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Nature and evolution of the lower crust in the eastern North China craton: A review

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ABSTRACT

In this paper, published data for granulite terrain rocks exposed at the surface, lower crustal xenoliths, and Mesozoic intermediate-felsic igneous rocks from the eastern North China craton (NCC) are integrated to constrain the nature and evolution of the lower crust in this area. U–Pb zircon dating shows that the protolith ages for most of the granulite terrain rocks are 2500 to 2600 Ma and that many of them experienced 1800–1900 Ma metamorphism. Lower crustal xenoliths entrained in volcanic rocks with ages varying from ~460 to ~10 Ma suggest that the lower crust is dominated by Neoarchean rocks, although there may be minor rocks with ages of Meso- to Paleoarchean (>3000 Ma), ~45 Ma and possibly ~1900 Ma locally. The Mesozoic intrusive rocks, although varying from diorite to granite and spanning from Triassic to Cretaceous, contain ~2500 Ma inherited zircons and have magmatic zircons with Hf crust model ages ($T_{DM}^{Hf,C}$) ages of 2500–2700 Ma and whole-rock Sr–Nd isotopic compositions falling within the field of the granulite terrain rocks, pointing to their derivation by the melting of Neoarchean lower crust. The combined data for the granulite terrain rocks, lower crustal xenoliths and Mesozoic intermediate-felsic igneous rocks indicate that the present lower crust is dominated by rocks with Neoarchean ages and is intermediate to mafic in composition (i.e., $SiO_2 < 62\%$). The $(^{87}Sr/^{86}Sr)_i$, $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ of the lower crust at 130 Ma are considered to be 0.705 to 0.716, −10 to −28 and −13 to −28, respectively. The $\varepsilon_{Nd}(t)$ range is very different from that proposed previously (−32 to −44). The large range of $\varepsilon_{Hf}(t)$ for the lower crust implies that significant $\varepsilon_{Hf}(t)$ variations for magmatic zircons from the Mesozoic intermediate-felsic igneous rocks do not necessarily reflect mixing of mantle– and crustal–magmas as commonly thought, instead they may reflect heterogeneity in the ancient lower crust. Given that the voluminous Mesozoic intermediate to felsic igneous rocks in the eastern NCC are derived dominantly by partial melting of the Archean lower crust, it requires that a large amount of Archean lower crust be restitic. A restite origin can explain some of the Hannuoba granulite xenoliths having higher Mg# than the granulite terrains. It may be applicable to other parts of the world.

Contents

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1. Introduction

Determining the compositional variation and origin of lower continental crust is essential to our understanding of the growth and evolution of the continental crust. Due to its inaccessibility, the nature and evolution of the lower continental crust is still not well constrained in spite of decades of research on this topic. High-pressure granulite facies rocks exposed at surface offer one approach to investigate the lower crust. Another method of studying the lower crust is lower crustal xenoliths that are carried rapidly to Earth's surface by young alkali basalts and kimberlites. However, a number of studies show that two major differences exist between the two types of lower crustal rocks (Rudnick, 1992). Granulite terrains are dominantly of Archean ages, whereas granulite xenoliths are mostly found in Mesozoic–Cenozoic basalts. Granulite xenoliths are more mafic than granulite terrains. The reason regarding the differences remains debated.

Although granulite xenoliths have the advantage of directly sampling portions of the lower crust, they are rare and represent only small-scale and possibly biased samples. An alternative method of investigating the lower crust can be provided by exposed continental igneous rocks that crystallized from magmas derived either wholly or in part by melting the deep crust (Farmer, 1992). Such rocks represent remote probes of the lower crust on a large scale and can provide important constraints regarding the nature of the lower crust.

The North China craton (NCC) is perhaps a good place for investigating the nature and evolution of the lower continental crust because the above three methods can be combined. Exposures of Proterozoic–Archean basement are extensive in the craton with the oldest rocks ≥3800 Ma in age (Liu et al., 1992) (Fig. 1). Many of the Archean rocks are granulite facies with pressure–temperature conditions similar to those prevailing in the lower crust (Zhai et al., 2001; Guo et al., 2005). Lower crustal xenoliths have been found in several locations (Fig. 1) and are entrained in volcanic rocks with ages varying from ~460 to ~10 Ma (Wilde et al., 2003; Huang et al., 2004; Liu et al., 2004; Zheng et al., 2004a,b,c). These xenoliths thus can be taken as representatives of the lower crust at different times from early Paleozoic to Cenozoic. In particular, the Hannuoba granulite xenoliths have abundant Mesozoic zircons (Fan et al., 1998; Wilde et al., 2003; Liu et al., 2004), in contrast with the 1800–1900 Ma and ~2500 Ma zircons for the granulite terrains. Compositionally, many of the granulite xenoliths have higher Mg# than rocks of the granulite terrain (Liu et al., 2001; Huang et al., 2004). Therefore, they can be used as good examples to address the long-lasting issue on the age and composition differences between granulite terrains and granulite xenoliths.

Compared with the limited occurrence of granulite xenoliths, Mesozoic intermediate-felsic igneous rocks are widespread in the eastern NCC. Many of the Mesozoic intermediate-felsic rocks have been demonstrated to crystallize from magmas derived from the lower crust (Jiang et al., 2007; Yang et al., 2007a; Jiang et al., 2011). Therefore, the intermediate-felsic igneous rocks provide information on the nature of the lower crust during the Mesozoic that cannot otherwise be provided by the granulite terrains and xenoliths. In this paper, we integrate available published data on the granulite terrains, granulite xenoliths and Mesozoic intermediate-felsic igneous rocks in the eastern NCC to constrain the nature of the lower crust and its evolution through time.

