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Secular Evolution of Lithospheric Mantle Beneath the Central North China Craton: Implication from Basaltic Rocks and Their Xenoliths

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1. Introduction

The old lithospheric mantle beneath the North China Craton (NCC, Fig. 1a) was extensively thinned during the Phanerozoic, especially in the Mesozoic and Cenozoic, resulting in the loss of more than 100 km of the rigid lithosphere (Menzies et al., 1993; Fan et al., 2000). This inference comes from the studies on the Ordovician diamondiferous kimberlites (Fig. 1b), Mesozoic lamprophyre-basalts and Cenozoic basalts, and their deep-seated xenoliths (e.g. Lu et al., 1995; Griffin et al., 1998; Menzies & Xu, 1998; Zhang et al., 2002). This remarkable evolution of the subcontinental lithosphere mantle, which has had profound effects on the tectonics and magmatism of this region, has attracted considerable attention (e.g. Guo et al., 2003; Deng et al., 2004; Gao et al., 2004; Rudnick et al., 2004; Xu et al., 2004; Ying et al., 2004; Zhang et al., 2004a, 2005, 2008; Wu et al., 2005; Tang et al., 2006, 2007, 2008, 2011; Zhao et al., 2010). However, the cause of such a dramatic change, from a Paleozoic cold and thick (up to 200 km) cratonic mantle (Griffin et al., 1992; Menzies et al., 1993) to a Cenozoic hot and thin (< 80 km) "oceanic-type" lithospheric mantle, is still controversial.

Based on the Mesozoic basalt development, Menzies and Xu (1998) argued that thermal and chemical erosion of the lithosphere was perhaps triggered by circum-craton subduction and subsequent passive continental extension. This suggestion was first supported by the geochemical studies on the Mesozoic basalts and high-Mg# basaltic andesites on the NCC (Zhang et al., 2002, 2003). A partial replacement model was proposed, having a subcontinental lithospheric mantle in this region composed of old lithosphere in the uppermost part and newly created lithosphere in the lower part (Fan et al., 2000; Xu, 2001; Zheng et al., 2001). The clearly zoned mantle xenocrysts found in Mesozoic Fangcheng basalts (Zhang et al. 2004b) provide the evidence for such a replacement of lithospheric mantle from high-Mg peridotites to low-Mg peridotites through peridotite-melt reactions (Zhang, 2005). Another different model was also proposed that ancient lithospheric mantle was totally replaced by juvenile material in the Late Mesozoic (Gao et al., 2002; Wu et al., 2003). On the basis of Os isotopic evidence from mantle xenoliths enclosed in Cenozoic basalts, Gao et al. (2002) suggested that two times replacement existed in the NCC. They attributed the replacement of the old lithospheric mantle beneath the Hannuoba region to the collision of the Eastern

Block with the Western Block and the second time perhaps to the collision of the Yangtze Craton with the NCC. Based on the study of Mesozoic Fangcheng basalts, Zhang et al. (2002) proposed that the replacement of the lithospheric mantle beneath the southern margin of the NCC was triggered by the collision between the Yangtze and the NCC. Zhang et al. (2003) further suggested that the secular lithospheric evolution was related to the subduction processes surrounding the NCC, which produced the highly heterogeneous Mesozoic lithospheric mantle underneath the NCC (Zhang et al., 2004a). In contrast, Wu et al. (2003) thought that subduction of the Pacific plate during the Mesozoic was the main cause of lithospheric thinning. Meanwhile, Wilde et al. (2003) correlated this event with the lithospheric thinning resulting from the breakup and dispersal of Gondwanaland and suggested that the removal was partial loss of mantle lithosphere, accompanied by wholesale rising of asthenospheric mantle beneath eastern China.

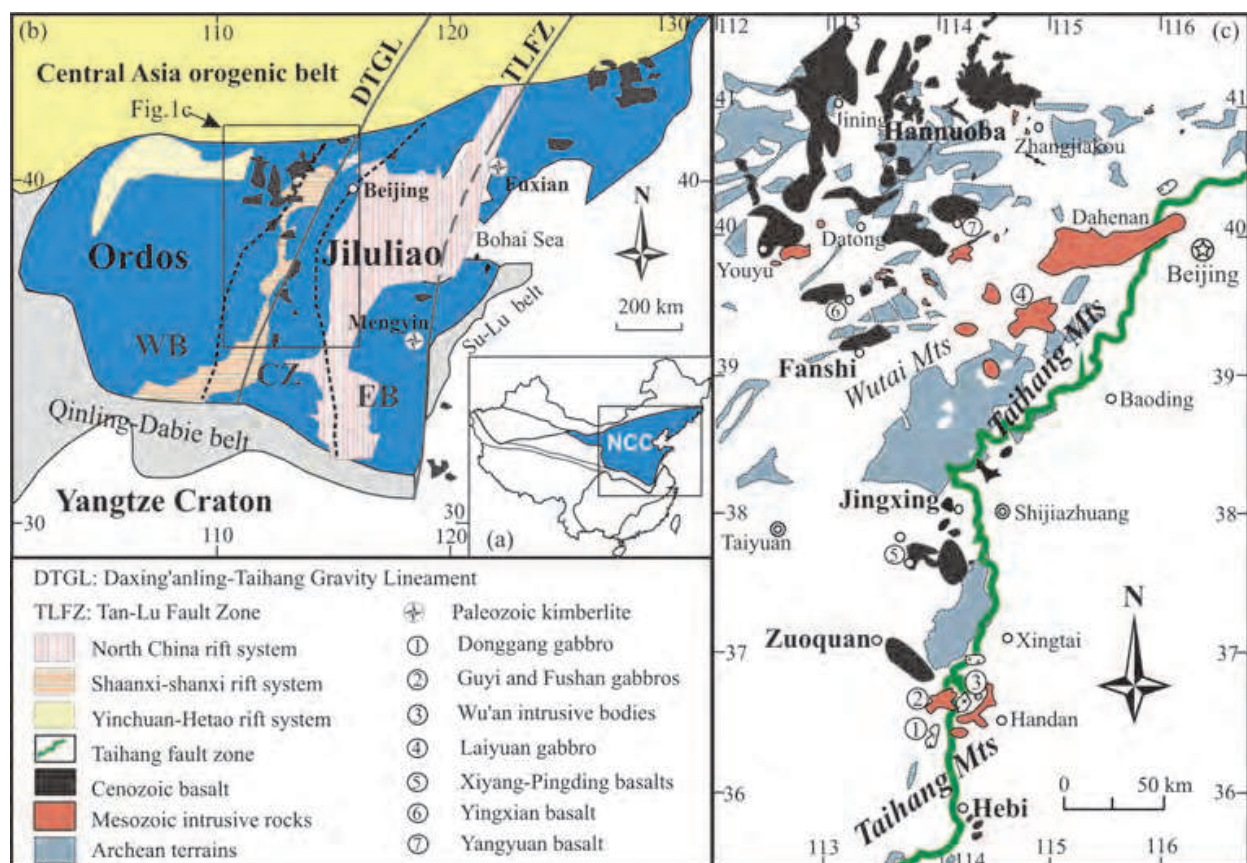


Fig. 1. (a) Map showing the location of the North China Craton (NCC); (b) Three subdivision of the NCC (modified from Zhao et al., 2001). Two dashed lines outline the Central Zone (CZ), the Western Block (WB) and the Eastern Block (EB); (c) The distribution of Cenozoic basalts, Mesozoic mafic intrusive rocks and of Archean terrains in the studied area.

