the Cenozoic lithospheric mantle below the Eastern Block of the North China Craton, which has Sr–Nd–Pb isotopic compositions similar to those of mid-ocean ridge basalt (MORB) and ocean island basalt (OIB) (Peng *et al.* 1986; Song *et al.* 1990; Basu *et al.* 1991). Apparently, the lithospheric mantle of the Eastern Block of the North China Craton was

From: Zhai, M.-G., Windley, B. F., Kusky, T. M. & Meng, Q. R. (eds) *Mesozoic Sub-Continental Lithospheric Thinning Under Eastern Asia*. Geological Society, London, Special Publications, **280**, 55–75. DOI: 10.1144/SP280.3
0305-8719/07/$15

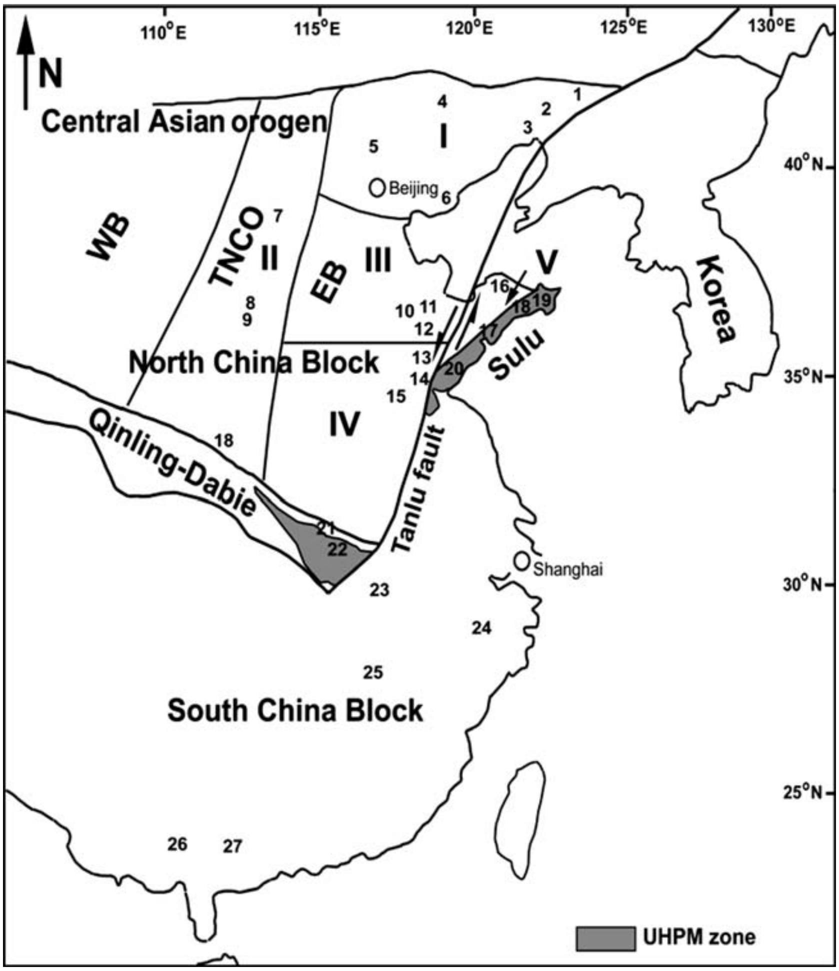

Fig. 1. Simplified map showing major locations of Mesozoic mantle-derived mafic rocks in Eastern China. Mesozoic lithospheric mantle provinces and locations of Mesozoic mantle-derived mafic rocks are modified from Li & Yang (2003) and Zhang *et al.* (2004). I, North margin (Liaoning region); II, Taihang; III, Luzhong; IV, Luxi; V, Jiaodong. Localities of Mesozoic mantle-derived mafic rocks from Eastern China are from Table 2. UHPM zone, ultrahigh-pressure metamorphic zone; WB, Western Block; TNCO, Trans-North China Orogen; EB, Eastern Block.

replaced between the Palaeozoic and Cenozoic (Zheng *et al.* 2003).

The reason for the removal and replacement of the Palaeozoic lithospheric mantle is still not well known. Possible mechanisms include destabilization of the North China Craton as a result of the Indo-Eurasian collision (Menzies *et al.* 1993), replacement by asthenosphere upwelling (Xu Y. *et al.* 2004*a*), and destruction of the lithosphere as a result of the subduction of oceanic crust in the Palaeozoic and continental crust in the Mesozoic beneath both the northern and southern margins of the North China Craton (Zhang *et al.* 2003).

Because the Mesozoic lithospheric mantle of the North China Craton is transitional, it can provide critical constraints on understanding the lithospheric evolution during the Phanerozoic. Widespread Mesozoic mantle-derived mafic magmatism within the North China Craton provides important insights into the Mesozoic lithospheric mantle (Fig. 1 and Table 2). It is well known that Mesozoic mantle-derived mafic igneous rocks are characterized by typical 'continental' geochemical signatures, including depletion of high field strength elements (HFSE), enrichment of large ion lithophile elements (LILE), negative ε_{Nd} (most ranging from -10 to -20), variable $^{87}Sr/^{86}Sr$ (EMI-type with lower $^{87}Sr/^{86}Sr$ and EMII-type with higher $^{87}Sr/^{86}Sr$), and unradiogenic Pb isotope ratios (Qiu *et al.* 2000; Guo F. *et al.* 2001, 2003; Qiou *et al.* 2002;

Table 1. *Comparison of Sr–Nd–Pb isotopic compositions of Mesozoic mantle-derived mafic rocks and carbonatites from the North China Craton with Palaeozoic and Cenozoic lithospheric mantle*

	Palaeozoic lithospheric mantle	Mesozoic				Cenozoic lithospheric mantle
		Liaoning	Taihang	Luzhong	Luxi–Jiaodong	
Mantle type	EMII	EMI	EMI	EMI	EMII	DMM
$^{87}Sr/^{86}Sr$ (130 Ma)	0.704–0.711	0.7049–0.7078	0.7049–0.7066	0.7040–0.7069	0.7087–0.7114	0.703–0.706
ε_{Nd}(130 Ma)	~ -5	−4.9 to −9.1	−9.3 to −16.7	−4.0 to −21.1	−9.8 to −18.0	−2 to +8
$^{206}Pb/^{204}Pb$ (130 Ma)	19.2–20.8	16.77–17.26	16.51–17.77	17.04–17.50	16.57–17.65	17.0–18.6

Data sources for mantle-derived rocks: Liaoning, Zhou *et al.* (2001), Zhang *et al.* (2003) and Yang *et al.* (2004*b*); Taihang, Chen B. *et al.* (2003, 2004), Zhang *et al.* (2004) and Wang *et al.* (2006); Luzhong, Guo F. *et al.* (2001), Xu Y. *et al.* (2004*a*) and Zhang *et al.* (2004); Luxi–Jiaodong, Qiou *et al.* (1997, 2002), Zhang *et al.* (2002), Xu Y. *et al.* (2004*a*), Yang *et al.* (2004*a*) and Ying *et al.* (2004). Palaeozoic lithospheric mantle is from Zheng & Lu (1999) and Zhang *et al.* (2002). Cenozoic lithospheric mantle is from Peng *et al.* (1986), Song *et al.* (1990) and Basu *et al.* (1991). DMM, depleted MORB mantle.

Table 2. *Summary of Mesozoic mantle-derived rocks in Eastern China*

Location	Rock type	Age (Ma)	Dating method	Reference
North China Block				
Liaoning region				
South of Chifeng–Kaiyuan fault, Liaoxi (1)*	Andesite, basaltic andesite, alkali basalt, sub-alkali basalt	–	–	Zhou *et al.* (2001)
Wulahada, Fuxin–Yixian (1)	High-Mg andesite	142.4 ± 2.2	Whole-rock K–Ar	Zhang *et al.* (2003)
Liaodong (2)	Diorite, mafic enclave	122–127	LA-ICP-MS zircon U–Pb	Yang *et al.* (2004*b*)
Taihang region				
Wang'an (3)	Monzogabbro–diorite	130–145	Zircon U–Pb, Rb–Sr isochron	Chen *et al.* (2003*a*)
Laiyuan (3)	Gabbro	135–145	Whole-rock K–Ar	Zhang *et al.* (2004)
Hanxing	Gabbro	150–160	Whole-rock K–Ar	Zhang *et al.* (2004)
Guyi and Fushan (4)	Gabbro	155	–	Zhang *et al.* (2004)
Xishu, Wu'an, Hongshan (4)	Monzogabbro, monzodiorite, syenite	129–138	Zircon U–Pb, Rb–Sr isochron	Chen *et al.* (2004)
Donggang (4)	Gabbro	155	–	Zhang *et al.* (2004)
Dongye (4)	Gabbro	125.2 ± 4.5	SHRIMP zircon U–Pb	Wang *et al.* (2006)
Xinyang (5)	Xenolith-bearing volcanic pipe	178.3 ± 3.8	Whole-rock K–Ar	Lu *et al.* (2003)
Luzhong region				
Jinan (6)	Gabbro	115	Whole-rock K–Ar	Lin *et al.* (1996)
Zouping (7)	Gabbro	120 ± 5	Strata	Guo F. *et al.* (2001)
Laiwu (8)	Gabbro, diorite	126–132	Whole-rock K–Ar, SHRIMP zircon U–Pb	Xu Y. *et al.* (2004*a*); Zhang *et al.* (2004)
Luxi–Jiaodong region				
Mengyin (9)	K-rich basalts, lamproite	115–124	Whole-rock K–Ar	Qiou *et al.* (1997, 2002)
Yinan (10)	Gabbro, diorite	126–132	SHRIMP zircon U–Pb	Xu Y. *et al.* (2004)
Fangcheng (10)	Alkaline basalt, olivine tholeiite	124.9 ± 1.8	Whole-rock K–Ar	Zhang *et al.* (2002)
Laiwu–Zibo	Carbonatite	118–122.9	Phlogopite K–Ar, Rb–Sr isochron	Ying *et al.* (2004)
Zibo basin	Olivine dolerite, gabbro, pyroxenite	106–107	Whole-rock K–Ar	Liu *et al.* (2004*a*)
Linglong (16)	Basalt	123.9–132.5	Whole-rock K–Ar	Yang *et al.* (2004*a*)
Mouping (16)	Basalt	120 ± 1.1	Whole-rock K–Ar	Yang *et al.* (2004*a*)
Sulu orogenic belt				
Jimo (17)	Basalt	110–130	Whole-rock K–Ar	Fan *et al.* (2001)

Sanjia lode-gold deposit (18)	Calc-alkaline lamproite	122–127	Whole-rock and mineral K–Ar	Guo *et al.* (2004)
Jiazishan, Shidao (19)	Mafic enclave, pyroxene syenite, mafic dyke	201–215	SHRIMP zircon U–Pb, mineral Ar–Ar, zircon U–Pb	Chen J. F. *et al.* (2003); Yang *et al.* (2005*a*)
Shijiusuo (20)	Mafic dykes and enclave, biotite–pyroxene monzodiorite	108–124	Whole-rock and mineral K–Ar, SHRIMP zircon U–Pb	Yang *et al.* (2005*b*)
Dabie orogenic belt				
North Huaiyang (21)	Basaltic trachyandesite, trachyandesite	116–132	K–Ar	Fan *et al.* (2004)
Shacun (22)	Gabbro, diorite	122–128	SHRIMP zircon U–Pb, Rb–Sr and Sm–Nd isochron	Jahn *et al.* (1999); Zhao *et al.* (2005)
Jiaoziyan (22)	Gabbro	120–133	Rb–Sr, Sm–Nd isochron, Ar–Ar	Hacker *et al.* (1998); Jahn *et al.* (1999)
Zhujiapu (22)	Gabbro, pyroxenite, hornblendite	130.2 ± 1.4	Zircon U–Pb	Li *et al.* (1999)
Dongshichong, Dahuaping, Guanzhuang, Shutan, Anjiahe, Luoerling (22)	Diabase, gabbro, lamprophyre, trachyandesite	127.6–131.8	Whole-rock K–Ar	Wang *et al.* (2005)
Liujiawa (22)	Gabbro	–	–	Ma *et al.* (1998)
South China Block				
Ningwu (23)	Alkaline gabbro, trachyandesite, phonolite	–	–	Xing (1996)
Middle–lower reach of the Yangtze River (23)	Gabbro, pyroxene diorite, basalt	–	–	Yan *et al.* (2003)
SE Zhejiang (24)	Basalt	120	–	Yu *et al.* (1993); Zhou *et al.* (1993); Yang *et al.* (1999)
Jiangxi (25)	Olivine basalts–shoshonite	130	–	Liao *et al.* (1999)
Jiangshan–Guangfeng (25)	Tholeiite, alkaline basalt	98–105	Whole-rock K–Ar	Yu *et al.* (2004)
East–south of Guangxi (26)	Gabbro	–	–	Guo X.-S. *et al.* (2001)
Mashan (27)	Hornblende monzonite	164 ± 2	Mineral K–Ar	Li *et al.* (2000)

*Numbers in parentheses indicate localities of Mesozoic mafic rocks from Eastern China shown in Figure 1.