2. Geological setting

The NCC consists of Paleoarchean to Paleoproterozoic basement overlain by Mesoproterozoic to Cenozoic unmetamorphosed cover. Based on age, lithological assemblage, tectonic evolution and P–T–t paths, the NCC can be divided into the Western Block, the Eastern Block and the intervening Trans-North China Orogen (inset of Fig. 1; Zhao et al., 2000, 2001). The Western Block forms a stable platform composed of Neoarchean to Paleoproterozoic metasedimentary belts that unconformably overlie Archean basement (Zhao et al., 2000). The

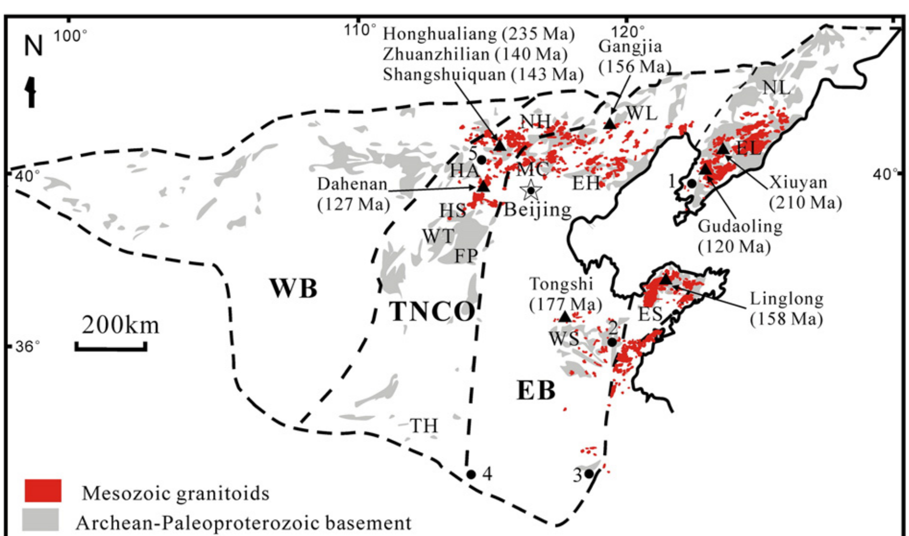

Fig. 1. Distribution of basement rocks and Mesozoic intermediate-felsic igneous rocks in the North China craton. WB, EB and TNCO denote the Western Block, Eastern Block and Trans-North China Orogen, respectively (Zhao et al., 2001). The Archean–Paleoproterozoic basement domains include Northern Liaoning (NL), Western Liaoning (WL), Southern Liaoning (SL), Western Shandong (WS), Eastern Shandong (ES), Taihua (TH), Fuping (FP), Wutai (WT), Hengshan (HS), Huai'an (HA), Miyun–Chengde (MC), Northern Hebei (NB), Eastern Hebei (EH). Filled circles are locations of lower crust xenoliths. 1—Fuxian, 2—Mengyin, 3—Nushan, 4—Xinyang, and 5—Hannuoba. Filled triangle denotes locations of selected Mesozoic intermediate-felsic igneous rocks discussed in the text.

Eastern Block consists of dominantly ~2500 Ma granulite facies tonalite–trondhjemite–granodiorite (TTG) gneisses with minor amphibolites and intermediate-mafic granulites. Paleoarchean basement rocks composed predominantly of mafic amphibolites, granitic gneisses and sedimentary supracrustal rocks with ages from 3850 to 3200 Ma (Huang et al., 1986; Jahn et al., 1987; Liu et al., 1992; Song et al., 1996) and Mesoarchean basement consisting mainly of mafic granulites, amphibolites and greenschists with minor pelitic and granitic gneisses that range in age from 3200 to 2800 Ma (Huang et al., 1986; Jahn et al., 1987; Kröner et al., 1988; Wu et al., 1991; Shen and Qian, 1995) occur as enclaves, boudins and sheets within Neoarchean basement rocks. The Trans-North China orogen is composed of Neoarchean amphibolites and granulites and 2500 Ma granite–greenstone terrains (Zhao et al., 2000, 2001). These are overlain by Paleoproterozoic bimodal volcanic rocks in the southern part of the orogen and thick carbonate and terrigenous sedimentary rocks intercalated with basaltic flows in the central part of the orogen. The Eastern and Western blocks of the NCC are considered to be finally amalgamated by a major collisional event between 1800 and 1900 Ma, which formed the Central Orogenic Belt (Zhao et al., 2000, 2001). Afterwards, the craton was stabilized and subsequently covered by a thick sequence of Proterozoic to Paleozoic sediments (Zhao et al., 2001). In this paper, the Eastern block and the Trans-North China Orogen are collectively referred to as the eastern NCC.

The eastern NCC has been intruded by Paleozoic diamondiferous kimberlites in Fuxian (southern Liaoning Province) and Mengyin (western Shandong Province) (Fig. 1). U–Pb dating of perovskites and whole-rock Rb–Sr and Sm–Nd, and phlogopite Rb–Sr dating yield similar eruption ages (457–475 Ma) for these kimberlites (Dobbs et al., 1994; Lu et al., 1998; Zhang and Yang, 2007). The kimberlites host a number of deep-seated xenoliths/xenocrysts (Zheng et al., 2004b, 2009a). During the Mesozoic–Cenozoic, the eastern NCC experienced widespread tectonothermal reactivation (Menzies et al., 1993). Mesozoic igneous (both volcanic and intrusive) rocks are widely distributed in the eastern NCC. The Mesozoic igneous rocks are dominated by felsic rocks, with subordinate intermediate rocks and minor mafic rocks. Voluminous Cenozoic basalts have been found in a number of localities.

3. Granulite terrains

As shown in Fig. 1, the Archean–Paleoproterozoic basement in the eastern NCC includes a number of domains. TTG gneisses, granites and amphibolites are ubiquitous in all the domains and granulites can be found in most of the domains. The granulites in western and eastern Hebei province yield pressure estimates of 10–14 kb (Jahn and Zhang, 1984; Zhai, 1996), corresponding to conditions similar to those prevailing in the lower crust. U–Pb zircon dating shows that the protolith ages for most of the basement rocks are 2500 to 2600 Ma (Kröner et al., 1988; Zhao et al., 2001). In some domains, for example, in Fuping and Huai'an domains, CL images of zircons from TTG gneisses show core–rim structure. The cores have ages of 2500–2600 Ma and the rims have ages of 1800–1900 Ma. The rims have been considered to form by metamorphic recrystallization and the oscillatory zoned cores represent magmatic grains (Zhao et al., 2002). The 1800–1900 Ma metamorphism is also confirmed by some amphibolite and high-pressure mafic granulites that have U–Pb ages of 1800 to 1900 Ma but whole-rock Nd depleted mantle model ages (T^{Nd}_{DM}) of 2700–2800 Ma (Guo et al., 2005; Jiang et al., 2010).