Based on the Daxing'anling-Taihang gravity lineament (DTGL), the NCC can be divided into western and eastern parts (Ordos and Jiluliao terrains, Fig. 1b). The temporal variations in geochemistry of Cenozoic basalts from both sides of the DTGL suggest an opposite trend of lithospheric evolution between the western and eastern NCC (Xu et al., 2004), i.e. the progressive lithospheric thinning in the western NCC and the lithospheric thickening in the eastern NCC during the Cenozoic. Considering that the Taihang Mountains are in the Central Zone of the NCC, which geographically coincides with the DTGL (Fig. 1b), the

Mesozoic-Cenozoic lithospheric evolution beneath this region is an important issue to comprehensively decipher the mechanism for the lithospheric evolution beneath the NCC. In this paper, a summary of geochemical compositions of Mesozoic gabbros, Cenozoic basalts and their peridotite xenoliths in the Central Zone are presented to trace the petrogenesis of these rocks, the Mesozoic-Cenozoic basaltic magmatism, and further to discuss the potential mechanism of the lithospheric evolution in this region.

2. Geological background and petrology

The NCC is one of the oldest continental cratons on earth (3.8~2.5 Ga; Liu et al., 1992a) and is composed of two Archean nuclei of Eastern and Western Blocks (Fig. 1b). The Eastern Block has thin crust (<35 km), weakly negative to positive Bouguer gravity anomalies and high heat flow because of widespread lithospheric extension during Late Mesozoic and Cenozoic, which produced the NNE-trending North China rift system (Fig. 1b), and the lithosphere is inferred to be <80~100 km (Ma, 1989). The Western Block has thick crust (>40 km), strong negative Bouguer gravity anomalies, low heat flow and a thick lithosphere (>100 km) (Ma, 1989). The Yinchuan-Hetao and Shanxi-Shaanxi rift systems (Fig. 1b) appeared in the Early Oligocene or Late Eocene, and the major extension developed later in the Neogene and Quaternary (Ye et al., 1987; Ren et al., 2002).

The basement of the NCC is composed of amphibolite to granulite facies rocks, such as Archaean grey tonalitic gneisses and greenstones and Paleoproterozoic khondalites and interlayered clastic, and an overlying neritic marine sedimentary cover (Zhao et al., 1999, 2001). It was considered that the NCC underwent the ~1.8 Ga subduction/collision between the Eastern and Western Blocks (Zhao et al., 1999, 2001) resulting in the amalgamation of the NCC. The east edge of the orogenic belt coincides with the Taihang Mountains rift zone.

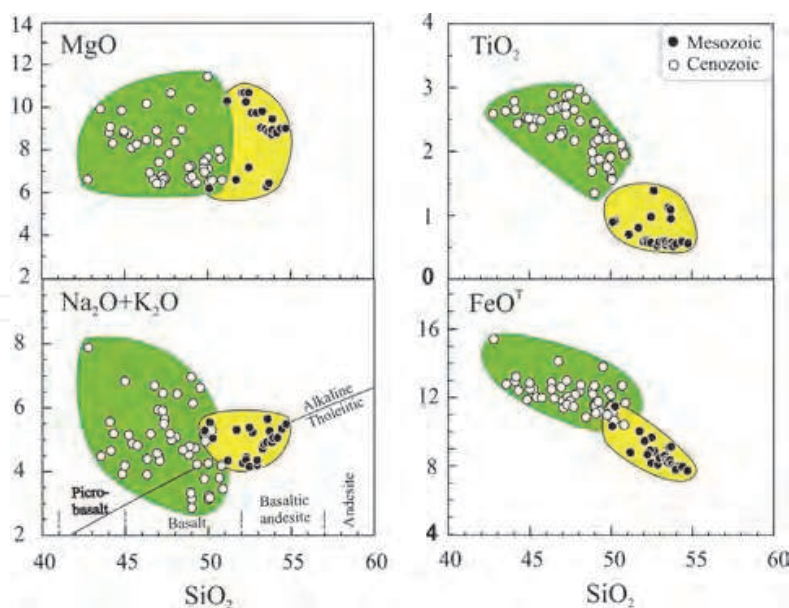


Fig. 2. Major oxide variations of the Mesozoic and Cenozoic basaltic rocks from the Central Zone. Data sources: Cenozoic basalts (Zhou & Armstrong, 1982; Xu et al., 2004; Tang et al., 2006), Mesozoic rocks (Cai et al., 2003; Chen et al., 2003, 2004; Chen & Zhai, 2003; Peng et al., 2004; Zhang et al., 2004), classification of volcanic rocks (TAS diagram, Le Bas et al., 1986), the boundary between alkaline and tholeiitic basalts (Irving & Baragar, 1971).

In the Central Zone of the NCC, the Mesozoic mafic intrusions are widespread, e.g. Donggang, Guyi, Fushan gabbros (150~160 Ma), Wuan monzonitic-diorites (126~127 Ma), Laiyuan gabbro, Wang'anzen and Dahenan monzonites (135~145 Ma) (Fig. 1c), which were cut by minor, late stage calc-alkaline lamprophyres (~120 Ma) that occur as dykes or small intrusions (Chen et al., 2003, 2004; Chen & Zhai, 2003; Peng et al., 2004 and references therein; Zhang et al., 2004a). These Mesozoic gabbros are of small volume and occur as laccoliths, knobs, or as xenoliths in Mesozoic dioritic intrusions.

Cenozoic basalts in the Central Zone (Fig. 1c) are distributed in the Hebi (~4 Ma), Zuoquan (~5.6 Ma), Xiyang-Pingding (7~8 Ma) and Fanshi-Yingxian regions (24~26 Ma) (Liu et al., 1992b), which are mainly composed of alkaline basalts and olivine basalts, including alkaline and tholeiitic sequences (Fig. 2). Abundant mantle-derived peridotite xenoliths are found in the basalts from the Fanshi and Hebi regions (Zheng et al., 2001; Xu et al., 2004), and mantle olivine xenocrysts are entrained in the Xiyang-Pingding basalts, which are interpreted as the relict of old lithospheric mantle (Tang et al., 2004).

3. Methodology and samples

Experiments have demonstrated that more SiO₂-undersaturated magmas are produced at higher pressures than tholeiitic lavas (e.g., Falloon et al., 1988). Because the lithospheric mantle and asthenosphere generally are different in geochemical signatures, it can be inferred that the lithosphere is >80 km thick if the alkali basalts have an isotopic signature of sub-continental lithospheric mantle. Conversely, if the tholeiitic basalts have an asthenospheric signature the lithosphere is inferred to be <60 km thick (DePaolo and Daley, 2000). The geochemistry of mantle-derived magmas is dependent on the depth of melting (Herzberg, 2006), thus the geochemistry of basaltic rocks can be used to monitor variation in lithospheric thickness and geochemistry through time (e.g., DePaolo and Daley, 2000).