Zhang & Sun 2002; Zhang *et al.* 2002, 2003, 2004; Chen B. *et al.* 2003; Li & Yang 2003; Xu Y. *et al.* 2004*a*, *b*; Yang *et al.* 2004*a*; Ying *et al.* 2004; Zhang *et al.* 2005). These signatures are not consistent with either the Palaeozoic or Cenozoic lithospheric mantle (Peng *et al.* 1986; Song *et al.* 1990; Basu *et al.* 1991; Chung 1999; Zhang *et al.* 2002; Table 1).

It is widely considered that such 'continental' geochemical signatures of Mesozoic mantle-derived mafic rocks from the North China Craton were derived from an enriched subcontinental lithospheric mantle (e.g. Guo *et al.* 2003; Yang *et al.* 2004*a*); two main models have been proposed. The first is that the subcontinental lithospheric mantle is an EMI-type resulting from multiple metasomatism related to subduction-related processes in the Archaean and Mesoproterozoic in the course of accretion of the North China Craton (e.g. Yang *et al.* 2004*a*); partial melting of the ancient subcontinental lithospheric mantle at different depths can explain the variation of geochemical features of Mesozoic mantle-derived mafic magmas (Guo *et al.* 2003). However, there is no evidence for the existence of an EMI-like enriched subcontinental lithospheric mantle with low ε_{Nd} (up to -21) before the Mesozoic because the Palaeozoic kimberlites and peridotites have EMII-type isotopic features with a limited range of ε_{Nd} from -5 to -7, high $^{206}Pb/^{204}Pb$, and a large variation of $^{87}Sr/^{86}Sr$ from 0.705 to 0.712 (Zheng & Lu 1999; Zhang *et al.* 2002).

The second model suggests that the Mesozoic subcontinental lithospheric mantle of the North China Craton was severely modified by a Si–Al-rich melt by partial melting of deeply subducted materials from the South China Block or Palaeo-Pacific plate (Zhang *et al.* 2002, 2003; Chen & Zhou 2005). This model is supported by mantle–melt reactions observed in olivine xenocrysts from Fangcheng basalts (Zhang 2005) and from composite dunite–orthopyroxene xenoliths captured in Laiwu high-Mg diorites (Chen & Zhou 2005). This model can explain the EMII-type signatures of mafic rocks and carbonatites from Western Shandong (Luxi) and Jiaodong peninsula (the Luxi–Jiaodong region hereafter), but it cannot explain EMI-type signatures in Mesozoic mafic rocks from the centre of the North China Craton (Taihang and Luzhong regions) where the effect of the subducted South China Block or Palaeo-Pacific plate is insignificant. Thus, the origin of the enriched signatures in Mesozoic mantle-derived mafic rocks remains controversial.

This paper compiles recently published geochemical data from Mesozoic mantle-derived mafic igneous rocks to constrain the origin of their enriched signatures and understand the transformation of the subcontinental lithospheric mantle of the North China Craton from the Palaeozoic to Cenozoic. The purpose of this study is (1) to reveal that geochemical signatures of Mesozoic mantle-derived mafic igneous rocks are consistent with the contribution of lower crust to the Mesozoic uppermost mantle of the North China Craton, but do not support derivation from a lithospheric mantle enriched by ancient fluid or melt metasomatism, and (2) to provide a delamination model to explain the lithospheric thinning process of the North China Craton during the Mesozoic.

Geological background

Archaean rocks with ages of 3.6–3.8 Ga occur in the north to centre of the North China Craton, indicating that this is one of the oldest cratons in the world (e.g. Zheng *et al.* 2004, and references therein). However, the North China Craton is different from other old cratons in many respects, including high heat flow, thinned lithosphere, presence of earthquakes, unusually evolved bulk chemical crustal composition, and widespread magmatism from the late Mesozoic to Cenozoic (Gao *et al.* 2004). The North China Craton can be divided into the Western Block and Eastern Block, which are separated by the Trans-North China Orogen (Fig. 1). The North China Craton was stabilized when the Western and Eastern blocks collided along the Trans-North China Orogen at 1.8 Ga (Zhao *et al.* 2000). The North China Craton collided with the South China Block to the south along the Qinling–Dabie–Sulu Orogen in the early Triassic (Li *et al.* 1993) and to the north with the Centre Asian Orogen at the Solonker suture in the end-Permian (Xiao *et al.* 2003). The North China Craton and attached southern Central Asian Orogen collided with northern Central Asian Orogen along the Mongol–Okhotsk suture in the Jurassic (Tomurtugoo *et al.* 2005).

The Western Block of the North China Craton did not undergo lithospheric thinning or experience significant magmatism after the stabilization of the North China Craton at 1.8 Ga (Zhao *et al.* 2000; Zhang *et al.* 2003). However, magmatism occurred widely in the Eastern Block of the North China Craton after the Palaeozoic. The presence of Ordovician diamond-bearing kimberlites in the Eastern Block (e.g. in Mengyin and Fuxian) indicates that the lithosphere was cold and thick at that time (e.g. Griffin *et al.* 1998). Mesozoic magmatic rocks ranging from basalts to andesites and granites are widespread in Eastern China. Figure 1 and Table 2 show localities, rock types and ages of mafic intrusions in Eastern China. Mesozoic igneous carbonatites occur in the Luxi region

(Ying *et al.* 2004). Mesozoic mantle-derived mafic rocks show distinct regional heterogeneity (Zhang *et al.* 2004). On the basis of geochemical differences of Mesozoic mantle-derived mafic rocks, the North China Craton is divided into five major units following a slightly modified scheme proposed by Zhang *et al.* (2004) (Fig. 1): Liaoning (province I); Tainang (province II); Luzhong (province III); Luxi (province VI); Jiaodong (province V). The geochemical features of these provinces are discussed below.

Geochemical database of Mesozoic mantle-derived mafic rocks from Eastern China

The main purpose of this study is to understand the evolution of the lithospheric mantle of the North China Craton from the Palaeozoic to Cenozoic. Therefore, to avoid crustal-derived rocks, we have selected only basalts and basaltic andesites with a SiO_2 content <56 wt% and MgO content >4 wt% (most >5 wt%) from the data pool of Mesozoic magmatic rocks; the data sources are listed in Table 1. Some samples are mafic enclaves from Mesozoic granitoids, which Yang *et al.* (2004*a*, 2005*a*, *b*) suggested have mantle characteristics. Igneous carbonatites are from the Luxi region (Western Shandong) (Ying *et al.* 2004). For the northern margin of the North China Craton only samples older than 110 Ma were used because basalts later than 110 Ma in this area were produced by partial melting of asthenosphere in an extensional tectonic environment in the continental margin of Eastern Asia (Zhang *et al.* 2004). Coeval mantle-derived mafic rocks from the South China Block and Dabie–Sulu Orogen were also studied for comparison.

Trace element contents of most samples were analysed by inductively coupled plasma-mass spectrometry (ICP-MS) with precision better than $\pm 5\%$ shown by more than two rock standards (e.g. Zhang *et al.* 2002; Yang *et al.* 2005*a*, *b*) or reproducibility of duplicated analyses (e.g. Guo F. *et al.* 2001). A few samples were measured by isotope dilution (ID) methods and X-ray fluorescence (XRF) spectrometry, including those of Jahn *et al.* (1999), which were useful to check for the consistency of Rb–Sr contents between the XRF and ID methods as a means of demonstrating the quality of trace element compositions. Because Sr–Nd–Pb isotopic compositions of the mantle-derived mafic rocks were measured in different laboratories, we corrected the isotopic ratios based on the same standard values: NBS-987 $^{87}Sr/^{86}Sr = 0.71025$; BCR-1 $^{143}Nd/^{144}Nd = 0.512630$; NBS981 $^{207}Pb/^{204}Pb = 0.9142 \pm 0.0015$. All initial isotopic ratios were calculated to 130 Ma.

Geochemistry of Mesozoic mantle-derived mafic rocks from the North China Craton

Mesozoic mantle-derived mafic rocks share some common trace element compositions. Their trace element patterns are similar to those of continental crust (Rudnick & Gao 2003). They are enriched in light rare earth elements (LREE) relative to heavy rare earth elements (HREE) (Fig. 2a). Furthermore, mafic rocks from the North China Craton are enriched in LILE (Cs, Ba, U) and Pb, and depleted in HFSE (Nb, Zr, Ti) relative to N-MORB and OIB (Fig. 2b). Rb is also depleted relative to Ba, distinct from the upper crust but similar to the lower crust (Fig. 2b).

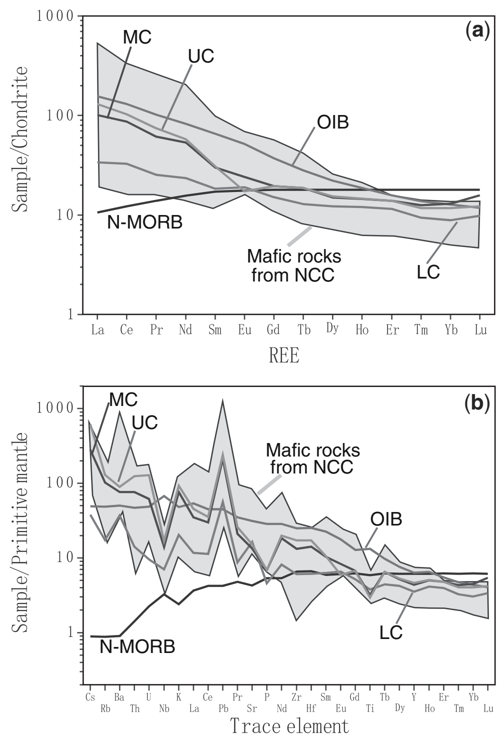

Fig. 2. Chondrite-normalized REE patterns (**a**) and primitive mantle-normalized trace element spidergrams (**b**) of Mesozoic mafic rocks from the North China Craton (NCC). Chondrite and primitive mantle values are from Sun & McDonough (1989). Data sources of Mesozoic mafic rocks from the North China Craton are listed in Table 1. Data for Mesozoic mafic rocks from the South China Block are from Yu *et al.* (1993), Zhou *et al.* (1993), Xing (1996), Liao *et al.* (1999), Yang *et al.* (1999), Li *et al.* (2000), Guo X-S. *et al.* (2001), Yan *et al.* (2003) and Yu *et al.* (2004). OIB and MORB are from Sun & McDonough (1989); upper crust (UC), middle crust (MC), and lower crust (LC) are from Rudnick & Gao (2003).

In the ε_{Nd} (130 Ma)–$^{87}Sr/^{86}Sr$ (130 Ma) diagram (Fig. 3), Mesozoic mantle-derived mafic rocks and carbonatites from the North China Craton show regional variations and are distinct from mafic rocks in the South China Block (Zhang & Sun 2002; Zhang *et al.* 2002, 2003, 2004, 2005; Guo *et al.* 2003, 2004; Xu Y. *et al.* 2004*a*; Yang *et al.* 2004*a*, 2005*a*; Ying *et al.* 2004; Wang *et al.* 2006). Sr–Nd–Pb isotopic ratios of mafic rocks from the North China Craton are summarized in Table 1. $^{87}Sr/^{86}Sr$ (130 Ma) increases gradually from the Taihang (province II) and Luzhong regions (province III) ($^{87}Sr/^{86}Sr$ (130 Ma) = 0.705–0.708) to the eastern North China Craton (Luxi–Jiaodong region, provinces IV and V with $^{87}Sr/^{86}Sr$ (130 Ma) = 0.709–0.711), and the ranges of ε_{Nd} (130 Ma) values are similar. The ε_{Nd} (130 Ma) values of samples from the Luzhong range from −4.0 to −21 (Guo F. *et al.* 2001, 2003; Xu Y. *et al.* 2004*a*), Taihang from −9.3 to −16.7 (Chen B. *et al.* 2003; Zhang *et al.* 2004; Wang *et al.* 2006), and Luxi–Jiaodong from −9.8 to −17.8 (Qiou *et al.* 1997, 2002; Xu Y. *et al.* 2004*a*; Yang *et al.* 2004*a*; Ying *et al.* 2004). Accordingly, the mantle-derived mafic rocks from the North China Craton are divisible into two groups based on $^{87}Sr/^{86}Sr$ (130 Ma): the Liaoning (province I), Taihang (province II) and Luzhong regions (province III), which are characterized by EMI-like isotopic features (Lustrino & Dallai 2003), and the Luxi–Jiaodong region (provinces IV and V), which is characterized by its EMII-like isotopic character. Zhang *et al.* (2004) interpreted these features as evidence for the existence of a highly heterogeneous lithospheric mantle underneath Eastern China in the Mesozoic. The highest ε_{Nd} (130 Ma) values of Mesozoic mantle-derived mafic rocks are roughly in agreement with those of Palaeozoic kimberlites and peridotites, which have ε_{Nd} (130 Ma) *c.* −5 (Zheng & Lu 1999; Zhang *et al.* 2002).