Fig. 2 shows the Rb–Sr and Sm–Nd isotopic compositions for major rocks from all domains of the eastern NCC that are shown in Fig. 1. The amphibolites and intermediate-mafic granulites are indistinguishable in $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios and the TTG gneisses have lower $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios. With a few exceptions, all the rocks plot along a regression line that yields an isochron age of 2611 ± 55 Ma (Fig. 2a). This age is in agreement with the 2500–2600 Ma U–Pb zircon ages. Therefore, in spite of the evidence for Proterozoic metamorphism, the Archean formation is preserved by the Sm–Nd system of the rocks. In contrast, the Rb–Sr data of the rocks are very scattered (Fig. 2b) and most of the rocks plot close to the 1900 Ma reference line. Therefore, the Rb–Sr system is significantly disturbed by the 1800–1900 Ma metamorphism.

4. Lower crustal xenoliths

4.1. Xenoliths and zircon xenocrysts in Paleozoic kimberlites (Mengyin and Fuxian)

Lower crustal xenoliths in the Paleozoic Fuxian kimberlites have been studied in detail by Zheng et al. (2004b) and here only a brief summary is given. The lower crustal xenoliths are all mafic in composition and include garnet granulite with minor pyroxene amphibolite, metagabbro, anorthosite and pyroxenite. The formation conditions of the amphibolites are estimated at 745–820 °C and 7.6–8.8 Kb (25–30 km). The granulites are considered to be derived from greater depths in the lower crust. U–Pb zircon dating shows concordant ages and upper intercept ages ranging from 2620 to 2430 Ma that are interpreted as minimum estimates for the time of magmatic crystallization and lower intercept ages from 1927 to 1852 Ma that are interpreted as reflecting metamorphic recrystallization.

Zircon xenocrysts in the Paleozoic kimberlites from Fuxian and Mengyin have similar formation ages (2500–2700 Ma) and Hf depleted mantle model ages (T^{Hf}_{DM}, 2700–2800 Ma) (Zheng et al., 2009a). These ages also are similar to the zircon ages of mafic granulite xenoliths from the Fuxian kimberlites, implying that the lower crust was similar beneath the Mengyin and Fuxian areas.

There are only two lower crust xenoliths from Fuxian that have reported Sm–Nd isotopic compositions (an amphibolite and a garnet granulite). The amphibolite xenolith has whole-rock T^{Nd}_{DM} of 2600 Ma, similar to its U–Pb zircon ages. Both xenoliths plot on the regression line defined by rocks from the terrains (Fig. 3a).

4.2. Granulite xenoliths in Mesozoic volcanic diatremes (Xinyang)

Felsic and high-pressure mafic granulite xenoliths have been collected from the Xinyang Mesozoic volcanic diatremes at the southern margin of the NCC (Fig. 1). U–Pb and Hf isotope analyses of zircons from felsic granulite xenoliths reveal Paleoarchean (~3600 Ma) lower crust. One sample records 2100–1900 Ma remelting of a 2500 Ma protolith, indicating existence of Neoarchean lower crust. Zircon ages are not available for the Xinyang mafic granulite xenoliths. Three mafic granulite xenoliths have been analyzed for Sm–Nd isotopic composition. One xenolith has Sm–Nd isotopic composition similar to the Fuxian garnet granulite xenolith and plots on the regression line defined by rocks from the terrains (Fig. 3a). The other two xenoliths plot off the regression line and have T^{Nd}_{DM} of 1900 Ma. They may reflect growth of new crust at 1900 Ma.

4.3. Granulite xenoliths in Cenozoic basalts (Hannuoba and Nushan)

4.3.1. Hannuoba

Granulite xenoliths from the Tertiary Hannuoba alkali basalts are the most abundant among all the xenolith localities. Here, mafic granulite xenoliths greatly outnumber felsic xenoliths. The Hannuoba xenoliths have a large range in SiO_2 from 41.43 to 72.95 wt.%, which is essentially identical to that of rocks of the Archean granulite terrains (Fig. 4). A prominent difference between the Hannuoba granulite xenoliths and rocks of the granulite terrains is that most of the xenoliths with SiO_2 <55% tend to have lower Al_2O_3, Na_2O and K_2O but higher MgO thus higher Mg# (molar MgO/(FeO + MgO)) than rocks of the Archean granulite terrains (Fig. 4). The Hannuoba granulite xenoliths

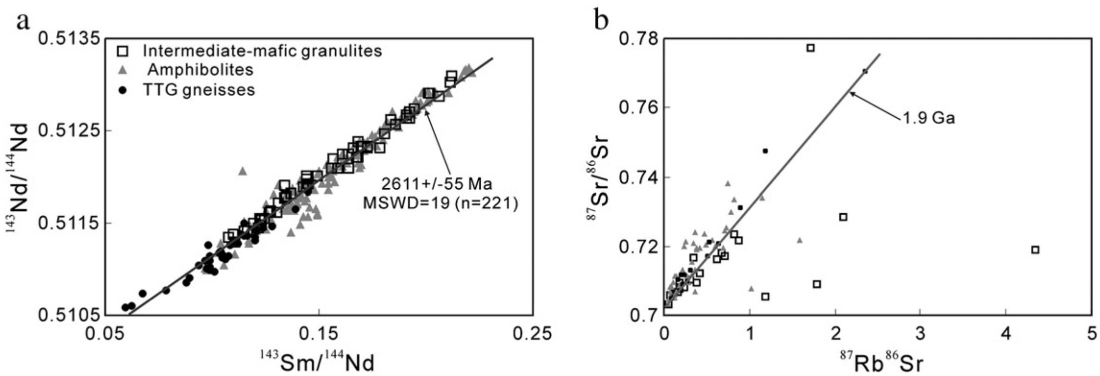

Fig. 2. Sm–Nd isotopic data (a) and Rb–Sr isotopic data (b) for rocks from the granulite terrains.
Data source: Li et al. (1987), Jahn et al. (1987, 1988), Jahn and Ernst (1990), Qiao et al. (1990), Zhang et al. (1991, 1996), Tian et al. (1992), Sun et al. (1992, 1993), Guo (1993), He et al. (1993), Sun and Hu (1993), Jin et al. (1993, 2000), Shen et al. (1994), Shen and Geng (1996), Rämö et al. (1995), Zhou et al. (1997), Lu (1998), Zhang and Li (1998), Geng et al. (1999), Liu et al. (1999), Mao et al. (1999), Guo and Zhai (2000), Guo et al. (2005), Liu et al. (2002), Fan et al. (2005), Jiang (2005) and Jiang et al. (2007, 2010).