Ideally, tracing the chemical evolution of the mantle lithosphere would be accomplished by measuring the compositions of coherent, pristine suites of direct mantle samples, lacking metasomatic overprints, and with a well-determined age and geological context. The chemical compositions of direct mantle samples such as abyssal peridotites and peridotite xenoliths, and of indirect probes of the mantle such as basalts from MORBs and OIBs, have provided strong evidence for chemical complexity and heterogeneity of the mantle (Hofmann, 2003). Complexity in the interpretation of chemical compositions of basalts often results from the modification of primary melt compositions due to crustal contamination during their generation and ascent. For this reason, the most primitive basalts, usually with the highest-MgO content, are taken to be the least affected by crustal interaction and therefore the best record of mantle compositions.

Mesozoic basaltic rocks in the Central Zone are dominantly gabbroic intrusions, which are derived from lithospheric mantle (Tan & Lin, 1994; Zhang et al., 2004). Some of them contain peridotite and/or pyroxenite xenoliths (Xu & Lin, 1991; Dong et al., 2003). Previous petrological and geochemical studies indicate that the gabbroic rocks have compositions of original basaltic magmas (Tan & Lin, 1994; Zhang et al., 2004). Although some workers report crustal contamination (Chen et al., 2003; Chen & Zhai, 2003; Chen et al., 2004), others suggest that in many cases isotopic composition of these rocks still reflect variation in the mantle source and can provide the information on the continental lithospheric mantle beneath the region (Tan & Lin, 1994; Dong et al., 2003; Zhang et al., 2004).

In contrast, the geochemical features of Cenozoic basalts from Taihang Mountains (Tang et al., 2006), are very similar to those of the Cenozoic Hannuoba basalts (e.g. Zhou & Armstrong, 1982; Song et al., 1990; Basu et al., 1991), suggest their derivation mainly from asthenosphere with negligible crustal contamination. The occurrence of mantle xenoliths and xenocrysts suggests that these lavas ascended rapidly, implying that significant interaction with crustal wall rocks could not happen. So, their chemical compositions can be used to probe their mantle sources. Although these basalts are dominantly of asthenospheric source, their variable Sr-Nd isotopic ratios indicate some contributions of lithospheric mantle (Tang et al., 2006), whereby we could indirectly trace the feature of the Cenozoic mantle lithosphere. Meanwhile, some available data of mantle xenoliths entrained in these Cenozoic basalts can be used to directly infer the nature of the lithospheric mantle beneath the craton.

Due to the biases brought about by variable assimilation-fractional crystallization processes, we use only gabbros and basalts with the geochemical compositions of relatively primitive samples ($\text{MgO} > 6 \text{ wt.}\%$) from each region, as well as their hosted peridotite xenoliths, to study the nature of mantle lithosphere beneath the Central Zone of the NCC.

4. Variations in geochemical compositions

Figures 2-7 show clear variations in geochemical compositions between the Mesozoic and Cenozoic basaltic rocks in the Central Zone. Compared with the Cenozoic basalts, the Mesozoic mafic intrusive rocks are: (1) higher in SiO_2 , lower in FeO^T and TiO_2 contents (Fig. 2); (2) enriched in light rare earth element (LREE) and large ion lithophile element (LILE, such as Ba, Th and U), but depleted in high field strength element (HFSE, e.g. Nb, Ta, Zr and Ti; Figs. 3 & 4); (3) high Sr and low Nd and Pb isotopic ratios (most $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.705 \sim 0.7065$, $^{143}\text{Nd}/^{144}\text{Nd}_i < 0.512$; Fig. 5; $^{206}\text{Pb}/^{204}\text{Pb}_i < 17.5$, $^{207}\text{Pb}/^{204}\text{Pb}_i < 15.5$, $^{208}\text{Pb}/^{204}\text{Pb}_i < 38.0$, Fig. 6), typically EM1 features. These features are completely different from those of MORB, OIB and Cenozoic basalts in this region, which are generally lower in SiO_2 , higher in FeO^T and TiO_2 contents (Fig. 2), depleted in Sr-Nd isotopes (Fig. 5) and have no HFSE depletion (Figs. 3 & 4). These geochemical distinctions reflect their mantle source differences between Mesozoic and Cenozoic times.

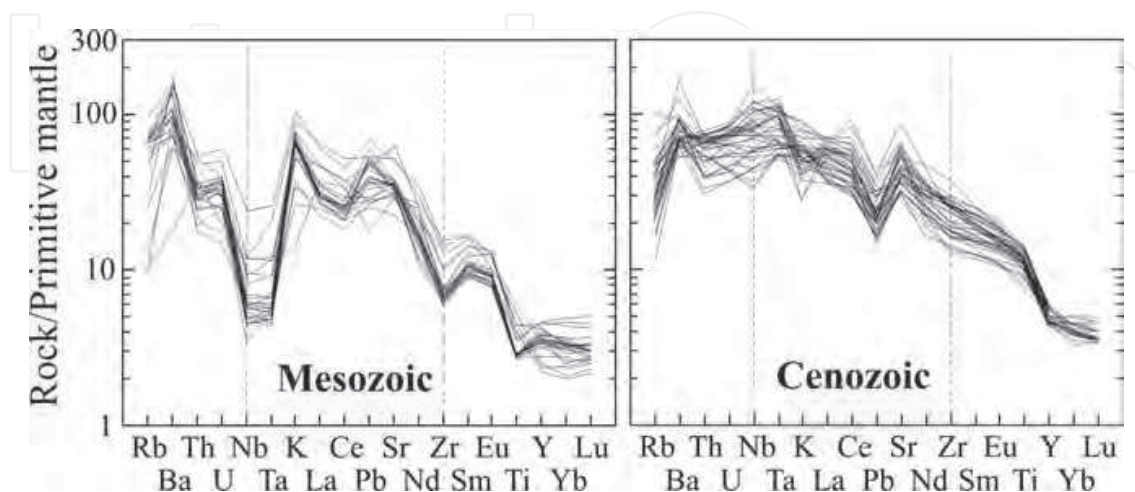


Fig. 3. Primitive mantle-normalized trace element diagrams for the basaltic rocks from the Central Zone. Data sources: primitive mantle (McDonough & Sun, 1995), others as in Fig. 2.

5. Discussion

5.1 Petrogenesis of Cenozoic basalts and lithospheric thickness

Cenozoic basalts from the Taihang Mountains have many similar features to those of Cenozoic Hannuoba basalts (Zhou & Armstrong, 1982; Peng et al., 1986; Song et al., 1990; Basu et al., 1991; Liu et al., 1994) and many alkali basalts from both oceanic and continental settings (Barry & Kent, 1998; Tu et al., 1991; Turner & Hawkesworth, 1995) in their elemental and isotopic compositions (Figs. 2-7). Their common geochemical features of OIB and/or MORB are interpreted as having been derived from the asthenospheric mantle.

