Late-Archean to Early Proterozoic lithospheric mantle beneath the western North China craton: Sr-Nd-Os isotopes of peridotite xenoliths from Yangyuan and Fansi

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Abstract

Sr-Nd-Os isotopic analyses are presented for peridotite xenoliths from Tertiary alkali basalts in Yangyuan and Fansi with the *aim of* identifying and characterizing the relics of ancient lithospheric mantle that survived lithospheric removal in the western North China Craton (NCC). The analyzed samples are residual lherzolites and harzburgites, ranging from fertile to highly depleted (0.36-4.0 wt% Al_2O_3) composition. Some LREE-enriched samples are characterized by moderate $^{87}Sr/^{86}Sr$ (0.7044 to 0.7047) and low ε_{Nd} (–6.9 to –10.6), pointing to an EMI-type signature. This is distinct from the predominant depleted isotopic composition in mantle xenoliths from eastern China. Os isotopic ratios range from 0.1106 to 0.1325. The lower limit is the most unradiogenic value measured so far for Cenozoic basalt-borne xenoliths from eastern China. Two samples show radiogenic Os ratios higher than that of the primitive upper mantle, one sample has an anomalously high Os concentration (>9 ppb). These samples also show high La/Yb, consistent with the addition of radiogenic components during the infiltration of asthenosphere-derived and/or subduction-related melts in the lithospheric mantle. The remaining samples define positive correlations between $^{187}Os/^{188}Os$ and indices of melt extraction, which yield model ages of 2.4-2.8 Ga. This age of melt extraction overlaps with the Nd model age of the overlying crust, indicating a coupled crust-mantle system in the western NCC. This contrasts with the decoupled nature in the eastern NCC, suggesting distinct mantle domains underneath the NCC. Such a heterogeneous age structure of the upper mantle is compatible with the view that the lithospheric removal was largely limited to the eastern NCC.

Keywords: Sr-Nd-Os isotopes, peridotite xenolith, lithospheric mantle, age, Yangyuan and Fansi, western North China Craton

1. Introduction

The North China Craton (NCC) experienced widespread lithospheric extension during the late Mesozoic and Cenozoic, whichresulted in the removal of a large portion (>100 km) of mantle lithosphere (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Gao et al., 2002). This lithospheric thinning was accompanied by a change in mantle composition, probably due to the replacement of the thick, old, cold and refractory lithospheric keel by thin, young, hot and fertile mantle. In recent years, the timing, mechanisms and tectonic driving forces responsible for lithospheric removal have been intensely debated. For instance, two end-member models have been proposed as mechanisms of lithospheric thinning, i.e., delamination *versus* thermo-mechanical erosion. Different physical mechanisms involved in lithospheric thinning have distinct implications for the vertical extent of lithospheric removal (Reisberg et al., 2005). Delamination would probably result in the removal of the entire mantle lithosphere and part of the lower crust (Wu et al., 2003; Gao et al., 2004). Geophysical data indicate that the current lithospheric thickness beneath eastern China is 60-100 km, thus the lithosphere may have been re-thickened by conductive cooling subsequent to the removal processes (Menzies and Xu, 1998; Xu, 2001). In this sense, the mantle lithosphere is young. In contrast, thermal erosion may remove only part of the mantle lithosphere, leading to the co-existence of old and young mantle lithosphere. If thermal erosion of the lithosphere induced by the upwelling of asthenosphere took place gradually from the base of the lithosphere, a stratified architecture is envisaged with the old lithospheric relict overlying the newly accreted one (Griffin et al., 1998; Menzies and Xu, 1998; Xu, 2001). If mantle upwelling preferentially focused along weak zones in the Archean lithospheric root (Yuan, 1996), dispersal of the ancient lithosphere in newly formed mantle will result.