have complicated age patterns. Fan et al. (1998), for the first time, dated three Hannuoba granulite xenoliths with the U–Pb zircon method. The concordant $^{206}Pb/^{238}U$ ages of 120–140 Ma, together with higher Mg# than the granulite terrains, led them to suggest that the Hannuoba intermediate-mafic granulite xenoliths were formed by Mesozoic basaltic underplating. This suggestion was subsequently widely accepted (Zhang, 1997; Chen et al., 2001; Liu et al., 2001; Zhou et al., 2002; Liu et al., 2004). However, Zheng et al. (2004c) reported two Hannuoba mafic granulite xenoliths containing exclusively >1730 Ma zircons, indicating that they are remnants of ancient lower crust. Jiang and Guo (2010) and Jiang et al. (2011) reported two mafic granulite xenoliths with ~2500 Ma zircon ages. They are no doubt remnants of Neoarchean lower crust. Further Hf isotopic analyses show that Mesozoic zircons from the Hannuoba granulite xenoliths have $\varepsilon_{Hf(t)}$ plotting along the evolution trend of the 2500 Ma average crust with $^{176}Lu/^{177}Hf$ of 0.015 (Fig. 5). In addition, these xenoliths with Mesozoic zircons have Sr–Nd isotopic compositions indistinguishable from those with ~2500 Ma ages and they all have similar Sr–Nd isotopic compositions to rocks from the granulite terrains (Fig. 3b). Therefore, the accumulated data strongly suggest that most of the Hannuoba intermediate-mafic granulite xenoliths are of Neoarchean lower crust derivation (Jiang and Guo, 2010) rather than products of Mesozoic underplating as suggested previously (Zhang, 1997; Chen et al., 2001; Liu et al., 2001; Zhou et al., 2002; Liu et al., 2004).

Recently, Zheng et al. (2009b) found five mafic xenoliths (granulite and pyroxenite) in the Hannuoba Cenozoic basalts with U–Pb zircon ages of 44.5–47.3 Ma. Most Paleogene zircons have positive εHf (up to +13.2). The xenoliths have been interpreted as the products of basaltic underplating and fractionation (cumulates) in Paleogene time, and their Hf isotope systematics supports of this interpretation.

4.3.2. Nushan

Granulite xenoliths from the Nushan basalts are basic to intermediate in composition with SiO_2 between 46 and 56% and resemble the Archean granulite terrains of the NCC in terms of mineral and whole rock compositions (Fig. 4). Zircon U–Pb dating shows that the protoliths of the Nushan granulite xenoliths were most likely formed at ca. 2500 Ma and metamorphosed at 1900 Ma (Huang et al., 2004). On Fig. 3b, the Nushan granulite xenoliths have similar Sr–Nd isotopic compositions to rocks from the granulite terrains. The Nushan granulite xenoliths are therefore interpreted as dominantly derived from the Neoarchean crystalline basement.

5. Mesozoic intermediate-felsic igneous rocks

A number of Mesozoic intrusive rocks with ages ranging from 235 to 120 Ma are chosen to provide constraints on the nature of the Mesozoic lower crust. They include the 235 Ma Honghualiang granite, the 140 Ma Zhuanzhilian diorite and the 143 Ma Shangshuiquan granite from the Zhangjiakou region (Jiang et al., 2007, 2009), the 177 Tongshi quartz monzonite from the western Shandong province (Xu et al., 2004, 2007), the 158 Ma Linglong granite from the eastern Shandong

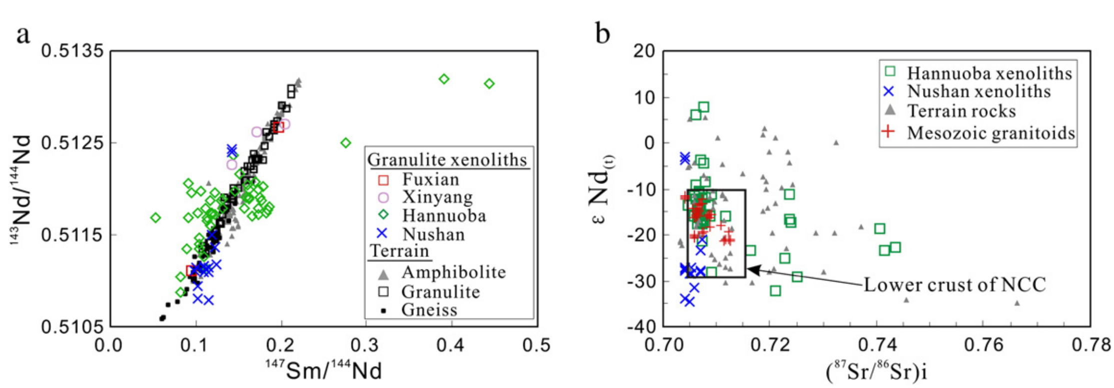

Fig. 3. Sm–Nd isotopic data (a) and εNd(t) vs. $(^{87}Sr/^{86}Sr)_i$ (b) plots for rocks from the granulite terrains, lower crustal xenoliths and Mesozoic intermediate-felsic igneous rocks. Data for the Archean basement rocks are the same as in Fig. 2. Data for the lower crustal xenoliths are from Huang et al. (2004), Liu et al. (2004), Zheng et al. (2004a,b,c), Fan et al., 2005, Jiang et al. (2009, 2010, 2011) and data for the Mesozoic intermediate-felsic igneous rocks are from Chen et al. (2003), Xu et al. (2004, 2007), Hou et al. (2007), Yang et al. (2007a), Jiang et al. (2007, 2009) and Zhang et al. (2008).