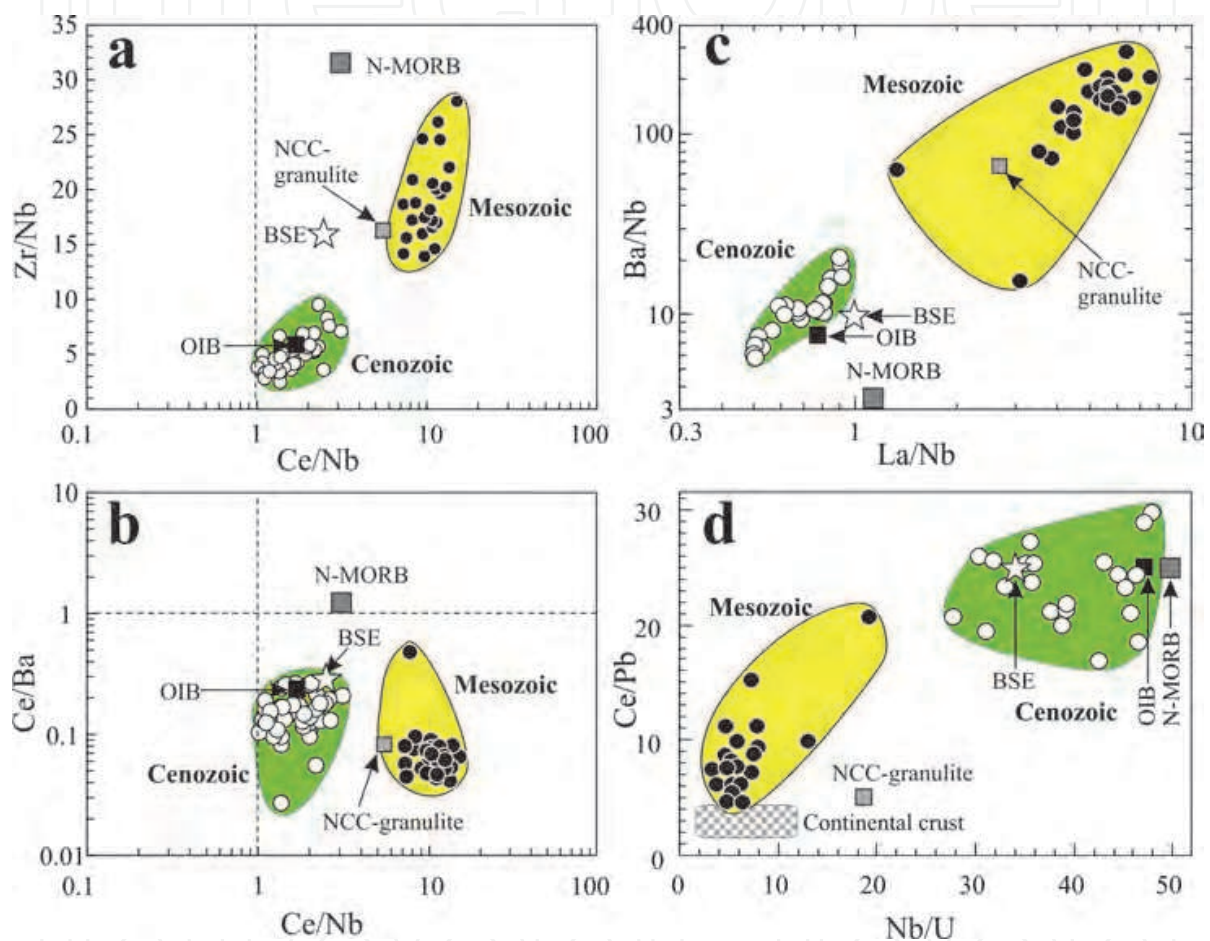


Fig. 4. Variations in trace-element ratios for the basaltic rocks from the Central Zone. Data sources: BSE, N-MORB and OIB (Sun & McDonough, 1989; McDonough & Sun, 1995); NCC-granulite, the average composition of old granulite terrains on the NCC (Gao et al., 1998); Continental crust (Rudnick & Gao, 2003). Other data sources and symbols as in Fig. 2.

Their incompatible trace element ratios, e.g. Ba/Nb, La/Nb, Zr/Nb, Ce/Nb, Ce/Ba, Nb/U and Ce/Pb values, are very close to those of OIB (Fig. 4). Some slightly lower and variable Nb/U ratios for these Cenozoic basalts (Fig. 4d) might suggest the involvement of lithospheric mantle in their source, because the metasomatised lithospheric mantle is probably involved in producing the negative Nb anomalies (Arndt & Christensen, 1992). Moreover, the lower initial ratios of $^{143}\text{Nd}/^{144}\text{Nd}_i$ (<0.5125) and higher $^{87}\text{Sr}/^{86}\text{Sr}_i$ (>0.705 ; Fig. 5) also indicate the involvement of old lithospheric mantle beneath the NCC. Three low ratios of Pb isotopes ($^{206}\text{Pb}/^{204}\text{Pb}_i < 16.9$) of the Cenozoic basalts (Fig. 6) are close to the field

of the Smoky Butte lamproites that were believed to have been derived from ancient EM1-type lithospheric mantle (Fraser et al., 1985). They are also similar to those of Cenozoic potassic basalts in the Wudalianchi, northeastern China (Zhang et al., 1998), whose source is interpreted as metasomatically enriched mantle. Integrating the isotopic ratios with the element compositions, the Cenozoic basalts from the Taihang Mountains are inferred to be derived from partial melting of an asthenospheric source with different degrees of the involvement of old lithospheric mantle.