Mesozoic mantle-derived mafic rocks from the North China Craton have Pb isotopic ratios with

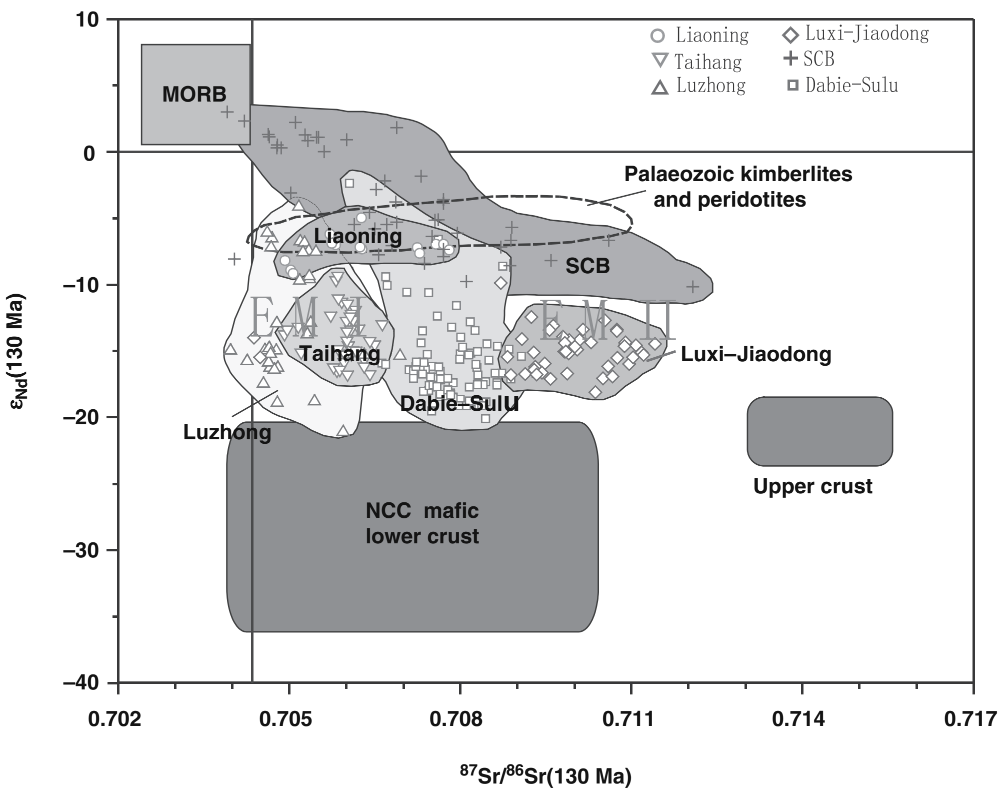

Fig. 3. Comparison of Sr–Nd isotopic ratios at 130 Ma of Mesozoic mantle-derived mafic samples from Eastern China. Data sources: North China Craton, Table 1; South China Block, Table 2; Dabie–Sulu Orogen, Ma *et al.* (1998), Jahn *et al.* (1999), Yang *et al.* (2004*a*, 2005*a*) Wang *et al.* (2005), Zhao *et al.* (2005) and Huang *et al.* (2007); MORB, Sun & McDonough (1989); Palaeozoic kimberlites and peridotites, Zheng & Lu (1999) and Zhang *et al.* (2002); lower crust, Zhang *et al.* (1998) and Liu *et al.* (2004*b*); upper crust, Jahn *et al.* (1999).

significant regional variations (Fig. 4). Their Pb isotopic ratios recalculated at 130 Ma are lower than those of contemporary mafic rocks from the South China Block, and they are located to the left side of the 4.55 Ga geochron. Samples from the Luxi–Jiaodong region have higher $^{207}Pb/^{204}Pb$ (130 Ma) ratios than those from the Liaoning, Luzhong and Taihang regions. Compared with Mesozoic mantle-derived mafic rocks from the Dabie Orogen (Wang *et al.* 2005; Huang *et al.* 2007), the mantle-derived mafic rocks from the North China Craton have similar uranogenic Pb isotopes ($^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$) but lower thorogenic Pb isotopes ($^{208}Pb/^{204}Pb$) (Fig. 4). The Palaeozoic kimberlites and peridotites from the North China Craton are characterized by high radiogenic Pb isotopic ratios (Fig. 4), which suggest that the contribution of Pb from the Palaeozoic enriched lithospheric mantle to the sources of Mesozoic mantle-derived mafic rocks in the North China Craton is insignificant.

The geochemical signatures of the mafic igneous rocks could reflect the characteristics of the mantle source or result from crustal contamination by assimilation and fractional crystallization (AFC) during the magma ascent. Many workers have argued against significant crustal contamination based on lack of correlation between the Sr–Nd–Pb isotopic ratios and other geochemical features sensitive to the assimilation and fractional crystallization process (such as SiO_2 content and Mg-number) (e.g. Zhang *et al.* 2004; Wang *et al.* 2005, 2006; Yang *et al.* 2005*a*; Zhao *et al.* 2005). However, with a limited range of SiO_2 in this study (46–56 wt%), the AFC process might not be shown clearly by the correlation between SiO_2 and Sr–Nd–Pb isotopes. Instead, Nb/U of Mesozoic mafic rocks from the North China Craton shows a large variation from 4.4 to 19, providing critical information on crustal contamination. The Nb/U of the bulk continental crust is *c.* 6.2 (Rudnick & Gao 2003), much lower than that of N-MORB and OIB (*c.* 47) (Hofmann *et al.* 1986). Thus crustal contamination during magma ascent can decrease Nb/U and change the Sr–Nd–Pb isotopic ratios of an evolved magma simultaneously, but fractional crystallization alone cannot change Nb/U and Sr–Nd–Pb isotopic ratios. The Nb/U ratio of Mesozoic mantle-derived mafic rocks for each individual province shows no obvious relationship with Sr–Nd–Pb isotopic ratios between the mantle and crust end-members in Figure 5. This precludes significant crustal contamination during the magma transport. However, it does not preclude the source mixing of three or more components. Samples from the Luxi–Jiaodong region have higher $^{87}Sr/^{86}Sr$ and lower Nb/U than those from the Liaoning, Taihang and Luzhong regions (Fig. 5a). This may suggest that a greater contribution of upper crustal material to the mantle source of the Luxi–Jiaodong samples compared with samples from other regions.

The possible contribution of lower crust to the subcontinental lithospheric mantle of the North China Craton

Enrichment of LREE relative to HREE, high LILE/HFSE, and a positive Pb anomaly are widely observed in arc magmas (e.g. Regelous *et al.* 1997). Arc magmas are produced as a result of partial melting of the overlying mantle wedge metasomatized by slab-derived fluids derived from subducted oceanic crust and sediments with high LREE/HREE and LILE/HFSE ratios as well as a positive Pb anomaly (Brenan *et al.* 1995; Keppler 1996; Kogiso *et al.* 1997; Peate *et al.* 2001; Manning 2004). Such fluids also have EMII-type radiogenic Sr and Pb isotopic ratios (e.g. Regelous *et al.* 1997). Accordingly, mantle-derived mafic rocks form the Luxi–Jiaodong region (provinces IV and V) could be derived from enriched lithospheric mantle metasomatized by fluid derived from ancient continental sediments during subduction-related processes (Zhang *et al.* 2002) based on their high $^{87}Sr/^{86}Sr$ (130 Ma) and $^{207}Pb/^{204}Pb$ (130 Ma) as well as low Nb/U ratio. However, the subduction-related, fluid-addition model cannot explain the EMI-type Sr–Nd–Pb isotopic ratios in Mesozoic mantle-derived mafic rocks from the Liaoning, Taihang and Luzhong regions.

Alternatively, the EMI-type isotopic signatures of Mesozoic mantle-derived mafic rocks could reflect the characteristics of the subcontinental lithospheric mantle of the North China Craton, caused by former metasomatism that formed phlogopite-bearing lithospheric mantle (Guo *et al.* 2003; Yang *et al.* 2004*a*). The EMI-type subcontinental lithospheric mantle with its extremely low $\varepsilon_{Nd}(t)$ values and unradiogenic Sr and Pb isotopes, similar to that which gave rise to the Smoky Butte lamproites (Fraser *et al.* 1985), is a possible source. However, the lower Rb/Ba and much higher Ce/Pb ratios of the Smoky Butte lamproites than the mantle-derived mafic rocks in the North China Craton argue against a major contribution from an EMI-like subcontinental lithospheric mantle to Mesozoic mantle-derived mafic rocks from the North China Craton (Fig. 6a). As shown in Figure 6, the high Ba/Nb and La/Nb, and low Ce/Pb and Nb/U ratios of Mesozoic mantle-derived mafic rocks from the North China Craton share for more affinities with the crustal estimates, but are clearly different from those of the OIB, N-MORB (Hofmann *et al.* 1986), and primitive mantle (Sun & McDonough 1989). EMI-type