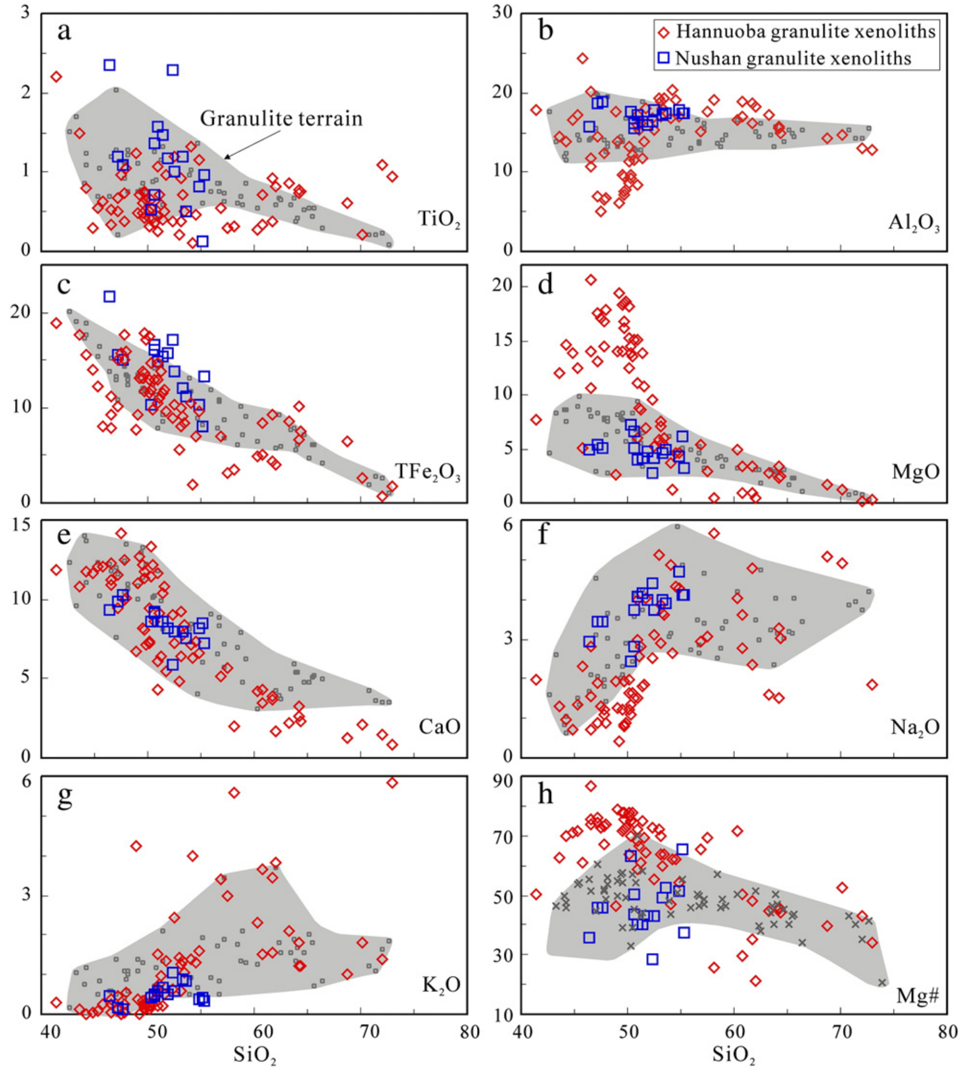

Fig. 4. Plots of oxides vs. SiO_2 for the Hannuoba intermediate-mafic granulite xenoliths (Zhang, 1997, Liu et al., 2001) in comparison with rocks of the granulite terrains from the Zhangjiakou region (Guo, 1993, Shen et al., 1994; Zhang et al., 1996; Jiang, 2005, Jiang et al., 2007).

province (Hou et al., 2007), the 156 Ma Gangjia leucogranite from the western Liaoning province (Zhang et al., 2008), the 127 Ma Dahenan diorite–monzonite–granite suite from the Taihang area (Chen et al., 2003, 2007) and the 210 Ma Xiuyan quartz diorite–granodiorite–monzogranite suite and the 120 Ma Gudaoling monzogranite from the eastern Liaoning province (Yang et al., 2007a,b). Their locations and ages are given in Fig. 1. The Mesozoic intrusions vary in lithology from diorite through quartz monzonite to granite and have SiO_2 from 56% to 78%. The 235 Ma Honghualiang granite, 177 Ma Tongshi quartz monzonite, 158 Ma Linglong granite and the 120 Gudaoling monzogranite all have ~2500 Ma inherited zircons. These inherited zircons have $\varepsilon_{Hf(t)}$ indistinguishable from zircons from the granulite terrains (Fig. 5). An inherited zircon core from the Linglong granite yielded a nearly concordant $^{207}Pb/^{206}Pb$ age of ~3400 Ma (Wang et al., 1998), indicating the existence of Mesoarchean lower crust beneath the Linglong region. The magmatic zircons from the Mesozoic intermediate-felsic igneous rocks have $T_{DM}^{Hf,\ C}$ ages of 2500–2700 Ma and their $\varepsilon_{Hf(t)}$ all plot roughly along the evolution trend of the 2500 Ma average crust (Fig. 5). Individual plutons have a very limited range for both $(^{87}Sr/^{86}Sr)_i$ and ε_{Nd} (t) with ε_{Nd} (t) varying less than 2 units. However, the intermediate-felsic igneous rocks as a whole have a relatively large range for both $(^{87}Sr/^{86}Sr)_i$, ε_{Nd} (t) and ε_{Hf} (t). $(^{87}Sr/^{86}Sr)_i$ varies from 0.7040 to 0.7124, ε_{Nd} (t) from −11.4 to −21.3 (Fig. 3b), and ε_{Hf} (t) from −10 to −26 (with a few exceptions for the Xiuyan pluton) (Fig. 5). Most Mezosoic zircons from mafic microgranular enclaves from the Gudaoling and the Xiuyan plutons have much higher ε_{Hf} (t) than those from their host monzogranites (Fig. 5).