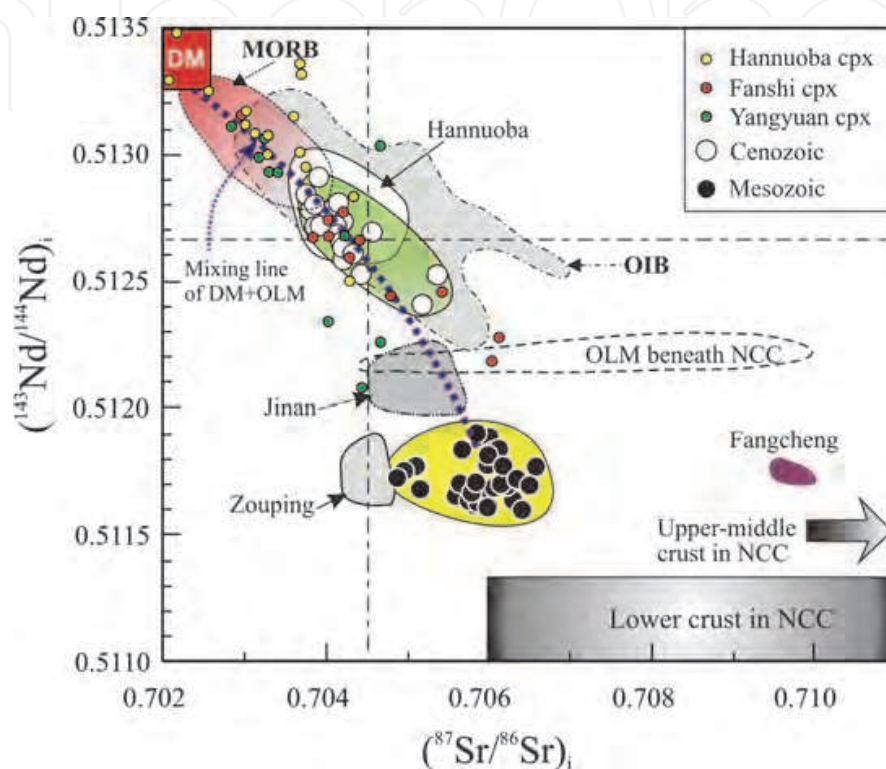


Fig. 5. $^{87}\text{Sr}/^{86}\text{Sr}_i$ vs. $^{143}\text{Nd}/^{144}\text{Nd}_i$ diagrams for the basaltic rocks from the Central Zone, compared with the Hannuoba basalts (Song et al., 1990; Zhi et al., 1990; Basu et al., 1991; Xie & Wang, 1992), old lithospheric mantle (OLM) beneath the NCC (Zhang et al., 2002), CPX in peridotite xenoliths in the Fanshi (Tang et al., 2008; 2011), Yangyuan (Ma & Xu, 2006) and Hannuoba basalts (Song & Frey, 1989; Tatsumoto et al., 1992; Fan et al., 2000; Rudnick et al., 2004), DM, MORB and OIB (Zindler & Hart, 1986), Mesozoic Fangcheng basalts (Zhang et al., 2002), Mesozoic Jinan gabbros (Zhang et al., 2004) and Zouping gabbros (Guo et al., 2003; Ying et al., 2005), the upper-middle crust and lower crust of the NCC (Jahn & Zhang, 1984; Jahn et al., 1988). Other data sources and symbols as in Fig. 2.

The clinopyroxenes (CPX) in mantle peridotite xenoliths entrained in the Cenozoic basalts have significant variations in Sr-Nd isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7022 \sim 0.7060$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.5135 \sim 0.5118$; Fig. 5), that could be explained by the peridotite-melt reaction (Tang et al., 2008). On the one hand, the difference between major-element compositions of basaltic melt derived from partial melting of asthenosphere (Fo in olivine ~ 89) and those of mantle peridotites (Fo in olivine ~ 92) is relatively small and thus the decrease of olivine Fo in mantle peridotites, caused by the asthenospheric melt-peridotite reaction, is small. On the other hand, the asthenospheric melt-peridotite interaction causes the depletion in Sr-Nd isotopic compositions of mantle peridotites due to the depleted Sr-

Nd isotopic ratios in asthenospheric melts. Possibly, the peridotite-melt interaction could not cause a large variation in Re-Os isotopic system of mantle peridotites because Os isotope systematics for cratonic peridotites appear to be dominantly influenced by the ancient differentiation events that caused them to separate from the convecting mantle, whereas Sr-Nd isotope systematics record later events (Pearson, 1999). Thus, the debate between Os isochron ages (~1.9 Ga) and Sr-Nd isotopic compositions (depleted) of Hannuoba mantle xenoliths can be explained with the fairly recent effect of the peridotite-melt reaction. The abundance of garnet-bearing pyroxenites in Hannuoba xenoliths indicates the presence of peridotite-melt reaction (Liu et al., 2005; Zhang et al., 2009).

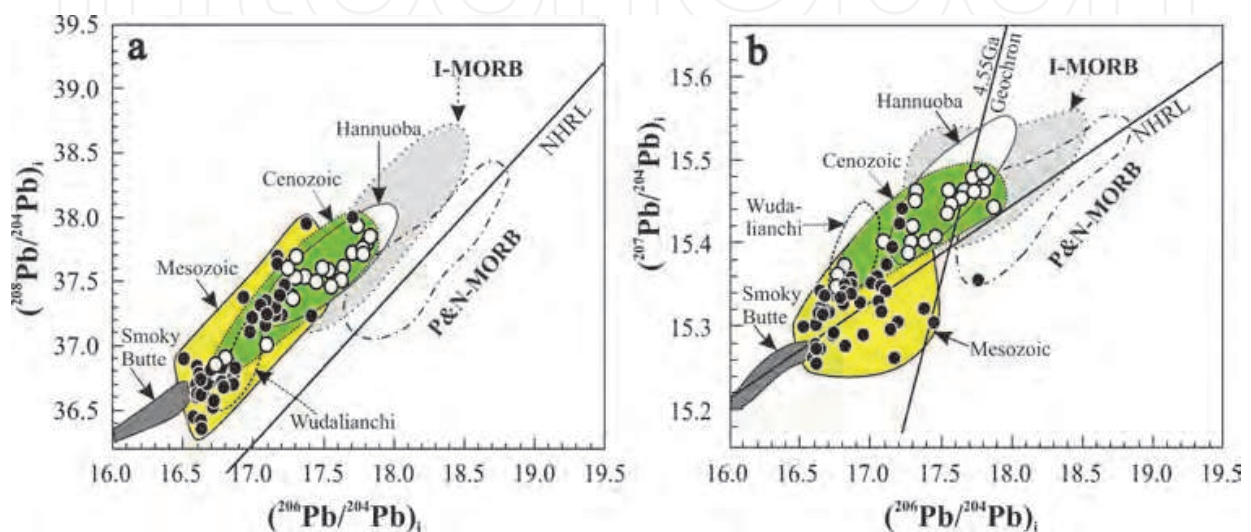


Fig. 6. $^{206}\text{Pb}/^{204}\text{Pb}_i$ vs. $^{208}\text{Pb}/^{204}\text{Pb}_i$ and $^{207}\text{Pb}/^{204}\text{Pb}_i$ diagrams for the basaltic rocks. Data sources: Fields of I-MORB (Indian MORB), P&N-MORB (Pacific & North Atlantic MORB) and NHRL (north hemisphere reference line) (Barry & Kent, 1998; Hart, 1984; Zou et al., 2000), field for Smoky Butte lamproites (Fraser et al., 1985), Wudalianchi basalts (Liu et al., 1994), Hannuoba basalts as in Fig. 5, other data sources and symbols as in Fig. 2.

Similarly, some peridotite xenoliths entrained in the Hannuoba and Fanshi basalts have pyroxenite veins, indicating the presence of peridotite-melt reaction in the mantle lithosphere beneath the Central Zone of the NCC. The variations in isotopic ratios of these xenoliths might indicate the heterogeneity of peridotite-melt reaction (Tang et al., 2011). As a result, the enriched isotopic composition of cpx from the Fanshi and Yangyuan peridotite xenoliths could represent the signatures of old lithospheric mantle, which have experienced/or not such a peridotite-melt reaction.