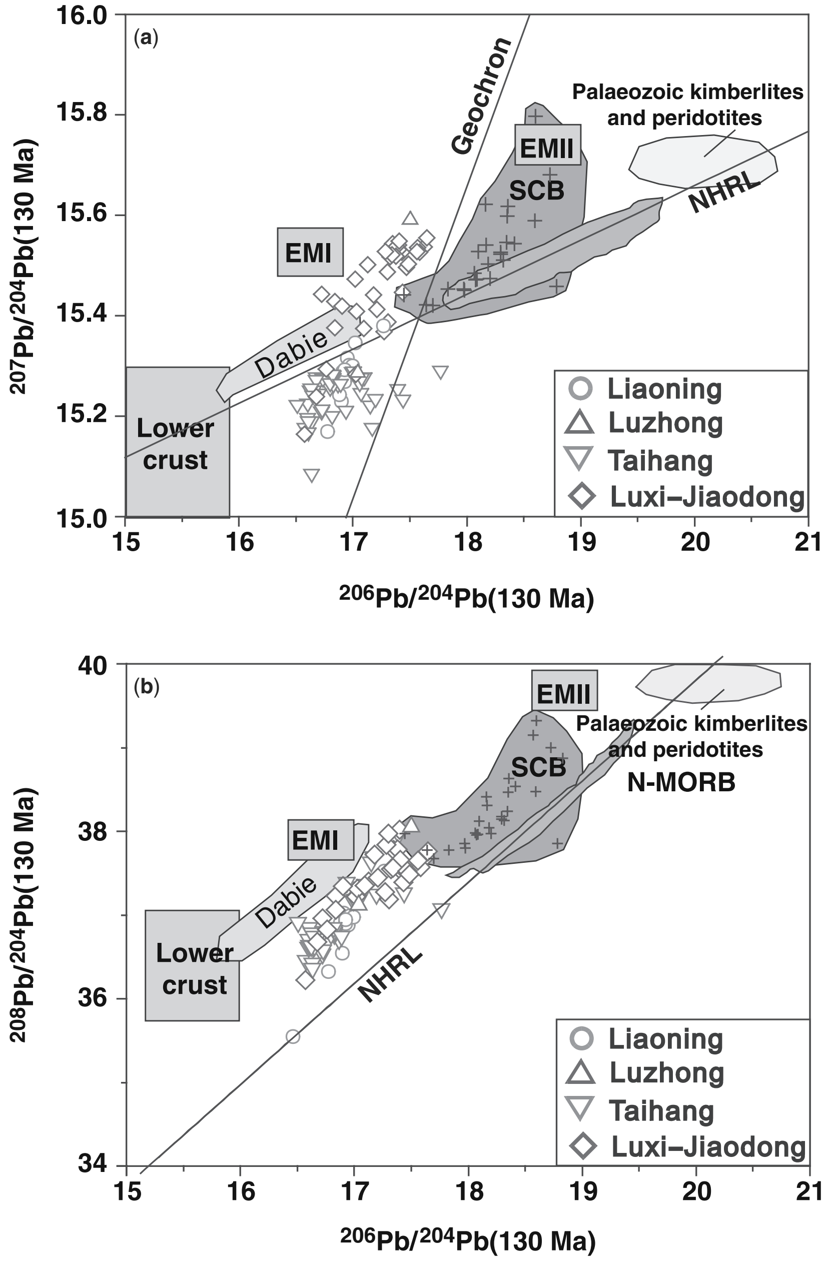

Fig. 4. Pb isotopic compositions calculated at 130 Ma of Mesozoic mantle-derived mafic rocks from Eastern China. Data source: Dabie, Wang *et al.* (2005) and Huang *et al.* (2007); Liaoning, Zhou *et al.* (2001) and Zhang *et al.* (2003); Taihang, Zhang *et al.* (2004) and Wang *et al.* (2006); Luzhong, Xu Y. *et al.* (2004*a*); Luxi–Jiaodong, Qiou *et al.* (1997, 2002), Zhang *et al.* (2002), Xu Y. *et al.* (2004*b*) and Yang *et al.* (2004*a*); South China Block (SCB), Chen *et al.* (1994), Zhang (1995) and Yan *et al.* (2003); MORB, Zindler & Hart (1986); EMI and EMII are from Lustrino & Dallai (2003); lower crust, Tu *et al.* (1993). NHRL, Northern Hemisphere Reference Line (Hart 1984). $(^{207}Pb/^{204}Pb)_{NHRL} = 0.1084 \times (^{206}Pb/^{204}Pb)$ (130 Ma) + 13.491; $(^{208}Pb/^{204}Pb)_{NHRL} = 1.209 \times (^{206}Pb/^{204}Pb)$ (130 Ma) + 15.627.

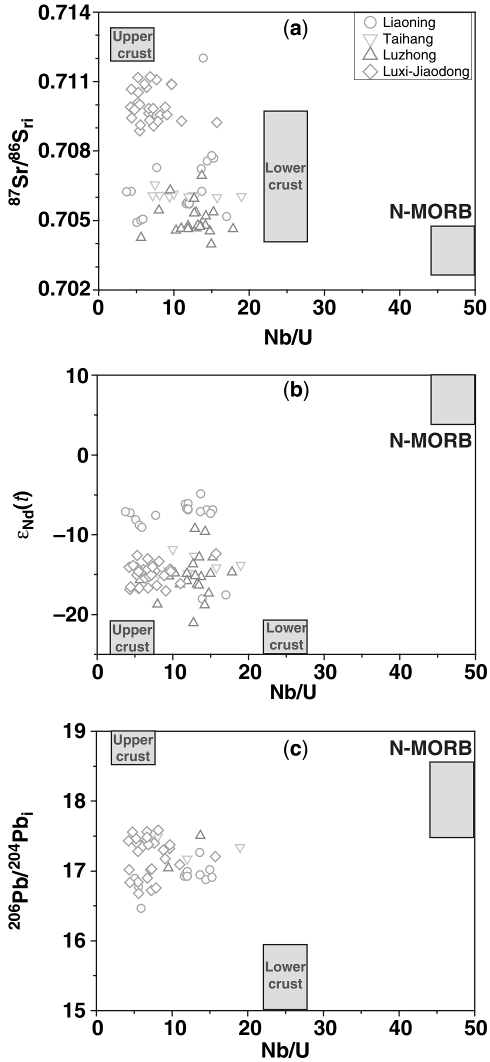

Fig. 5. Correlation of Nb/U with Sr–Nd–Pb isotopic compositions of Mesozoic mantle-derived mafic rocks from the North China Craton. Nb/U ratios of N-MORB and upper and lower crust are from Hofmann *et al.* (1986) and Rudnick & Gao (2003), respectively. Sr–Nd–Pb isotopic compositions: lower crust, granulite xenoliths from Zhang *et al.* (1998) and Liu *et al.* (2004*b*); upper crust, Xu Y. *et al.* (2004*b*); mafic rocks from the North China Craton, Table 1.

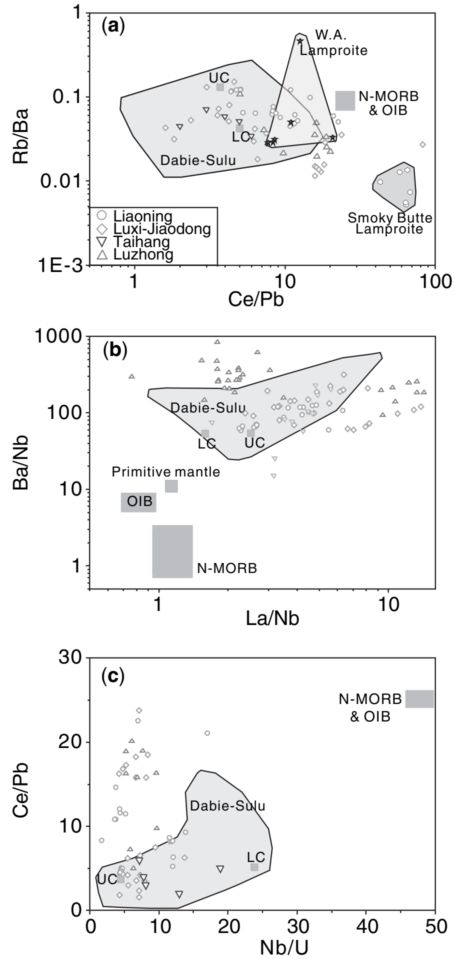

Fig. 6. Variation of trace element ratios of Mesozoic mantle-derived mafic rocks from the North China Craton. The crustal values of the upper and lower crust are from Rudnick & Gao (2003). Data sources for other fields: Western Australia (W.A.) and Smoky Butte lamproites, Fraser *et al.* (1985); OIB and MORB, Hofmann *et al.* (1986). The high Ba/Nb and La/Nb, and low Nb/U and Ce/Pb ratios of Mesozoic mafic rocks from Eastern China relative to the mantle values show clear involvement of crustal materials.

lithospheric mantle recently discovered in Taihang region has ε_{Nd} (130 Ma) ranging from −6.9 to −10.6 with Ce/Pb ratios from 41.5 to 72.0 (Ma & Xu 2006), higher than most Mesozoic mantle-derived mafic rocks from the North China Craton. This reinforces the involvement of crustal materials in the source of Mesozoic mantle-derived mafic rocks from the North China Craton.

Moreover, fluid-related metasomatism can increase Rb/Sr, Pb/U and Nd/Sm ratios of the lithospheric mantle, which will generate high $^{87}Sr/^{86}Sr$, and low $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ with time, and a negative correlation between the Sr and Pb isotopic ratios (Hawkesworth *et al.* 1990*a*, *b*). This is supported by the negative correlation between the Sr and Pb isotopic ratios of the peridotite xenoliths from Kimberley, South Africa and that of lamproites from Western Australia (Fraser *et al.* 1985; Hawkesworth *et al.* 1990*a*, *b*). However, as Figure 7 shows, the $^{87}Sr/^{86}Sr$ (130 Ma) values of the samples from the Luxi–Jiaodong region show a slightly positive correlation with $^{206}Pb/^{204}Pb$ (130 Ma) as well as the samples from the Taihang and Liaoning regions, which is not consistent with the possible predicted scenario of an ancient fluid metasomatism. Wang *et al.* (2006) suggested that the low $^{87}Sr/^{86}Sr$

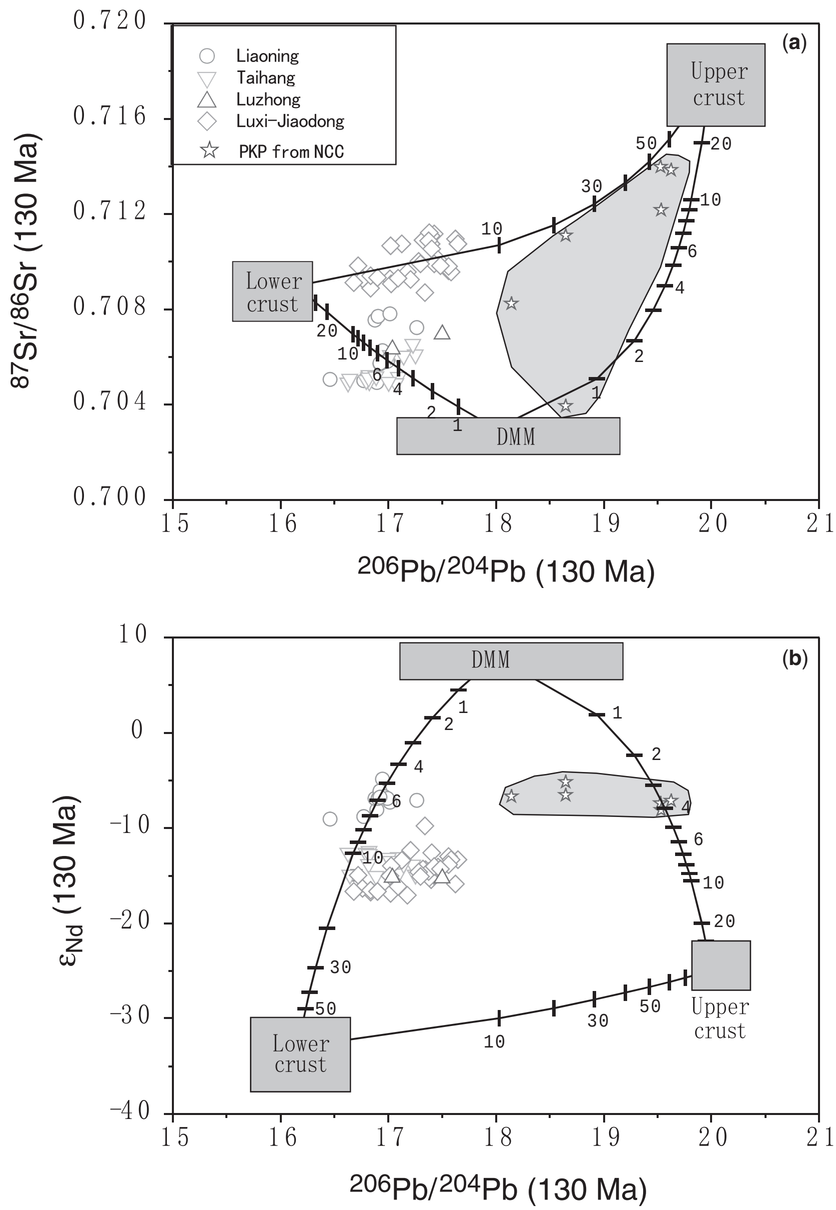

Fig. 7. Sr–Nd–Pb isotopic composition of Mesozoic mantle-derived mafic rocks from the North China Craton. The data sources are as in Figures 3 and 4. The results of a source-mixing model between continental crust and depleted MORB mantle (DMM) show that Mesozoic mantle-derived mafic rocks from the North China Craton can be interpreted as derived from DMM modified by lower crust with a few percent of upper crust. Proportions of components are marked in wt%. The parameters used in the mixing calculation are listed in Table 3. PKP, Palaeozoic kimberlites and peridotites from the North China Craton (Zheng & Lu 1999; Zhang *et al.* 2002).