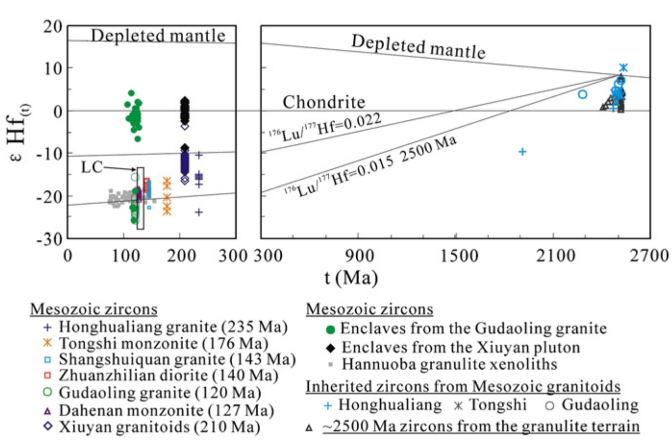

Fig. 5. Age-corrected $\varepsilon_{Hf(t)}$ vs. age diagram. Data source: Chen et al. (2007), Xu et al. (2007), Yang et al. (2007a, 2007b), Jiang et al. (2007, 2009, 2010, 2011) and Jiang and Guo (2010). The $^{176}Lu/^{177}Hf$ of 0.015 for average crust is from Griffin et al. (2002) and the $^{176}Lu/^{177}Hf$ of 0.022 for mafic crust from Amelin et al. (2000). LC denotes $\varepsilon_{Hf(t)}$ suggested for the lower crust of the eastern NCC which ranges from −13 to −28.

6. Discussion

6.1. Timing of lower crust formation

Zircons from the Fuxian granulite xenoliths and zircon xenocrysts from the Paleozoic Fuxian and Mengyin kimberlites have magmatic crystallization ages of 2500–2600 Ma and metamorphic ages of 1800–1900 Ma. These ages are identical to those of rocks from the granulite terrains. In addition, the Fuxian lower crustal xenoliths have Sm–Nd isotopic systematics identical to those of the 2500–2600 Ma rocks from the granulite terrains. Therefore, the lower crust beneath the two areas at ~460 Ma was predominantly Archean in age.

Granulite xenoliths from the Mesozoic Xinyang volcanic diatremes reveal ~3600 Ma, ~2500 Ma, and possibly ~1900 Ma lower crust. The Hannuoba granulite xenoliths indicate that the lower crust during the Cenozoic is dominated by Neoarchean rocks with minor Paleogene crustal growth beneath Hannuoba. Granulite xenoliths from the Nushan basalts resemble the Archean granulite terrains of the NCC in terms of ages, mineral and whole rock compositions and Sr–Nd isotopic compositions, also indicating that the lower crust during Cenozoic is dominated by Neoarchean rocks beneath Nushan.

Although the Mesozoic intermediate-felsic igneous rocks span from Triassic to Cretaceous, they have many characteristics in common, i.e., the ubiquitous ~2500 Ma inherited zircons, magmatic zircons with $T_{DM}^{Hf,C}$ ages of 2500–2700 Ma and Sr–Nd isotopic compositions falling within the field of rocks of the granulite terrains. In fact, these characteristics are shared by most Mesozoic intermediate-felsic igneous rocks from the eastern NCC except a few early Cretaceous granitoids and felsic dikes having whole-rock $\varepsilon_{Nd}(t)$ around zero and positive zircon $\varepsilon_{Hf}(t)$ that indicate depleted mantle contribution (Yang et al., 2008). These similarities allow us to draw the conclusion that the lower crust during the Mesozoic is dominated by Neoarchean rocks all over the eastern NCC.

In summary, the present NCC lower crust is dominated by rocks with Neoarchean ages, although there may be minor rocks with ages of Meso- to Paleoarchean (>3000 Ma), ~45 Ma and possibly ~1900 Ma locally.

6.2. Composition of the lower crust

The approximate compositional range of the lower crust can be constrained directly from the granulite xenoliths and indirectly from the Mesozoic granites.

The lower crustal xenoliths from various localities reveal that the lower crust is dominated by Neoarchean rocks with SiO_2 lower than 62%. The Fuxian and Nushan lower crustal xenoliths have zircon ages and Sm–Nd isotopic compositions overlapping those of the rocks from the granulite terrains. The Nushan xenoliths have compositions with SiO_2 between 46 and 56% (Huang et al., 2004). Based on modal percentage of the constituent minerals and their mineral compositions (Zheng et al., 2004b), the Fuxian lower crustal xenoliths are calculated to have SiO_2 between 45 and 62%. Although the Hannuoba granulite xenoliths have a large range in SiO_2 from 41 to 73%, 80% of 50 examined xenoliths have SiO_2 lower than 62%. Therefore, based on the xenoliths, the lower crust is constrained to be dominated by rocks with SiO_2 lower than 62%.

The Mesozoic intrusive rocks from the eastern NCC have Sr–Nd isotopic compositions overlapping those of lower crustal xenoliths with $SiO_2 < 62\%$, significantly different from those of lower crustal xenoliths with $SiO_2 > 62\%$ which have Sri > 0.715 and/or εNd < −22 (Fig. 3b). This feature suggests that the Mesozoic intrusive rocks are derived from sources similar in isotopic composition to lower crustal rocks that have $SiO_2 < 62\%$, which again supports the idea that the lower crust is dominated by intermediate-mafic rocks.

Unlike the Fuxian and Nushan granulite xenoliths that resemble the Archean granulite terrains of the NCC in terms of mineral and whole rock compositions, many of the Hannuoba intermediate-mafic granulite xenoliths have whole-rock and mineral Mg# significantly higher than rocks of the Archean granulite terrains. These xenoliths have been interpreted to represent restites left behind after the partial melting of the Neoarchean lower crust to produce the Mesozoic low Mg# intermediate-felsic igneous rocks (Jiang and Guo, 2010). The low highly incompatible element and high compatible element contents and unrealistic old $T^{Nd}{}_{DM}$ ages for these granulites support the idea that they obtained their trace element characteristics as the result of the removal of partial melts during the Mesozoic. The shallow slope of the Sm–Nd isotope data for the Hannuoba xenoliths (Fig. 3a) further supports substantial modification of the compositional characteristics of these rocks by events occurring in the Mesozoic.