The existence of old lithospheric mantle beneath the Central Zone during the Cenozoic is also proved by the discovery of mantle olivine xenocrysts in the Xiyang-Pingding basalts (Tang et al., 2004) and high Mg# ($\text{Fo} \geq 92$) peridotite xenoliths hosted by the Hebi basalts (Zheng et al., 2001), which are interpreted as the relics of old lithospheric mantle. The involvement of old lithospheric mantle in asthenospheric mantle source might well account for the isotopic features of the Cenozoic basalts (Fig. 5). In terms of Sr and Nd elemental contents and isotopic ratios of $^{87}\text{Sr}/^{86}\text{Sr}_i$ and $^{143}\text{Nd}/^{144}\text{Nd}_i$, the hypothetical mixing modeling between depleted mantle (DM; Zindler & Hart, 1986; Flower et al., 1998) and old lithospheric mantle (represented by the mantle-derived xenoliths with radiogenic isotopic compositions) reveals that the addition of 4~20% old lithospheric component into the DM will generate the observed Sr-Nd isotopic compositions for these Cenozoic basalts (Fig. 5).

According to the modelling results from the classic, non-modal batch melting equations of Shaw (1970), small degrees of partial melting of a garnet-bearing lherzolitic mantle source are required to explain the REE patterns observed in these basalts (Fig. 7, Tang et al., 2006), which is consistent with the low HREE contents of these Cenozoic basalts. The systematic presence of garnet as a residual phase requires melting depth in excess of 70-80 km, where garnet becomes stable. The results (Fig. 7) also suggest a deeper origin for the Zuoquan and Xiyang-Pingding basalts due to the higher garnet contents in their mantle source than those for the Fanshi-Yingxian basalts, as garnet becomes more with increasing depth.

A lithospheric profile model (Fig. 8c) illustrates the lithospheric evolution and the Cenozoic magmatism in the Central Zone. The Cenozoic tensional regime likely related to the Indian-Eurasian collision (Ren et al., 2002; Liu et al., 2004; Xu et al., 2004) might reactivate old faults, then the old lithospheric mantle was heated by progressively thermo-mechanical erosion processes with the upwelling of asthenosphere. As a result, the base lithosphere was gradually removed by the convecting mantle, forming a mixture of material from the old lithospheric mantle with the magmas from the asthenosphere, which finally produced the Cenozoic basalts through partial melting.

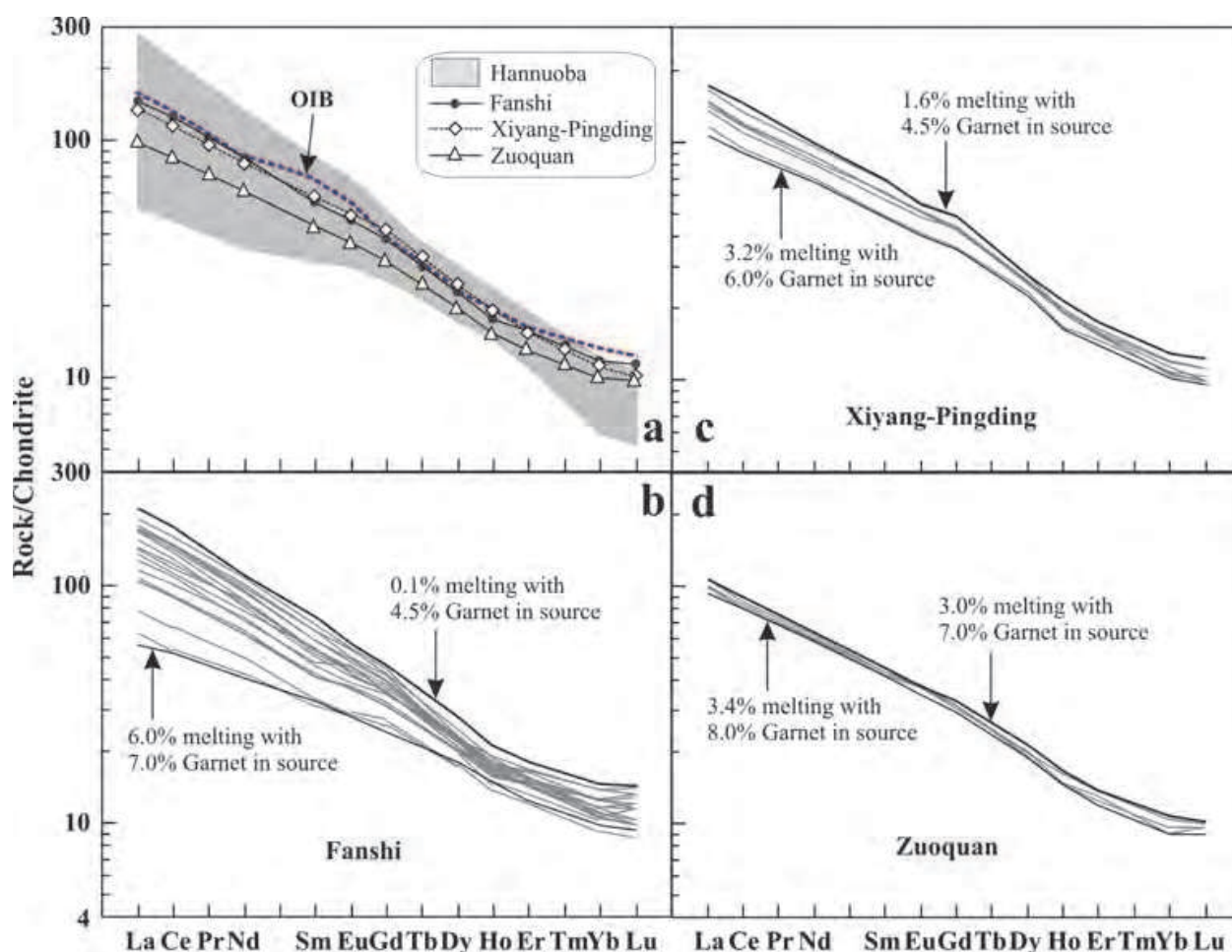


Fig. 7. Chondrite-normalized REE patterns for the Cenozoic basalts (Tang et al., 2006). Mean values of the REE for the basalts (a). Non-modal batch melting models used to approach partial melts for Fanshi (b), Xiyang-Pingding (c) and Zuoquan basalts (d). Data sources: Chondrite (Anders & Grevesse, 1989), OIB (Sun & McDonough, 1989).

5.2 Nature of the Mesozoic lithospheric mantle

Compared with the Cenozoic basalts, the Mesozoic basaltic rocks have obviously higher SiO_2 content with lower FeO^T and TiO_2 , and are depleted in HFSE, displaying typical EM1 character in isotopic compositions, which show the clear distinction between their mantle sources.