(130 Ma), ε_{Nd} (130 Ma) and Pb isotopic ratios observed in basaltic rocks from the Taihang region might result from an ancient metasomatism caused by an SiO_2-rich melt derived from subducting plate during the collision between the Western and Eastern Blocks of the North China Craton. However, high polymerization of the SiO_2-rich melt can enhance the partition coefficient of Sr more than Rb because Sr^{2+} has a larger charge/radius radio than Rb^{+} (Ryerson & Hess 1978; Huang *et al.* 2006). Such a SiO_2-rich melt could also have high Rb/Sr. For instance, Wulff-Pedersen *et al.* (1999) reported that SiO_2-rich glasses in mantle xenoliths (sample PAT2-4, PAT2-68 and PAT2-41) have a high Rb content (up to 274 ppm) and Rb/Sr (up to 0.6). The metasomatized lithospheric mantle will produce a high $^{87}Sr/^{86}Sr$ with time, not consistent with the observations on the Taihang samples. Actually, the positive correlation between $^{87}Sr/^{86}Sr$ (130 Ma) and $^{206}Pb/^{204}Pb$ (130 Ma) is a typical feature of continental crustal rocks. Ancient lower crustal rocks have lower $^{87}Sr/^{86}Sr$ and much lower $^{206}Pb/^{204}Pb$, whereas upper crustal rocks have higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$. Therefore, the positive correlation between $^{87}Sr/^{86}Sr$ (130 Ma) and $^{206}Pb/^{204}Pb$ (130 Ma) of the mantle-derived mafic rocks may suggest the involvement of continent crustal materials in their source (Lustrino *et al.* 2007). A source-mixing modelling reveals that the contribution of lower continental crust (or with a few percent of upper continental crust) to the depleted MORB mantle can produce the Sr–Nd–Pb isotopic features of Mesozoic mantle-derived mafic rocks in the North China Craton (Fig. 7, Table 3). The samples from the Luxi–Jiaodong region (provinces IV and V) require a higher proportion of upper crust in their mantle source than those from the centre of the North China Craton far away from the Phanerozoic subduction zones, which might be due to the metasomatism of SiO_2-rich melts related to the subduction of the South China Block (Zhang *et al.* 2002; Zhang 2005) or Palaeo-Pacific Ocean to the North China Craton (Chen & Zhou 2005).

In summary, Mesozoic mafic rocks from the North China Craton cannot simply result from partial melting of the subcontinental lithospheric mantle enriched by a subduction-related fluid or ancient fluid or melt metasomatism, but are due to involvement of continent crustal materials (mostly lower crust). Notably, the contribution of the lower continental crust has been recognized in the genesis of Plio-Pleistocene tholeiitic and alkaline volcanic rocks in Sardinia (Italy) (Lustrino *et al.* 2000, 2007). In this case, low Nb/U, Ce/Pb and $^{206}Pb/^{204}Pb$ values have been used as evidence for involvement of the lower crust in the volcanic rocks that have low radiogenic Pb isotopic ratios.

How was the lower crust incorporated into the uppermost mantle?

Lower continental crust can be recycled and modify geochemical features of the upper mantle in subduction and continental collision zones as a result of deep subduction (Huang *et al.* 2007) or lithospheric delamination (e.g. England 1993; Kay & Kay 1993; Lee *et al.* 2000; Gao *et al.* 2004; Lustrino 2005). Because the North China Craton has been stable for 1.8 Ga (Zhao *et al.* 2000), and the subducted South China Block has different Pb isotopic ratios compared with the lower crust and Mesozoic lithospheric mantle of the North China Craton (Huang *et al.* 2007), we propose that the lower crust of the North China Craton was incorporated into the upper mantle by lithospheric delamination. Briefly, underneath over-thickened lithosphere caused by oceanic subduction or continental collision, high-pressure metamorphism can lead to the formation of eclogite or garnet pyroxenite in the lower continental crust (e.g. Kay & Kay 1993; Gao *et al.* 2004). The density of the garnet-bearing metamorphic rocks can be as high as 3.8 g cm^{-3} depending on the quantity of garnet, which has a density higher than that of lithospheric and asthenospheric mantle (*c.* 3.3 g cm^{-3}) (Lustrino 2005, and references therein). Therefore, eclogitic lower crust and lithospheric mantle might sink into warmer mantle because of its negative buoyancy.

Table 3. *Parameters for source mixing between lower crust and mantle components*

	$^{87}Sr/^{86}Sr$	Sr (ppm)	ε_{Nd}	Nd (ppm)	$^{206}Pb/^{204}Pb$	Pb (ppm)
DMM*	0.703	20	8	1.2	18	0.2
Lower crust†	0.709	348	−33	11	16.2	4
Upper crust†	0.718	320	−25	27	20	17

*Sr–Nd data for the depleted MORB mantle (DMM) are from Jahn *et al.* (1999); Pb data are from Sun & McDonough (1989).
†Sr–Nd–Pb contents of the lower and upper crust from Rudnick & Gao (2003). Isotope data: lower crust, lower crustal xenoliths from Liu *et al.* (2004*b*); upper crust from Xu Y. *et al.* (2004*b*).

Many geological data from of the North China Craton are remarkably consistent with the proposed scenarios of the lithospheric delamination model.

1. An over-thickened lithosphere could have been present in the Mesozoic as a result of the collision of the North China Craton with the South China Block in the south and with the Central Asian Orogenic Belt in the north in the Permian–Triassic (Li *et al.* 1993; Zhang *et al.* 2003). Discovery of eclogite xenoliths in Mesozoic diorite intrusions in the Xu–Su region with an inherited zircon U–Pb age of 2.4–2.5 Ga and a metamorphic zircon U–Pb age of *c*. 206 ± 15 Ma as well as a Sm–Nd age of 219.4 Ma indicates that an over-thickened mafic lower crust with eclogite facies existed in the North China Craton in the late Triassic (Gao *et al.* 2004; Xu Y. *et al.* 2004).
2. Petrological and geochemical evidence from Late Jurassic high-magnesium andesites, dacites and adakites in the North China Craton demonstrates that foundering of mafic lower continental crust into convecting upper mantle occurred in the North China Craton (Gao *et al.* 2004).
3. Granulite xenoliths entrained in the Hannuoba basalts indicate that the Precambrian lower crust of the North China Craton has unradiogenic Pb, low $\varepsilon_{Nd}(t)$, and variable radiogenic Sr (Zhang *et al.* 1998; Liu *et al.* 2004*b*), in agreement with the isotopic signatures of Mesozoic mantle-derived mafic rocks from the North China Craton.
4. Study of Mesozoic lower crustal xenoliths also indicates that up to 10 km of Mesozoic mostly lower crust was delaminated into the upper mantle before Cenozoic basaltic magmatism (Zheng *et al.* 2003).
5. Widespread coeval granitic rocks coexist with the mantle-derived rocks in the North China Craton, which was a thermal high corresponding to the lithospheric delamination (Wu *et al.* 2003*a*, *b*).

Following lithospheric delamination, a hot asthenospheric mantle rises to replace the volume previously occupied by detached mafic lower crust and lithospheric mantle. Consequently, decompression melting of the rising asthenospheric mantle took place, creating a basaltic melt with a depleted isotopic signature. Thus, the geochemical signature of the mantle-derived mafic rocks should change abruptly shortly after the delamination. Therefore, the temporal variation of the geochemical signatures of the mantle-derived mafic rocks could have provided the critical temporal constraint on the lithospheric thinning (e.g. Xu Y. *et al.* 2004*a*). However, the abrupt variation in geochemical features of the mantle-derived mafic magma from the North China Craton developed more than 40 Ma after the lithospheric delamination. For instance, volcanic eruptions occurred several times in Western Liaoning from the mid-Jurassic to Cenozoic, providing a good opportunity to test the geochemical correspondence to the lithospheric delamination and the mantle-derived mafic magmas (Zhang *et al.* 2003; Gao *et al.* 2004). Gao *et al.* (2004) suggested that the delamination was initiated at 159 Ma. As Figure 8 shows, there is no significant variation in $\varepsilon_{Nd}(t)$ of Mesozoic basaltic rocks from Western Liaoning from 166 Ma (the Lanqi Formation) to 125 Ma (the Yixian Formation) until the Zhanglaogongtun (ZLGT) Formation at 106–90 Ma. Thus the $\varepsilon_{Nd}(t)$ values of the mantle-derived mafic magma were constant for a long period after the start of delamination. This is not in agreement with the abrupt geochemical variation as suggested in the previous delamination model. Therefore, although the delamination model can explain the aspects mentioned above, there is still a contradiction between the model and the data.

The new delamination model of Lustrino (2005) might solve the contradiction by assuming that the asthenosphere was modified by delaminated lower crust before partial melting. Delaminated mafic lower crust can undergo partially melting to produce a tonalite–trondhjemite–granodiorite magma with a crustal geochemical signature. SiO_2-rich melts tend to percolate upwards and erupt as adakitic magma (e.g. Xu *et al.* 2002; Gao *et al.* 2004) or they metasomatize the uprising asthenospheric mantle, leading to continental geochemical characteristics (Lustrino 2005). After the lithospheric delamination and detachment, new lithospheric mantle with a strong crustal signature forms by cooling of the asthenospheric mantle, which replaces the volume formerly occupied by the sunken lithospheric mantle and lower crust. Such metasomatized mantle may be reactivated by regional extension tectonics, producing a mantle-derived mafic magma with a similar 'continental' geochemical signature (Lustrino 2005).

Alternatively, the 'continental' geochemical signatures of the Yixian Formation basalts (124 Ma) could be due to a second delamination occurring in the Early Cretaceous in the Liaoxi region. Because it is highly unlikely that the lithospheric delamination can occur in the same area several times, the distribution of the Lanqi and Yixian Formations should be spatially separated in different areas. However, this is not consistent with the geographical observation in the western Liaoning region, where the Lanqi and Yixian Formations are developed in the almost the same area (e.g. Beipiao).

A lithospheric thinning model

As discussed above, lithospheric delamination played an important role in lithospheric thinning below the North China Craton. Here, we propose a

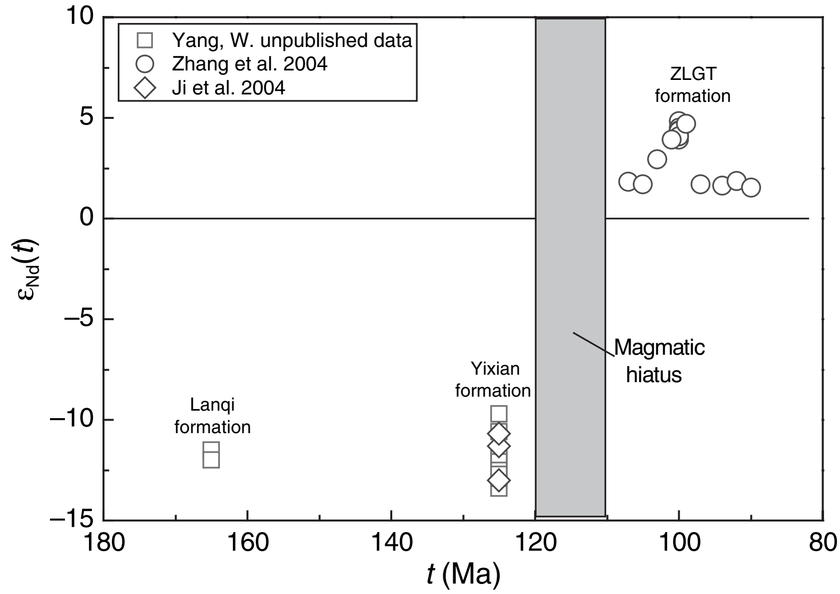

Fig. 8. Variation of $\varepsilon_{Nd}(t)$ with time of the mafic rocks from Western Liaoning. Data sources: Lanqi formation, W. Yang, unpubl. data; Yixian, Ji *et al.* (2004) and W. Yang, unpubl. data; ZLGT (Zhanglaogongtun) Formation, Zhang *et al.* (2004).

geodynamic model (Fig. 9) showing that Palaeozoic subduction zones around the North China Craton were critical to the over-thickening and later thinning of the lithosphere, and that interaction between the delaminated lower crust and upwelling asthenosphere was responsible for the 'continental' signature of Mesozoic mantle-derived mafic rocks.

It has been suggested that the lithospheric thickening of the North China Craton was caused by continental collision between the North China Craton and South China Block (Gao *et al.* 2004; Zhang 2005), subduction of the Palaeo-Pacific slab (Tatsumoto *et al.* 1992; Wu *et al.* 2005), or collision of the North China Craton–Mongolia with the Siberian plate during closure of the Mongol–Okhotsk Ocean. Although the mechanism of the lithospheric thickening is still an open question, the subduction-related events surrounding the North China Craton from the late Palaeozoic to early Jurassic are important because they may be responsible for the condition of hydrous fluids to weaken the lithospheric mantle (Fig. 9a), resulting in an over-thickened lithosphere during the continental collisions (Fig. 9b) (B. F. Windley, talk in Symposium on Mesozoic Lithospheric Evolution of North China and Adjacent Regions, 2005). Metamorphic reactions occurred in the lower mafic continental crust with the formation of eclogite and garnet pyroxenite beneath the North China Craton leading to negative buoyancy in over-thickened lithosphere in the early Mesozoic. The unstable lithosphere may then have delaminated from the overlying lithosphere above and subsided into the upper mantle (Lustrino 2005; Fig. 9c).