6.3. Sr–Nd–Hf isotopic compositions of the lower crust

The Sr–Nd–Hf isotopic compositions of the lower crust of the NCC are a key issue in understanding the petrogenesis of Mesozoic igneous rocks from the NCC and adjacent regions. Previous studies have defined the $(^{87}Sr/^{86}Sr)_i$ and $\varepsilon_{Nd}(t)$ of the lower crust of the NCC at 130 Ma to be ca. 0.706 to 0.713 and −32 to −44, respectively (Fig. 10a of Jahn et al., 1999). These values have been widely used to determine whether the Mesozoic igneous rocks were derived from the lower crust or from mantle-derived magmas with some lower crust contamination. Below we will address whether these values reflect the range of the lower crust at 130 Ma.

As shown in Fig. 3b, of 73 lower crustal xenoliths, only 5 xenoliths have $\varepsilon_{Nd}(t) < -28$ and none of the Mesozoic intermediate-felsic igneous rocks has $\varepsilon_{Nd}(t) < -22$. Furthermore, given that the lower crust is dominated by Neoarchean rocks with $SiO_2 < 62\%$, it is mostly likely that the $\varepsilon_{Nd}(t)$ of the lower crust could be similar to those of intermediate-mafic granulites and amphibolites from the terrains. None of the intermediate-mafic granulites and amphibolites from the terrains have $\varepsilon_{Nd}(t) < -27$ (Fig. 2a). The combined data show that $\varepsilon_{Nd}(t)$ of −10 to −28 more likely reflects the range of the lower crust at 130 Ma.

The $(^{87}Sr/^{86}Sr)_i$ of the lower crust is more difficult to constrain since the Rb–Sr system is less robust than Sm–Nd system during later events. This is well illustrated on Fig. 2 for the Neoarchean rocks from the terrains where the granulites and the amphibolites overlap each other in Sm–Nd isotope systematics (Fig. 2a), whereas their Rb–Sr isotope systems are significantly different (Fig. 2b). Nevertheless, most of the granulites have $(^{87}Sr/^{86}Sr)_i$ between 0.705 and 0.716. A similar range also is seen for the lower crustal xenoliths and the Mesozoic intermediate-felsic igneous rocks. Therefore, we consider that this range may represent that of the lower crust at 130 Ma, which is essentially similar to that suggested by Jahn et al. (1999).

If the $\varepsilon_{Hf}(t)$ of the magmatic zircons from the Mesozoic intermediate-felsic igneous rocks mentioned above are calculated at 130 Ma, they will have a range from −13 to −26. This range is similar to the whole–rock $\varepsilon_{Hf}(t)$ of −13 to −28 for the Hannuoba granulite xenoliths with $SiO_2 < 60\%$ (Jiang, N. unpublished data). Therefore, we conclude that the $\varepsilon_{Hf}(t)$ of the lower crust of the NCC at 130 Ma is −13 to −28 (Fig. 5). Such values again are inconsistent with εNd values as low as suggested by Jahn et al. (1999), and instead suggest εNd between −7 and −18 if the lower crust follows the crustal Hf–Nd array defined by Vervoort and Patchett (1996).

Taken together, we propose that the $(^{87}Sr/^{86}Sr)_i$, $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ of the lower crust in the eastern NCC at 130 Ma are 0.705 to 0.716, −10 to −28 and −13 to −28, respectively. It does not preclude the existence of minor rocks in the lower crust with Sr–Nd–Hf isotopic compositions beyond the ranges. In addition, the Sr–Nd–Hf isotopic compositions do not necessarily have to be the same in different regions. For example, the Nushan granulite xenoliths have lower $\varepsilon_{Nd}(t)$ than the Hannuoba granulite xenoliths. The Tongshi quartz monzonites from western Shangdong province have (^{87}Sr/^{86}Sr)$_i$ of ~0.704 and ε_{Nd} (t) of ~−12, whereas the Linglong granites from eastern Shandong province have (^{87}Sr/^{86}Sr)$_i$ of ~0.712 and ε_{Nd} (t) of ~−21. These differences may reflect heterogeneity in both chemical and isotopic compositions in the lower crust of different regions. The lower crust beneath these areas likely has similar isotopic compositions, the Mesozoic intermediate-felsic igneous rocks are derived from different segments of the lower crust.

7. Implications

The results have implications for the sources and generation of the NCC Mesozoic intermediate-felsic igneous rocks. The available data show that most of the NCC Mesozoic intermediate-felsic igneous rocks have whole-rock ε_{Nd} (t) between −13 and −21 and zircon ε_{Hf} (t) between −15 and −25. However, based on the previously assumed ε_{Nd} (t) of −32 to −44 for the lower crust at 130 Ma (Jahn et al., 1999), many of the intermediate-felsic igneous rocks have been considered to be derived either from melting of enriched portions of subcontinental lithospheric mantle (Chen et al., 2003) or from mixing of mantle– and crustal–magmas (Chen et al., 2007). Both hypotheses, for example, have been suggested for the above mentioned 127 Ma Dahenan diorite–monzonite–granite suite from the Taihang area (Chen et al., 2003, 2007). Although rocks from the suite range in SiO_2 from 54.5 to 76.4%, they have limited ranges in both (^{87}Sr/^{86}Sr)$_i$ (0.7055 to 0.7064, with one exception of 0.7086 due to extremely high ^{87}Rb/^{86}Sr ratio of 8.8), and ε_{Nd} (t) (−14.4 to −15.8). In addition, samples with lower SiO_2 do not have lower (^{87}Sr/^{86}Sr)$_i$ and higher ε_{Nd} (t) (Chen et al., 2003). Therefore, there is no evidence for mixing between mantle– and crustal–magmas. Magmatic zircons from a quartz monzonite sample of the suite yielded homogeneous ε_{Hf} (t) from −18.5 to −21, again precluding mixing between mantle– and crustal–magmas. In fact, they plot along the evolution trend of the 2500 Ma average crust (Fig. 5), pointing to a Neoarchean lower crust derivation. We thus suggest that most of the eastern NCC Mesozoic intermediate-felsic igneous rocks are derived mainly from the melting of Neoarchean lower crust with limited or no mixing with whatever mantle-derived mafic magmas that may have been involved in this event.