The lateral extent of lithospheric thinning in the NCC is equally poorly constrained. The contrast in crustal and lithospheric thickness, topographic height and gravity anomaly across the Daxin'anling-Taihang Gravity Lineament (DTGL, Fig. 1) suggests that lithospheric removal may be largely limited to the region east of the DTGL (Griffin et al., 1998; Menzies and Xu, 1998). Temporal and spatial evolution of Cenozoic volcanism further reveals that lithospheric thinning was probably diachronous with that in the western NCC being later than in the eastern NCC (Xu et al., 2004b). If thermo-mechanical erosion is the main mechanism of lithospheric thinning (Griffin et al., 1998; Xu, 2001; Xu et al., 2004a), and assuming that the lithospheric protolith under the NCC was entirely ancient prior to the Mesozoic, one can speculate that the present lithosphere mantle under the western NCC consists mostly of the relics of ancient mantle, in contrast to the co-existence of ancient mantle and newly accreted mantle in the eastern NCC. Clearly, the age of mantle samples from throughout the NCC will be needed to ultimately understand the nature of the thinning event.

The Re-Os isotopic system has proven useful in constraining the age of lithospheric mantle formation (Walker et al., 1989; Carlson and Irving, 1994; Pearson et al., 1995; Pearson, 1999; Reisberg and Lorand, 1995; Peslier et al., 2000a, b; Handler et al., 2003; Gao et al., 2002; Wu et al., 2003, 2006; Reisberg et al., 2005). This is because Os has a highly compatible nature and Re is incompatible during mantle melting. Therefore, depleted peridotites have high Os contents and low Re/Os ratios. Melting residue, if isolated in the lithosphere, will develop low time-integrated $^{187}Os/^{188}Os$ relative to the convective mantle. The Re-Os isotopic system was originally considered to be immune from disturbance due to metasomatic alteration, because common mantle metasomatic agents (e.g., silicate and carbonatitic melt) are low in Os (Handler et al., 1997). Recent studies, however, have revealed a more complex response of the Re-Os system to metasomatic processes (Alard et al., 2002; Widom et al., 2003; Chesley et al., 2004; Griffin et al., 2004). A careful evaluation of the effect of metasomatism on the Re-Os system in peridotites is therefore necessary. When the effect of metasomatic sulfide addition is minimal, Re-Os isotope systematics remain a powerful tool to date the lithospheric mantle (Pearson et al., 2004).

In this study, analyses of major and trace element abundances and Sr-Nd-Os isotopic compositions have been carried out on a suite of peridotite xenoliths collected from Tertiary alkali basalts in Yangyuan (Hebei Province) and Fansi (Shanxi Province), western NCC. These data will be used to explore the effect of metasomatsim on the composition of highly siderophile elements and to determine the age of the lithospheric mantle in the western NCC. Coupled with available data, the implications for the extent and nature of lithospheric removal in the NCC will be discussed.

2 Geologic background and petrographic characteristics

The NCC can be separated into two different tectonic domains by the N-S trend Daxinganling-Taihangshan gravity lineament (DTGL) (Ma, 1989; Menzies and Xu, 1998). The region located west to the DTGL is characterized by thick crust (>40 km), large negative Bouguer gravity anomalies, low heat flow and a thick (> 150 km) lithosphere (Fig. 1). In contrast, the crust beneath eastern NCC is thin (<35 km), the regional Bouguer gravity anomaly is weakly negative to positive, heat flow is high and lithosphere is inferred to be thin. Compilation of Sm-Nd isotopic data on crustal rocks led Wu et al. (2005) to argue that the crust was largely formed during the early Proterozoic and late Archean. It has been recently suggested that the DTGL was formed by diachronous lithospheric extension/thinning in the NCC, with that in eastern NCC taking place during the Late Mesozoic and that in western NCC during the Cenozoic (Xu, 2007).

Samples analyzed in this study were collected from alkali basalts at Yangyuan (western Hebei Province; 30-35 Ma, Liu et al., 1992) and Fansi (northern Shanxi Province; 38-40 Ma). Both localities are situated adjacent to the northern part of the S-shape Cenozoic Shaanxi-Shanxi Rift system which extends from the southern margin of the Loess Plateau north-northeastward across the plateau (Fig. 1). Oligocene to Quaternary basalts are distributed in this region. The xenoliths from Yangyuan are large and fresh with maximum diameters of over 50 cm. The dominant xenoliths are spinel peridotites with subordinate pyroxenites. Xenoliths from Fanshi are generally small (mostly ~1-5 cm) and are loose.