Timing of the delamination event in the North China Craton is still controversial. Because the ages of most Mesozoic igneous rocks in the North China Craton cluster around 130 Ma (Wilde *et al.* 2003; Gao *et al.* 2004; Xu Y. *et al.* 2004*a*; Wu *et al.* 2005), Wu *et al.* (2005) suggested that the lithospheric delamination in Eastern China occurred in the early Cretaceous, resulting from Kula–Pacific plate subduction, possibly aided by a superplume associated with global-scale mantle upwelling. However, because a high-Mg adakite in Western Liaoning region has an age of 159 Ma, the delamination should have begun in the middle Jurassic (Gao *et al.* 2004). As discussed above, because the 'continental' geochemical signature of the mantle-derived mafic rocks from the North China Craton is due to the contribution of lower continental crust to the mantle source, the first magma event producing mafic rocks with these signatures should be a sharp response to lithospheric delamination. The negative $\varepsilon_{Nd}(t)$ of the Lanqi Formation basalts (166 Ma) indicates that the upper mantle beneath Western Liaoning had already been modified by delaminated lower crust. Thus lithospheric delamination should have occurred in Western Liaoning in the mid-Jurassic (Fig. 9c).

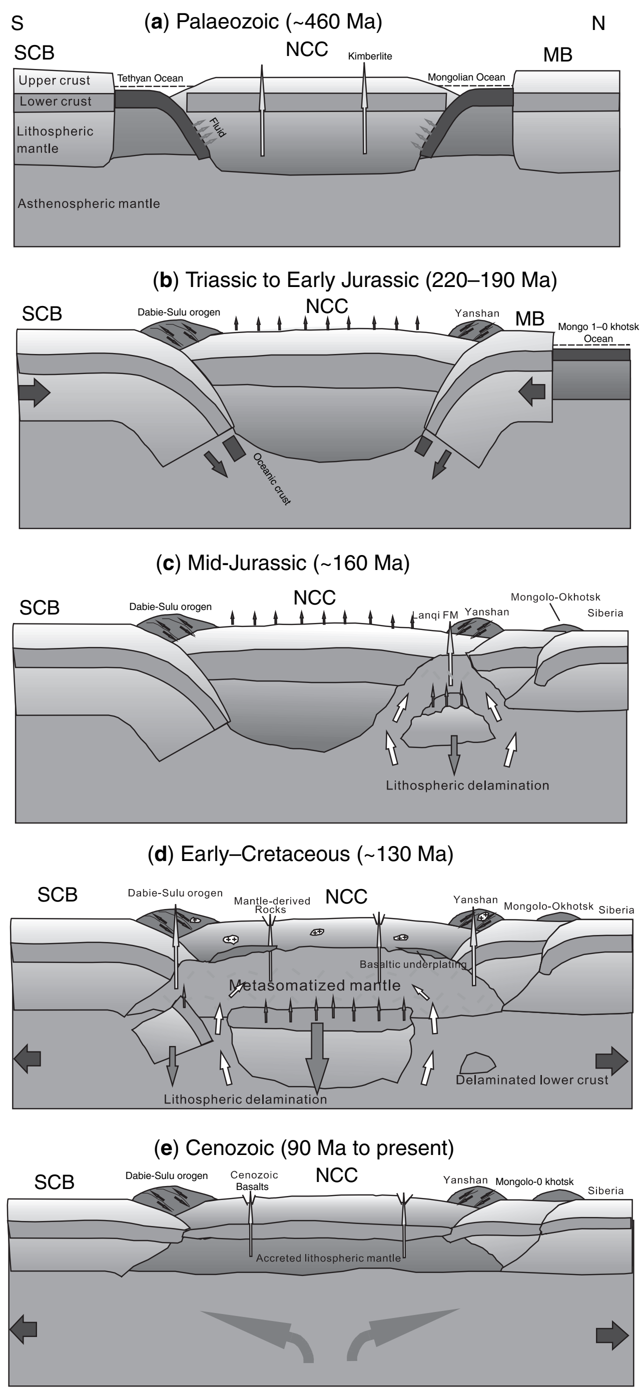

Fig. 9. Schematic illustration of the stages of evolution of the lithosphere of the North China Craton (NCC) from the Palaeozoic to Cenozoic. (**a**) Palaeozoic (*c*. 460 Ma): the Palaeo-Tethyan Ocean and Mongolian Ocean subducted towards the North China Craton from the south and north, respectively; hydrous fluids were released from the subducted oceanic slabs and metasomatized the overlying mantle wedge; kimberlite with peridotite xenoliths was developed in the North China Craton. (**b**) Triassic to Early Jurassic (220–190 Ma): collision of the North China Craton with South China Block (SCB) along the Dabie–Sulu Orogen and with the Mongolian Block (MB) along the Yanshan

Partial melts from the delaminated lower crust metasomatized the upwelling asthenospheric mantle that replaced the volume formerly occupied by the sunken lithospheric mantle and the lower crust (Fig. 9c and d). Regional extension in the early Cretaceous led to partial melting of the new metasomatized mantle and crust in Western Liaoning, producing igneous rocks with variable chemical compositions from basalts to andesites and granites (Fig. 9d). Because no mid-Jurassic high-Mg adakitic rocks have yet been observed in the southern margin of the North China Craton and Dabie–Sulu Orogen, where all reported adakitic rocks formed in the early Cretaceous (Xu J. F. *et al.* 2002; Xu W. L. *et al.* 2006), the lithospheric delamination in the southern margin of the North China Craton and Dabie–Sulu Orogen probably occurred in the early Cretaceous (Fig. 9d). Thus the delamination of lithosphere of the North China Craton took place earlier in the northern margin than the southern margin and the Dabie–Sulu Orogen. It is possible that the delamination in the northern margin could be related to the closure of the Okhotsk Sea in the late Jurassic, which formed large-scale thrust faults in the Yanshan belt in Northern China (the northern margin) but had no significant effect on the southern margin (Davis *et al.* 1998). The delamination of the southern margin of the North China Carton and Dabie–Sulu Orogen could be triggered by oblique westward subduction of the Palaeo-Pacific plate at *c*. 130 Ma (Tatsumoto *et al.* 1992; Wu *et al.* 2005). Further studies focusing on the tectonic relationship between the North China Craton and its adjacent regions will help resolve the time variation of delamination.

We emphasize that the entire lithospheric thinning in the North China Craton was unlikely to have been caused by any single event. Lithospheric delamination could have reduced the lithosphere thickness to a normal level (*c*. 110 km). In the late Cretaceous–Cenozoic, the lithosphere of the North China Craton was thinned further by NNE–SSW extension in Eastern Asia, which resulted in partial melting of upwelling asthenosphere mantle with depleted isotopic signatures (Zhang *et al.* 2003) (Fig. 9e).

Conclusions

Mesozoic mantle-derived mafic rocks from the North China Craton have geochemical signatures similar to those of ancient lower continental crust in trace element and Sr–Nd–Pb isotopic compositions. $^{87}Sr/^{86}Sr$ (130 Ma) of Mesozoic mantle-derived mafic rocks from the North China Craton correlate positively with $^{206}Pb/^{204}Pb$ (130 Ma). Because an enriched mantle metasomatized by ancient fluids or melts produces a negative correlation between $^{87}Sr/^{86}Sr$ (130 Ma) and $^{206}Pb/^{204}Pb$ (130 Ma), and because of the low Ce/Pb and Nb/U, and high Ba/Nb and La/Nb of Mesozoic mafic rocks from the North China Craton, the geochemical features mentioned above argue against derivation from an old enriched subcontinental lithospheric mantle. Instead, the typical 'continental' signatures in Mesozoic mantle-derived mafic rocks from the North China Craton mainly reflect the contribution of lower mafic continental crust to the uppermost mantle.

Much geochemical and petrological evidence indicates that the continental lower crust and lithospheric mantle of the North China Craton could have been delaminated and sunk into the upper mantle in the Mesozoic. Melting of the delaminated continental lower crust would have created SiO_2-rich melts, which metasomatized the upper mantle and resulted in the 'continental' geochemical signatures of Mesozoic upper mantle of the North China Craton. Thus, magma events, producing the mantle-derived mafic rocks with these 'continental' geochemical features, provide critical constraints on the timing of lithospheric delamination. According to the temporal variation of geochemical features of the Mesozoic mafic

Fig. 9. (*Continued*) belt resulted in an over-thickened lithosphere. (**c**) Mid-Jurassic (160 Ma): the Mongol–Okhotsk Ocean was closed and the Siberian plate collided with the North China Craton–Mongolia plate; the eclogitic mafic lower crust underneath the northern margin of the North China Craton was delaminated together with the lithospheric mantle as a result of negative buoyancy; SiO_2-rich melts from the lower crust metasomatized the asthenospheric mantle, filling the vacancy of the delaminated lithosphere; volcanic rocks were developed in the Lanqi Formation (Lanqi FM). (**d**) Early Cretaceous (130 Ma): lithosphere underneath the southern margin of the North China Craton and Dabie Orogen was delaminated; partial melting of the metasomatized lithospheric mantle took place widely in an extensional tectonic environment, producing Mesozoic mantle-derived mafic rocks; crustal melting produced granitic intrusions; basaltic magmas were underplated beneath the crust; post-collisional magmatism also occurred in the Dabie–Sulu and Yanshan belts. (**e**) Cenozoic (*c*. 90 Ma to present): NNE–SSW extension along the continental margin of Eastern Asia thinned the lithosphere further; the lithospheric mantle of the North China Craton was completely replaced by newly accreted lithospheric mantle; Cenozoic basaltic magmas with depleted Sr–Nd–Pb isotopic ratios were developed in some extensional basins.

rocks, the lithospheric thinning might have happened by the time of volcanic eruptions in Western Liaoning in the mid-Jurassic and in the southern margin of the North China Craton and Dabie–Sulu Orogen in the early Cretaceous. With further delamination and extension, the Palaeozoic lithosphere of the North China Craton was completely replaced by fertile lithospheric mantle in the Cenozoic.

We thank C. Lundstrom for suggestions on an earlier version of our manuscript. M. G. Zhai, Q. R. Meng, B. Windley and J. H. Yang are thanked for their considerable contribution to this special volume. F. Dong provided some Chinese references. Comments by M. Lustrino and an anonymous reviewer improved our manuscript significantly. We are grateful to B. Windley for help with English polishing. This work was funded by the Natural Science Foundation of China (Grant 40573010).

References

Basu, A. R., Wang, J.-W., Huang, W.-K., Xie, G.-H. & Tatsumoto, M. 1991. Major element, Ree, and Pb, Nd and Sr isotopic geochemistry of Cenozoic volcanic rocks of eastern China: implications for their origin from suboceanic-type mantle reservoirs. *Earth and Planetary Science Letters*, **105**, 149–169.

Brenan, J. M., Shaw, H. F., Ryerson, F. J. & Phinney, D. L. 1995. Mineral-aqueous fluid partitioning of trace elements at 900 °C and 2.0 GPa: constraints on the trace element chemistry of mantle and deep crustal fluids. *Geochimica et Cosmochimica Acta*, **59**, 3331–3350.

Chen, B., Jahn, B.-M. & Zhai, M. 2003. Sr–Nd isotopic characteristics of the Mesozoic magmatism in the Taihang–Yanshan orogen, North China Craton, and implication for Archaean lithosphere thinning. *Journal of the Geological Society*, *London*, **160**, 963–970.

Chen, B., Jahn, B. M., Arakawa, Y. & Zhai, M. G. 2004. Petrogenesis of the Mesozoic intrusive complexes from the southern Taihang Orogen, North China Craton: elemental and Sr–Nd–Pb isotopic constraints. *Contributions to Mineralogy and Petrology*, **148**, 489–501.

Chen, J. F., Xie, Z., Li, H. M. *et al.* 2003. U–Pb zircon ages for a collision-related K-rich complex at Shidao in the Sulu ultrahigh pressure terrane, China. *Geochemical Journal*, **37**, 35–46.

Chen, J. F., Zhou, T. X. & Zhang, Y. R. 1994. Isotope geochemistry studies of Cu-bearing intrusions developed, along the middle–lower reachers of the Yangtse river. *In*: Chen, H. (ed.) *Research of Isotope Geochemistry*, Zhejiang University Press, Hangzhou, 121–131 [in Chinese].

Chen, L. & Zhou, X. 2005. Subduction-related metasomatism in the thinning lithosphere: evidence from a composite dunite–orthopyroxenite xenolith entrained in Mesozoic Laiwu high-Mg diorite, North China craton. *Geochemisty, Geophysics, Geosystems*, **6**, Q06008, doi:10.1029/2005GC000938.