Element ratios, such as Nb/U, Ce/Nb, Zr/Nb, Ce/Ba and Ce/Pb, are demonstrated to be effective indicators for discriminating mantle source of asthenospheric or lithospheric origin and whether there were subducted materials involved in magma genesis (Salters & Shimizu, 1988; Kelemen et al., 1990; Hofmann, 1997; Turner & Foden, 2001). Plots of trace-element ratios (Fig. 4) show the remarkable differences between Mesozoic and Cenozoic basaltic rocks. Strong depletion in HFSE reveals some similarities of mantle sources between the Mesozoic rocks and arc magma in mantle wedges (Kelemen et al., 1990; Turner & Foden, 2001). Higher Ce/Nb, Zr/Nb, Ba/Nb, but lower Nb/U ratios (Fig. 4) in Mesozoic rocks relative to the Cenozoic basalts indicate that the source for these intrusive rocks are enriched in LREE and Zr relative to the Nb, and depleted in Nb. Their isotopic differences between Mesozoic and Cenozoic basaltic rocks are also obvious (Figs. 5 & 6). These geochemical signatures suggest that the Mesozoic rocks originated from a modified lithospheric mantle, and their low Nb/U ratios (Fig. 4d) and depletion in HFSE (Fig. 3) indicate the involvement of subducted crustal materials in magma genesis (Hofmann, 1997).

Geochemical compositions of the Mesozoic basaltic rocks from the Central Zone indicate that the secular evolution of old cratonic lithospheric mantle underwent processes of modification, which are believed to have originated from the influx of materials with old provenance age, which over time would develop isotopic enrichment (Zhang & Sun, 2002). The Sr-Nd isotopic compositions for these Mesozoic rocks indicate that the source was depleted in Rb but enriched in LREE. Their low Pb isotopic ratios (Fig. 6) define a trend towards the field for Smoke Butte lamproites, which originated from an EM1-like lithospheric mantle. These features, coupled with the clear depletion in HFSE and enrichment in LILE, suggest the involvement of an old component with low Sm/Nd, Rb/Sr and U/Pb ratios. It's the secular evolution of modified lithospheric mantle by old component leads to the striking features of very low ratios of $^{143}\text{Nd}/^{144}\text{Nd}_i$ (<0.5120) and $^{206}\text{Pb}/^{204}\text{Pb}_i$ (16.5~17.5), slightly low $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios (most = 0.7050~0.7065) of the Mesozoic basaltic rocks from the Central Zone (Figs. 5 & 6).

Mantle xenoliths, discovered in Palaeozoic kimberlites from the NCC, have very restricted Nd isotopic compositions (Fig. 5). In contrast, Nd isotopic compositions for Mesozoic Jinan gabbros, in the centre of the NCC, are slightly lower than those of Palaeozoic kimberlite-borne mantle xenoliths. The interpretation is that their mantle source inherited the characteristics of old lithospheric mantle with slight modification because the significant crustal contamination or AFC process during magma evolution has been excluded (Guo et al., 2001; Zhang et al., 2004a), as shown by their high MgO contents and the lack of a positive correlation of $^{87}\text{Sr}/^{86}\text{Sr}_i$ with SiO_2 or Mg# in these gabbroic rocks. Similarly, Mesozoic rocks from the Central Zone are lower in Nd isotopic ratios than the Jinan gabbros, indicating that the Mesozoic lithospheric mantle beneath the Central Zone was modified considerably by some mantle enrichment processes. It is interesting to note that the Nd isotopic ratios of the Mesozoic rocks are nearly equal to those of the Mesozoic Zouping gabbros from the centre of the NCC (Fig. 5), and the genesis of the latter are linked to carbonatitic metasomatism of lithospheric mantle (Ying et al., 2005).

On the basis of the above discussions, we propose that carbonatitic and silicic metasomatism may be a suitable candidate for the modification of the old lithospheric mantle beneath the Central Zone. The metasomatised agents should be enriched in LILE and Sr-Nd isotopic, depleted in HFSE and Pb isotopic ratios, and low in Sm/Nd, Rb/Sr and U/Pb ratios, whose geochemical features suggest that they can only be derived from old subducted crustal materials. As yet, there is no clear evidence to explain the occurrence of Phanerozoic subduction/collision in the interior of the NCC, except the Paleoproterozoic collision (~1.8 Ga) between the Eastern Block and the Western Block of the NCC (Gilder et al., 1991; Zhao et al., 2001; Wang et al., 2004). Thus, the carbonatitic and silicic metasomatism for the old lithospheric mantle beneath the Central Zone were probably related to the Paleoproterozoic collision between the two blocks.

5.3 Tectonic and magmatic model

The North China Craton is bounded on the south by the Paleozoic to Triassic Qinling-Dabie-Sulu orogenic belt (Li et al., 1993) and on the north by the Central Asian Orogenic Belt (Şengör et al., 1999; Jahn et al., 2000). The Triassic ages for the Dabie-Sulu UHP rocks in the southern margin of the NCC have been summarized (Zheng et al., 2003). The Central Asian Orogenic Belt formed through a complicated subduction and accretion processes and post-collisional magmatism over a long period of time ranging from the Early Paleozoic through the Triassic (Jahn et al., 2000). These subduction and the subsequent collisions may have affected the stability of the lithospheric mantle beneath the NCC (Zhang et al., 2003 and references therein). The westward subduction of the Pacific plate beneath the Euroasian continent provides the geodynamic setting of back-arc extension for the massive occurrence of Early Cretaceous igneous rocks in the east China continent (Wu et al., 2005). However, these magmatism just took place in Early Cretaceous rather than continuously from Jurassic to present, which requires a thermal pulse to cause the short-lived but large-scale anatexis of thickened lithosphere as a remote response to the Pacific superplume event (Zhao et al., 2005). This event may essentially act as mantle superwelling beneath the Euroasian continent that supply the excess heat to fuse the lithospheric mantle and overlying crust because material contribution of mantle plume hasn't been identified in the contemporaneous igneous rocks from the eastern edge of China continent.

On the basis of the above discussion and previous documents (Zhao et al., 2001, 2010; Zhang and Sun, 2002; Zhang et al., 2003; Wang et al., 2004; Faure et al., 2007; Zheng et al., 2009, 2010), we summarize a tectonic and magmatic model for the secular evolution of the lithospheric mantle beneath the Taihang Mountains (Fig. 8):

1. In the Late Archean to Paleoproterozoic, the Western Block (Zhao et al., 2001, 2010; Wang et al., 2004) and/or Eastern Block (Faure et al., 2007; Zheng et al., 2009) was subducted beneath the Central Zone with subduction of old continental and oceanic crustal component to mantle depths. Meanwhile, sedimentary rocks of the Eastern and Western Blocks were thrust over the Central Zone, which caused crustal-scale folding, thrusting and metamorphism, associated with the initial metasomatism of old lithospheric mantle by carbonatitic and silicic agents. At ~1.85 Ga, the orogenic belt suffered post-collision extensional collapse, which was associated with the subducted slab detachment and the development of the mantle metasomatism for the old lithospheric mantle. As a result, the Paleoproterozoic collision between the Eastern and Western Blocks led to the assembly of the NCC and the modification of old lithospheric

mantle by carbonatitic and silicic metasomatism (Fig. 8a). According to recent studies (Zhao et al., 2010; Zheng et al., 2010), the direction of subduction polarity in the Central Zone has still not been resolved. Whether the subduction polarity is westward or eastward the event(s) had led to the modification of the old lithospheric mantle by subducted crustal materials.