The results also shed new light on magma mixing. Variations in ε_{Hf} (t) of magmatic zircons for intermediate to felsic rocks are usually ascribed to mixing between mantle- and lower crust-derived magmas (Griffin et al., 2002; Kemp et al., 2007; Yang et al., 2007a; Gagnevin et al., 2011). The intermediate to felsic igneous rocks from the eastern NCC as a whole have a large range in both whole-rock ε_{Nd} (t) and zircon ε_{Hf} (t) although individual plutons have more limited ε_{Nd} (t) and ε_{Hf} (t) (Figs. 3 and 4). One may argue that rocks with higher ε_{Nd} (t) and ε_{Hf} (t) result from more input of mantle-derived magmas. This may be not true if the intermediate to felsic rocks are derived by melting of ancient lower crust with heterogeneous compositions. Even if rocks in the lower crust have the same initial isotopic compositions, their differences in Lu/Hf ratios due to compositional heterogeneity will drive them to have increasingly large range in ^{176}Hf/^{177}Hf ratios with time. This is best illustrated in Fig. 5 where 2500 Ma rocks with average and mafic crust ^{176}Lu/^{177}Hf ratios of 0.015 and 0.022 respectively will have an ε_{Hf} (t) difference of >10 epsilon units at 130 Ma. Therefore, if the ~2500 Ma rocks with different Lu/Hf ratios melted simultaneously to produce the Mesozoic magmas, the zircons that crystallized from the magmas will have a large range in ε_{Hf} (t). In this case, it is not necessary to invoke more input of mantle-derived magmas to explain the higher ε_{Hf} (t) for some rocks. Instead, they could be derived from sources with different Lu/Hf ratios. This could be illustrated by two granitic plutons (Gudaoling and Xiuyan) with mafic microgranular enclaves. As shown in Fig. 4, Mesozoic zircons in the mafic microgranular enclaves from the two plutons have similar zircon ε_{Hf} (t). In the mafic microgranular enclaves of the Cretaceous Gudaoling pluton, the zircons have ε_{Hf} (t) up to 4.5, indicating depleted mantle contribution. However, a few zircons have extremely negative ε_{Hf} (t) that is identical to those of the host monzogranite. They have $T_{DM}^{Hf,\ C}$ ages similar to the ~2500 Ma zircons from the outcropped Archean gneiss and plot along the evolution trend of the 2500 Ma average crust, indicating that they are derived from the Neoarchean lower crust. It seems that the monzogranites are derived mainly from the Neoarchean lower crust with little or no depleted mantle contribution, although input of depleted mantle is obvious in the mafic microgranular enclaves. This may be applicable to the Triassic Xiuyan pluton. Therefore, the differences in magmatic zircon ε_{Hf} (t) for the Gudaoling and Xiuyan monzogranites could be ascribed to different Lu/Hf ratios in their sources.

Since granulite xenoliths worldwide tend to have higher Mg# than Archean granulite terrains (Rudnick, 1992), most mafic granulites that occur within the lower crust of Archean cratons are generally inferred to have formed from post-Archean basaltic underplating (Rudnick, 1992; Downes, 1993; Davis, 1997; Kempton et al., 2001; Downes et al., 2002; Gorman et al., 2002). Similarly, the Hannuoba high Mg# granulite xenoliths have been considered to be products of Mesozoic underplating (Fan et al., 1998; Chen et al., 2001; Liu et al., 2001; Zhou et al., 2002; Liu et al., 2004; Fan et al., 2005). However, given that the voluminous Mesozoic low Mg# intermediate to felsic igneous rocks in the eastern NCC are derived dominantly by partial melting of the Archean lower crust, it can be inferred that a large amount of the lower crust could be restitic. The Hannuoba high Mg# granulite xenoliths are depleted in Al_2O_3, Na_2O, K_2O and incompatible elements but enriched in MgO and compatible elements, complementary to the low Mg# intermediate to felsic igneous rocks. Both the xenoliths and the intermediate to felsic igneous rocks have isotopic compositions similar to rocks of the granulite terrains (Figs. 3–5). A restite origin can best explain the Hannuoba high Mg# granulite xenoliths (see detail in Jiang and Guo, 2010). A similar origin may be applicable to some xenoliths from other parts of the world. For example, about half of the xenoliths from the McBride Cenozoic basalts in north Queensland, Australia, contain Proterozoic zircon ages that are coeval to the episodes of surface high-grade metamorphic rocks (Rudnick and Taylor, 1987). Some xenoliths have zircon ages and Sr–Nd isotopic compositions similar to the 300-Ma I-type granites (Rudnick and Taylor, 1987; Rudnick, 1990). A restite origin is suggested for some xenoliths (Rudnick and Taylor, 1987). An integrated study of the xenoliths, the Paleozoic granites and the surface metamorphic rocks can place better constrains on whether they are intrinsically linked. It is concluded that a restite origin for the granulite xenoliths could be a viable mechanism causing their higher Mg# than the granulite terrains.

8. Conclusions

Lower crustal xenoliths entrained in erupted rocks with ages varying from ~460 to ~10 Ma in various regions from the eastern NCC suggest that the lower crust at different times is dominated by rocks of 2500 to 2600 Ma age, although there may be minor rocks of Meso- to Paleoarchean (>3000 Ma), ~45 Ma and possibly ~1900 Ma locally. The Mesozoic intrusive rocks, although varying from diorite to granite and spanning from Triassic to Cretaceous, contain ~2500 Ma inherited zircons and have magmatic zircons with $T_{DM}^{Hf,\ C}$ ages of 2500–2700 Ma. In addition, they have whole-rock Sr–Nd isotopic compositions falling within the field of the ~2500 Ma granulite terrain rocks, pointing to a Neoarchean lower crust derivation. Combined data indicate that the present lower crust in the eastern NCC is dominated by rocks with Neoarchean ages and is intermediate-mafic in composition (i.e., SiO_2 < 62%). The (^{87}Sr/^{86}Sr)$_i$, ε_{Nd} (t) and ε_{Hf} (t) of the lower crust at 130 Ma are considered to be 0.705 to 0.716, −10 to −28 and −13 to −28, respectively. Since the lower crust has a large range in ε_{Hf} (t) at 130 Ma, significant variations in ε_{Hf} (t) for magmatic zircons from Mesozoic intermediate to felsic rocks may reflect their source heterogeneity rather than mixing of mantle- and crustal magmas as usually thought.

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