Chung, S. L. 1999. Trace element and isotope characteristics of Cenozoic basalts around the Tanlu fault with implications for the Eastern Plate Boundary between North and South China. *Journal of Geology*, **107**, 301–312.

Davis, G. A., Cong, W., Zheng, Y. D., Zhang, J. P., Zhang, C. H. & Gehrels, G. E. 1998. The enigmatic Yinshan fold-and-thrust belt of northern China; new views on its intraplate contractional styles. *Geology*, **26**(1), 43–46.

England, P. 1993. Convective removal of thermal boundary layer of thickened continental lithosphere: a brief summary of causes and consequences with special reference to the Cenozoic tectonics of the Tibetan Plateau and surrounding regions. *Tectonophysics*, **223**, 67–73.

Fan, W.-M., Guo, F., Wang, Y.-J., Lin, G. & Zhang, M. 2001. Post-orogenic bimodal volcanism along the Sulu orogenic belt in eastern China. *Physics and Chemistry of the Earth* (*A*), **26**, 733–746.

Fan, W.-M., Guo, F., Wang, Y.-J. & Zhang, M. 2004. Late Mesozoic volcanism in the northern Huaiyang tectono-magmatic belt, central China: partial melts from a lithospheric mantle with subducted continental crust relicts beneath the Dabie orogen? *Chemical Geology*, **209**, 27–48.

Fraser, K. J., Hawkesworth, C. J., Erlank, A. J., Mitchell, R. H. & Scott-Smith, B. H. 1985. Sr, Nd and Pb isotope and minor element geochemistry of lamproites and kimberlites. *Earth and Planetary Science Letters*, **76**, 57–70.

Gao, S., Rudnick, R. L., Yuan, H. L. *et al.* 2004. Recycling lower continental crust in the North China craton. *Nature*, **432**, 892–897.

Griffin, W. L., Zhang, A. D., O'Reilly, S. Y. & Ryan, C. J. 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean Craton. Flower, M. F. J., Chung, S. L., Lo, C. H. & Lee, T. Y. (eds) *Mantle Dynamics and Plate Interactions in East Asia*, American Geophysical Union Geodynamic Series, **27**, 107–126.

Guo, F., Fan, W.-M., Wang, Y. J. & Lin, G. 2001. Late Mesozoic mafic intrusive complexes in North China Block: constraints on the nature of subcontinental lithospheric mantle. *Physics and Chemistry of the Earth* (*A*), **26**, 759–771.

Guo, F., Fan, W., Wang, Y. & Lin, G. 2003. Geochemistry of later Mesozoic mafic magmatism in west Shandong Province, eastern China: characterizing the lost lithospheric mantle beneath the North China Block. *Geochemical Journal*, **37**, 63–77.

Guo, F., Fan, W., Wang, Y. & Zhang, M. 2004. Origin of early Cretaceous calc-alkaline lamprophyres from the Sulu orogen in eastern China: implications for enrichment processes beneath continental collisional belt. *Lithos*, **78**, 291–305.

Guo, X.-S., Chen, J.-F. & Zhang, X. 2001. Nd isotope ratios of K-enriched magmatic complex from south-eastern Guangxi Province: implications for upwelling of the mantle in south-eastern China during the Mesozoic. *Acta Petrologica Sinica*, **17**, 19–27 [in Chinese with English abstract].

HART, S. R. 1984. A large-scale isotope anomaly in the southern hemisphere mantle. *Nature*, **309**, 753–757.

HAWKESWORTH, C. J., ERLANK, A. J., KEMPTON, P. D. & WATERS, F. G. 1990*a*. Mantle metasomatism: isotope and trace-element trends in xenoliths from Kimberley, South Africa. *Chemical Geology*, **85**, 19–34.

HAWKESWORTH, C. J., KEMPTON, P. D., ROGERS, N. W., ELLAM, R. M. & VAN CALSTEREN, P. W. 1990*b*. Continental mantle lithosphere, and shallow level enrichment processes in the Earth's mantle. *Earth and Planetary Science Letters*, **96**, 256–268.

HOFMANN, A. W., JOCHUM, K. P., SEUFERT, M. & WHITE, W. M. 1986. Nb and Pb in oceanic basalts: new constraints on mantle evolution. *Earth and Planetary Science Letters*, **79**, 33–45.

HUANG, F., LUNDSTROM, C. C. & MCDONOUGH, W. F. 2006. Effect of melt structure on trace element partitioning between clinopyroxene and silicic, alkaline, aluminous melts. *American Mineralogist*, **91**, 1385–1400.

HUANG, F., LI, S.-G., DONG, F., LI, Q., CHEN, F., YANG, W. & WANG, Y. 2007. Recycling of deeply subducted continental crust in the Dabie Mountains, central China. *Lithos* (in press).

JAHN, B. M., WU, F., LO, C. H. & TSAI, C. H. 1999. Crust–mantle interaction induced by deep subduction of the continental crust: geochemical and Sr–Nd isotopic evidence from post-collisional mafic–ultramafic intrusions of the northern Dabie complex. *Chemical Geology*, **157**, 119–146.

JI, Q., CHEN, W., WANG, W. L., JI, X. C. & ZHANG, J. P. 2004. *Mesozoic Jehol Biota of Western Liaoning, China*. Geological Publishing House, Beijing.

KAY, R. W. & KAY, S. M. 1993. Delamination and delamination magmatism. *Tectonophysics*, **219**, 177–189.

KEPPLER, H. 1996. Constraints from partitioning experiments on the composition of subduction zone fluids. *Nature*, **380**, 237–240.

KOGISO, T., TATSUMI, Y. & NAKANO, S. 1997. Trace element transport during dehydration processes in the subducted oceanic crust: 1. Experiments and implications for the origin of ocean island basalts. *Earth and Planetary Science Letters*, **148**, 193–205.

LEE, C. T., YIN, Q., RUDNICK, R. L., CHESLEY, J. T. & JACOBSEN, S. B. 2000. Osmium isotopic evidence for Mesozoic removal of lithospheric mantle beneath the Sierra Nevada, California. *Science*, **289**, 1912–1916.

LI, S.-G. & YANG, W. 2003. Decoupling of surface and subsurface sutures in the Dabie orogen and a continent-collisional lithospheric-wedging model: Sr–Nd–Pb isotopic evidences of Mesozoic igneous rocks in eastern China. *Chinese Science Bulletin*, **48**, 831–838.

LI, S.-G., XIAO, Y., LIOU, D. *ET AL*. 1993. Collision of the North China and Yangtse Blocks and formation of coesite-bearing eclogites: timing and processes. *Chemical Geology*, **109**, 89–111.

LI, S.-G., HONG, J.-A. & LI, H.-M. 1999. U-Pb zircon ages of the pyroxenite-gabbro intrusions in the Dabie Mountains and their geological implications. *Geological Journal of China Universities*, **5**, 351–355 [in Chinese with English Abstract].

LI, X., ZHOU, H., LIU, Y., LEE, C., CHEN, Z., YU, J. & GUI, X. 2000. Mesozoic shoshonitic intrusives in the Yangchun Basin, western Guangdong, and their tectonic significance: I. Petrology and isotope geochronology. *Geochimica*, **29**, 513–520.

LIAO, Q.-A., WANG, X.-M. & XUE, C.-S. 1999. The characteristics of two kinds of basalts in Cretaceous basin and their relations with the basin's evolution, in Shangrao–Guangfeng district, Jiangxi Province. *Acta Petrologica Sinica*, **15**, 116–123 [in Chinese with English abstract].

LIN, J. Q., TAN, D. J. & JING, H. H. 1996. $^{40}Ar/^{39}Ar$ age for the Mesozoic igneous rocks from the west Shandong Province. *Journal of Petrology and Mineralogy*, **15**, 231–219 [in Chinese].

LIU, Y., HU, R., ZHAO, J. & FENG, C. 2004*a*. Petrogenesis and source characteristics of the late Cretaceous mafic dike from the Luxi area: petrology and geochemistry. *Geological Review*, **50**, 577–586 [in Chinese].

LIU, Y., GAO, S., YUAN, H. *ET AL*. 2004*b*. U–Pb zircon ages and Nd, Sr, and Pb isotopes of lower crustal xenoliths from North China Craton: insights on evolution of lower continental crust. *Chemical Geology*, **211**, 87–109.

LU, F. X., WANG, C. Y., ZHENG, J. P. & ZHANG, R. S. 2003. Lithospheric composition and structure of north boundary of Qinling: study on deep-seated xenoliths from Minggang area of Henan Province. *Science in China* (*Series D*) **33**, 1–9 [in Chinese].

LUSTRINO, M. 2005. How the delamination and detachment of lower crust can influence basaltic magmatism. *Earth-Science Reviews*, **72**, 21–38.

LUSTRINO, M. & DALLAI, L. 2003. On the origin of EM-I end-member. *Neues Jahrbuch für Mineralogie, Abhandlungen*, **179**, 85–100.

LUSTRINO, M., MELLUSO, L. & MORRA, V. 2000. The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy). *Earth and Planetary Science Letters*, **180**, 259–270.

LUSTRINO, M., MELLUSO, L. & MORRA, V. 2007. The geochemical peculiarity of 'Plio-Quaternary' volcanic rocks of Sardinia in the circum-Mediterranean area. *Geological Society of America Bulletin* (in press).

MA, C., LI, Z., EHLERS, C., YANG, K. & WANG, R. 1998. A post-collisional magmatic plumbing system: Mesozoic granitoid plutons from the Dabieshan high-pressure and ultrahigh-pressure metamorphic zone, east–central China. *Lithos*, **45**, 431–456.

MA, J. L. & XU, Y. G. 2006. Sm–Nd isotopic features of the mantle-derived xenolith from Yangyuan in the Hebei Province indicating EM-I type ancient enriched mantle in the North China Craton. *Chinese Science Bulletin*, **51**, 1–7.

MANNING, C. E. 2004. The chemistry of subduction-zone fluids. *Earth and Planetary Science Letters*, **224**, 1–16.

MENZIES, M. A., FAN, W.-M. & ZHANG, M. 1993. Paleozoic and Cenozoic lithoprobes and the loss of >120 km of Archaean lithosphere, Sino-Korean craton, China. *In*: PRICHARD, H. M., ALABASTER, T., HARRIS, N. B. W. & NEARY, C. R. (eds) *Magmatic Processes and Plate Tectonics*, Geological Society, London, Special Publications, **76**, 71–78.

PEATE, D. W., KOKFELT, T. F., HAWKESWORTH, C. J., VAN CALSTEREN, P. W., HERGT, J. M. & PEARCE,

J. A. 2001. U-series isotope data on Lau Basin glasses: the role of subduction-related fluids during melt generation in back-arc basins. *Journal of Petrology*, **42**, 1449–1470.

PENG, Z. C., ZARTMAN, R. E., FUTA, K. & CHEN, D. G. 1986. Pb-, Sr- and Nd-isotopic systematics and chemical characteristics of Cenozoic basalts, Eastern China. *Chemical Geology*, **59**, 3–33.

QIOU, J. S., WANG, D. D. & ZENG, J. H. 1997. Trace element and Sr–Nd isotopic geochemistry of the K-rich volcanic rocks and lamproite from Luxi area. *Geological Journal of China University*, **3**, 384–395 [in Chinese with English abstract].

QIOU, J. S., XU, X. S. & LO, C. H. 2002. Potash-rich volcanic rocks and lamprophyres in western Shandong Province: $^{40}Ar–^{39}Ar$ dating and source tracing from Luxi area. *Chinese Science Bulletin*, **47**, 91–99.

QIU, Y. M., GAO, S., MCNAUGHTON, N. J., GROVES, D. I. & LING, W. 2000. First evidence of >3.2 Ga continental crust in the Yangtze Craton of south China and its implication for Archaean crustal evolution and Phanerozoic tectonics. *Geology*, **28**, 11–14.

REGELOUS, M., COLLERSON, K. D., WART, A. & WENDT, J. I. 1997. Trace element transport rates in subduction zones: evidence from Th, Sr and Pb isotope data for Tonga–Kermadec arc lavas. *Earth and Planetary Science Letters*, **150**, 291–302.

RUDNICK, R. L. & GAO, S. 2003. Composition of the continental crust. *In*: RUDNICK, R. L. (ed.) *The Crust Treatise on Geochemistry*, Volume 3. Elsevier–Pergamon, Oxford, 1–64.