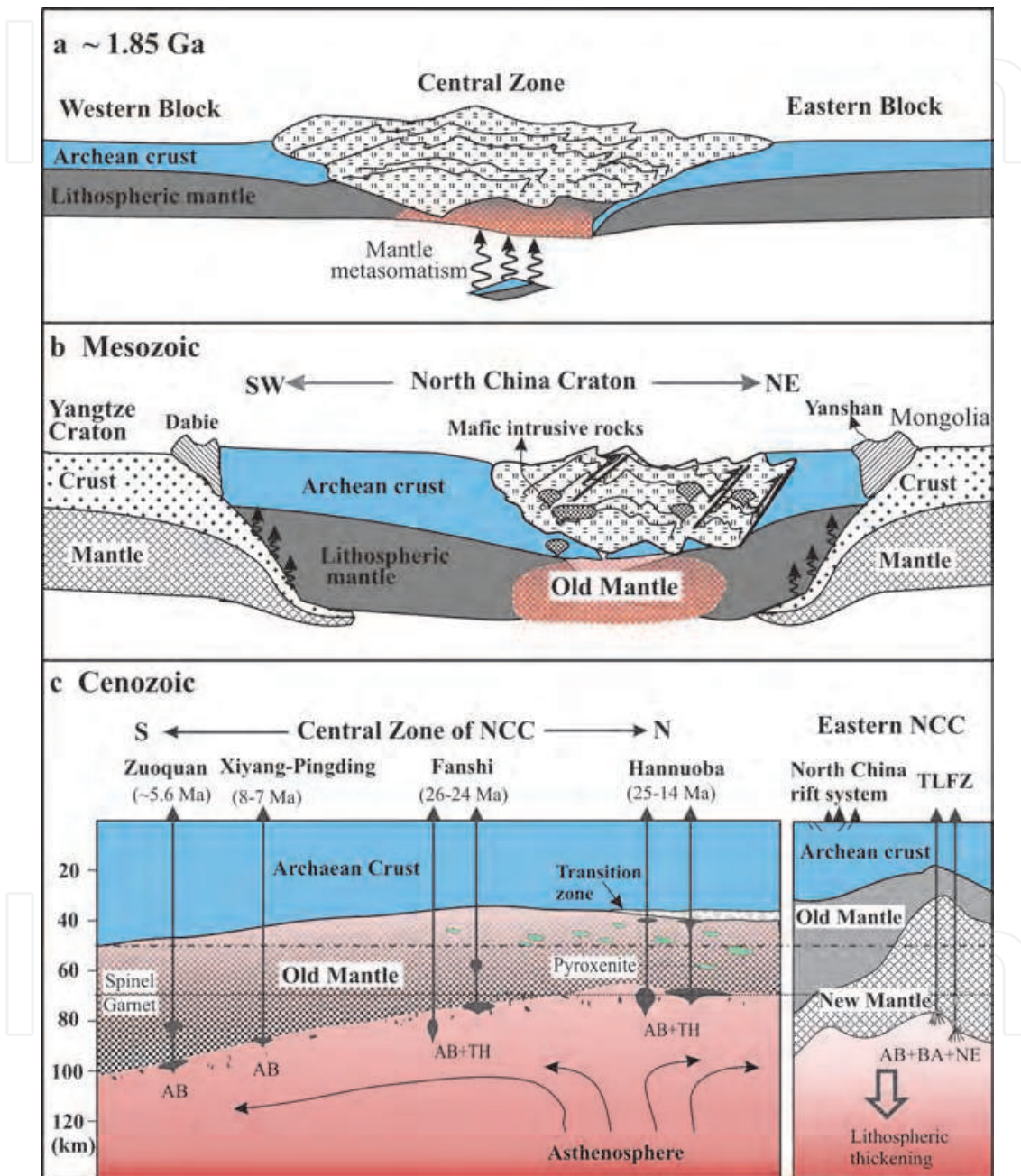


Fig. 8. Schematic cartoons of tectonic and magmatic model, showing the secular evolution of lithospheric mantle beneath the Central Zone of the NCC (a~c). Sketch map (a) is modified from Zhao et al. (2001), Wang et al. (2004) and Zheng et al. (2009); map (b) is modified from Zhang et al. (2003); map (c) is modified from Tang et al. (2006) and Menzies and Xu (1998). AB, alkaline basalt; AOB, alkaline olivine basalt; BA, Basanite; NE, nephelinite; OTH, olivine tholeiite. See text for the detail.

2. Subduction and collisions along the northern and southern margins of the North China Craton especially in Triassic initiated the cracking in the NCC interior. Late Mesozoic lithospheric thinning and mafic magmatism might have occurred with the upwelling of the asthenosphere probably also as a remote response to the Pacific superplume event (Zhao et al., 2005). With the change from convergent to extensional regime, the Mesozoic intrusive rocks might be generated by the partial melting of the metasomatised old lithospheric mantle beneath the Taihang Mountains (Fig. 8b).
3. With the continental extension in the Central Zone, possibly related to the Early Tertiary Indian-Eurasian collision, the Cenozoic basalts were produced by the decompression melting of asthenosphere and the interaction between asthenospheric magmas and old lithospheric mantle (Tang et al., 2006). The substantive existence of old lithospheric mantle with some modification by asthenospheric melt in the Central Zone is remarkably different from the Cenozoic lithospheric accretion in the eastern North China Craton (Fig. 8c).

6. Conclusion

Geochemical compositions indicate that the Mesozoic basaltic rocks from the Central Zone originated from lithospheric mantle, which was enriched in LREE, LILE and Sr-Nd isotopic ratios and depleted in HFSE and Pb isotopic compositions. The lithospheric mantle with these geochemical features had been probably produced by the modification of old cratonic lithospheric mantle with carbonatitic and silicic metasomatism, which were mainly derived from the subducted crustal materials during the Paleoproterozoic collision between the Eastern and Western blocks of the NCC.

Cenozoic basalts from the Central Zone were generated from the partial melting of asthenospheric mantle with/without some contributions of old lithospheric mantle during continental extension, which might be related to the Early Tertiary Indian-Eurasian collision. In conjunction with the data of mantle peridotite xenoliths, the Cenozoic lithospheric mantle has inherited the isotopic features of old lithosphere mantle in spite of some signatures of the modification by the asthenospheric melt-peridotite reaction.

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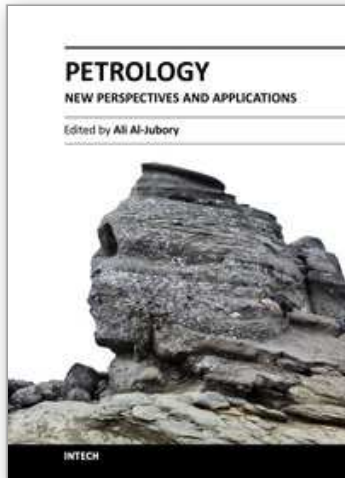
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