RYERSON, F. J. & HESS, P. C. 1978. Implications of liquid–liquid distribution coefficients to mineral–liquid partitioning. *Geochimica et Cosmochimica Acta*, **42**, 921–932.

SONG, Y., FREY, F. A. & ZHI, X. C. 1990. Isotopic characteristics of Hannuoba basalts, eastern China: implications for their petrogenesis and the composition of subcontinental mantle. *Chemical Geology*, **88**, 35–52.

SUN, S.-S. & MCDONOUGH, W. F. 1989. Chemical and isotopic systematics of oceanic basalts: implication for mantle composition and processes. *In*: SAUNDERS, A. D. & NORRY, M. J. (eds) *Magmatism in the Ocean Basins*, Geological Society, London, Special Publications, **42**, 313–345.

TATSUMOTO, M., BASU, A. R., HUANG, W., WANG, J. & XIE, G. 1992. Sr, Nd and Pb isotopes of ultramafic xenoliths in volcanic rocks of Eastern China: enriched components EMI and EMII in subcontinental lithosphere. *Earth and Planetary Science Letters*, **113**, 107–128.

TOMURTUGOO, O., WINDLEY, B. F., KRÖNER, A., BADARCH, G. & LIU, D. Y. 2005. Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: constraints on the evolution of the Mongol–Okhatsk ocean, suture and orogen. *Journal of the Geological Society, London*, **162**, 125–134.

TU, X. L., ZHU, B. Q., FAN, S. K. & HU, A. Q. 1993. Pb isotopes of the granulites from North China and comparison with other places over the world. *Science in China* (*Series B*), **23**, 537–544.

WANG, Y., FAN, W., PENG, T., ZHANG, H. & GUO, F. 2005. Nature of the Mesozoic lithospheric mantle and tectonic decoupling beneath the Dabie Orogen, central China: evidence from $^{40}Ar/^{39}Ar$ geochronology, elemental and Sr–Nd–Pb isotopic compositions of early Cretaceous mafic igneous rocks. *Chemical Geology*, **220**, 165–189.

WANG, Y., FAN, W., ZHANG, H. & PENG, T. 2006. Early Cretaceous gabbroic rocks from the Taihang Mountains: implications for a paleosubduction-related lithospheric mantle beneath the central North China Craton. *Lithos*, **86**, 281–302.

WILDE, S. A., ZHOU, X., NEMCHIN, A. A. & SUN, M. 2003. Mesozoic crust-mantle interaction beneath the North China craton: a consequence of the dispersal of Gondwanaland and accretion of Asia. *Geology*, **31**, 817–820.

WU, F. Y., JAHN, B. M., WILDE, S. A. *ET AL*. 2003*a*. Highly fractionated I-type granites in NE China (I): geochronology and petrogenesis. *Lithos*, **66**, 241–273.

WU, F. Y., JAHN, B. M., WILDE, S. A. *ET AL*. 2003*b*. Highly fractionated I-type granites in NE China (II): isotopic geochemistry and implications for crustal growth in the Phanerozoic. *Lithos*, **67**, 191–204.

WU, F. Y., LIN, J. Q., WILDE, S. A., ZHANG, X. O. & YANG, J. H. 2005. Nature and significance of the Early Cretaceous giant igneous event in eastern China. *Earth and Planetary Science Letters*, **233**, 103–119.

WULFF-PEDERSEN, E., NEUMANN, E. R., VANNUCCI, R., BOTTAZZI, P. & OTTOLINI, L. 1999. Silicic melts produced by reaction between peridotite and infiltrating basaltic melts: ion probe data on glasses and minerals in veined xenoliths from La Palma, Canary Islands. *Contributions to Mineralogy and Petrology*, **137**, 59–82.

XIAO, W. J., WINDLEY, B. F., HAO, J. & ZHAI, M. G. 2003. Accretion leading to collision and the Permian Solonker Suture, Inner Mongolia, China: termination of the central Asian orogenic belt. *Tectonics*, **22**(6), 1069, doi:10.1029/2002TC001484.

XING, F. 1996. Petrological and Sr, Nd, Pb isotopic evidence for genesis of Mesozoic magmatic rocks from Nanjing–Wuhu area. *Acta Petrologica et Mineralogica*, **15**, 126–137 [in Chinese with English abstract].

XU, J. F., SHINJO, R., DEFANT, M. J., WANG, Q. & RAPP, R. P. 2002. Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: partial melting of delaminated lower continental crust? *Geology*, **30**, 1111–1114.

XU, W. L., WANG, Q. H., WANG, D. Y., PEI, F. P. & GAO, S. 2004. Processes and mechanism of Mesozoic lithospheric thinning in eastern North China Craton: evidence from Mesozoic igneous rocks and deep-seated xenoliths. *Earth Science Frontiers*, **11**(3), 309–317 [in Chinese with English abstract].

XU, W. L., WANG, Q. H., WANG, D. Y., GUO, J. H. & PEI, F. P. 2006. Mesozoic adakitic rocks from the Xuzhou–Suzhou area, eastern China: evidence for partial melting of delaminated lower continental crust. *Journal of Asian Earth Sciences*, **27**, 454–464.

XU, Y., HUANG, X., MA, J. *ET AL*. 2004*a*. Crust–mantle interaction during the tectono-thermal reactivation of the North China Craton: constraints from SHRIMP zircon U–Pb chronology and geochemistry of

Mesozoic plutons from western Shandong. *Contributions to Mineralogy and Petrology*, **147**, 750–767.

XU, Y., MA, J., HUANG, X., IIZUKA, Y., CHUNG, S., WANG, Y. & WU, X. 2004*b*. Early Cretaceous gabbroic complex from Yinan, Shandong Province: petrogenesis and mantle domains beneath the North China Craton. *International Journal of Earth Science*, **93**, 1025–1041.

YAN, J., CHEN, J., YU, G., QIAN, H. & ZHOU, T. 2003. Pb isotopic characteristics of Late Mesozoic mafic rocks from the Lower Yangtze region: evidence from enriched mantle. *Geological Journal of China University*, **9**, 195–206 [in Chinese with English abstract].

YANG, J. H., CHUNG, S. L., ZHAI, M. G. & ZHOU, X. H. 2004*a*. 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. *Lithos*, **73**, 145–160.

YANG, J. H., WU, F. Y., CHUNG, S. L., WILDE, S. A. & CHU, M. F. 2004*b*. Multiple sources for the origin of granites: geochemical and Nd/Sr isotopic evidence from the Gudaoling granite and its mafic enclaves, northeast China. *Geochimica et Cosmochimica Acta*, **68**, 4469–4483.

YANG, J. H., CHUNG, S. L., WILDE, S. A., WU, F. Y., CHU, M. F., LO, C. H. & FAN, H. R. 2005*a*. Petrogenesis of post-orogenic syenites in the Sulu Orogenic Belt, East China: geochronological, geochemical and Nd–Sr isotopic evidence. *Chemical Geology*, **214**, 99–125.

YANG, J. H., WU, F. Y., CHUNG, S. L., WILDE, S. A., CHU, M. F., LO, C. H. & SONG, B. 2005*b*. Petrogenesis and tectonic significance of Early Cretaceous granitic magmatism in the Sulu ultrahigh-pressure orogenic belt, East China. *Chemical Geology*, **222**, 200–231.

YANG, Z. L., SHEN, W. Z. & TAO, K. Y. 1999. Sr, Nd and Pb isotopic characteristics of the early Cretaceous basaltic rocks from the coast of Zhejiang and Fujian: evidence for ancient enriched mantle source. *Acta Geologica Sinica*, **34**, 59–68 [in Chinese with English abstract].

YING, J., ZHOU, X. & ZHANG, H. 2004. Geochemical and isotopic investigation of the Laiwu–Zibo carbonatites from Western Shandong Province, China, and implications for their petrogenesis and enriched mantle source. *Lithos*, **75**, 413–426.

YU, X., SHU, L., YAN, T., YU, Y., ZU, F. & WANG, B. 2004. Geochemistry of basalts of late period of Early Cretaceous from Jiangshan–Guangfeng, SE China and its tectonic significance. *Geochemica*, **33**, 465–476 [in Chinese with English abstract].

YU, Y. W., ZHOU, T. X. & CHEN, J. F. 1993. The characteristics and origin of the Xuantandi bi-modal volcanic rock of the late stage of early Cretaceous, Zhejiang. *Journal of Nanjing University* (*Earth Science*), **5**, 420–429 [in Chinese with English abstract].

ZHANG, G. H., ZHOU, X. H., SUN, M., CHEN, S. H. & FENG, J. L. 1998. Sr, Nd and Pb isotopic composition and geologic implication of granulite and pyroxenite xenoliths from Hannuoba basalt, Hebei. *Acta Petrologica Sinica*, **14**(2), 190–197 [in Chinese with English abstract].

ZHANG, H. 2005. Transformation of lithospheric mantle through peridotite-melt reaction: a case of Sina-Korean craton. *Earth and Planetary Science Letters*, **237**, 768–780.

ZHANG, H. & SUN, M. 2002. Geochemistry of Mesozoic basalts and mafic dikes, Southeastern North China craton, and tectonic implications. *International Geological Review*, **44**, 370–382.

ZHANG, H., SUN, M., ZHOU, X., ZHOU, M., FAN, W. & ZHENG, J. 2003. Secular evolution of the lithosphere beneath the eastern North China Craton: evidence from Mesozoic basalts and high-Mg andesites. *Geochimica et Cosmochimica Acta*, **67**, 4373–4387.

ZHANG, H., SUN, M., ZHOU, M., FAN, W., ZHOU, X. & ZHAI, M. 2004. Highly heterogeneous Late Mesozoic lithospheric mantle beneath the North China craton: evidence from Sr–Nd–Pb isotopic systematics of mafic igneous rocks. *Geological Magazine*, **141**, 55–62.

ZHANG, H. F., SUN, M., ZHOU, X. H., FAN, W. M., ZHAI, M. G. & YING, J. F. 2002. Mesozoic lithosphere destruction beneath the North China Craton: evidence from major-, trace-element and Sr–Nd–Pb isotope studies of Fangcheng Basalts. *Contributions to Mineralogy and Petrology*, **144**, 241–253.

ZHANG, H. F., SUN, M., ZHOU, X. H. & YING, J. F. 2005. Geochemical constraints on the origin of Mesozoic alkaline intrusive complexes from the North China Craton and tectonic implications. *Lithos*, **81**, 297–317.

ZHANG, L. 1995. *Block-Geology of Eastern Asia Lithosphere*. Science Press, Beijing, 53–62 [in Chinese].

ZHAO, G. C., CAWOOD, P. A., WILDE, S. A., SUN, M. & LU, L. Z. 2000. Metamorphism of basement rocks in the Central zone of the North China Craton: implications for Paleoproterozoic tectonic evolution. *Precambrian Research*, **103**, 55–88.

ZHAO, Z. F., ZHENG, Y. F., WEI, C. S., WU, Y. B., CHEN, F. & JAHN, B. M. 2005. Zircon U–Pb age, element and C–O isotope geochemistry of post-collisional mafic–ultramafic rocks from the Dabie orogen in east–central China. *Lithos*, **83**, 1–28.

ZHENG, J., SUN, M., LU, F. & PEARSON, N. 2003. Mesozoic lower crustal xenoliths and their significance in lithospheric evolution beneath the Sino-Korean Craton. *Tectonophysics*, **361**, 37–60.

ZHENG, J., GRIFFIN, W. L., O'REILLY, S. Y. *ET AL*. 2004. 3.6 Ga lower crust in central China: new evidence on the assembly of the North China craton. *Geology*, **32**, 229–232.

ZHENG, J. P. & LU, F. X. 1999. Mantle xenoliths from kimberlites, Shandong and Liaoning: Paleozoic mantle character and its heterogeneity. *Acta Petrologica Sinica*, **15**, 65–74 [in Chinese with English abstract].

ZHOU, T. X., CHEN, J. F. & CHENG, Z. Q. 1993. *Sr and Nd Isotopic Researches of the Mesozoic Basalts in Eastern Zhejiang Province, Isotopic Geochemistry of Crust–Mantle Evolution and Petrological-Mineralization*, Seismic Press, Beijing, 45–46 [in Chinese].

ZHOU, X., ZHANG, G., YANG, J., CHEN, W. & SUN, M. 2001. Sr–Nd–Pb Isotopic mapping of the late Cretaceous volcanic rocks in north margin of North China craton and its tectonic implications. *Geochimica*, **30**, 10–23.

ZINDLER, A. & HART, S. 1986. Chemical geodynamics. *Annual Review of Earth and Planetary Sciences*, **14**, 493–571.