Pyroxenites are rare in this locality.

Peridotites from this region are similar to Group I peridotites (Frey and Prinz, 1978) with textural variation from protogranular to porphyroclastic (Mercier and Nicolas, 1975). Both lherzolite and harzburgite are present (Fig. 2a). The typical mineral assemblage is olivine (ol, 50–81%), orthopyroxene (opx, 20-34%), clinopyroxene (cpx, 1.4–16.7%) and spinel (sp, 0.8–3.8%). Volatile-bearing accessory minerals such as amphibole and carbonate are not observed. In a plot of modal olivine *versus* Fo (Fig. 2b), most samples plot in the Phanerozoic and Proterozoic domains, with only a few samples located marginally within the Archean field.

3. Analytical methods

Major and trace element compositions were determined using an X-ray fluorescence spectrometer (XRF) and inductively coupled plasma-mass spectrometry (ICP-MS), respectively, at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS). Analytical procedures are described by Goto and Tatsumi (1996) and Xu (2002). For Sr-Nd isotopic analyses, cpx separates (~50 mg) of a subset of samples were dissolved in distilled HF-HNO_3 Savillex screwtop Teflon beakers at 150 ºC overnight. Sr and REE were separated on columns made of Sr and REE resins of the Eichrom Company using 0.1% HNO_3 as elutant. Separation of Nd from the REE fractions was carried out on HDEHP columns with a 0.18N HCl elutant. The isotopic analyses were performed using a Micromass Isoprobe Multi-Collector ICPMS at GIGCAS. Measured Sr and Nd isotopic ratios were normalized using a $^{86}Sr/^{88}Sr$ value of 0.1194 and a $^{146}Nd/^{144}Nd$ value of 0.7219, respectively. The Sr and Nd blanks during the period of analyses were 0.5 ng and 0.3 ng, respectively. Analyses of standards during the period of analysis are as follows: NBS987 gave $^{87}Sr/^{86}Sr = 0.710243 \pm 14$ (2σ); Shin Etou gave $^{143}Nd/^{144}Nd = 0.512124 \pm 11$ (2σ), equivalent to a value of 0.511860 for the La Jolla international standard (Tanaka et al., 2000).

Osmium concentration and isotopic ratios were measured at Woods Hole Oceanographic Institution following the techniques described by Hassler et al. (2000). Powdered whole rock samples (about 1.5 g) were spiked with an in-house mixed spike enriched in ^{190}Os. The sample and spike mixtures were mechanically mixed in a ceramic crucible and were then combined with a ~5 g of flux consisting of sulfur, nickel and Na-borate with 1:2:15 proportions. Whole rock crucibles were fused at 1000 ^{o}C for 1.5 hours. The NIS beads from the whole rocks were dissolved in 6.2 N HCl at ~150 C and filtered through a 0.45 um cellulose filter. The filter paper was then dissolved in 1 ml concentrated HNO3, in a Teflon screw-cap beaker on hot plate at 100 ^{o}C for 45 min before sparging, during which oxidation of Os to OsO_4 was achieved. The acid solution was then diluted ~5-fold with ultrapure water and a screw cap with inflow and outflow tubes was placed on the breaker. This cap allowed argon to bubble through the solution, via perforated tubing, thereby carrying the volatile OsO_4 into the torch for analyses (Hassler et al. 2000). Measurement of Os composition and concentration was carried out on a Finnigan Element 2 ICP-MS with argon flow rates being adjusted to around 1.35 L/min. Each analysis consisted of 30 runs. During the course of this study the whole chemistry Os blank was about 0.93 pg/g with $^{187}Os/^{188}Os$ of 0.64. In-run 2 sigma precision for $^{187}Os/^{188}Os$ measurement was about 0.5 %-1%. Repeated analyses of 1.25 ng and 400 pg in-house Os standard solution yielded an average $^{187}Os/^{188}Os$ =0.17399±0.29% and $^{187}Os/^{188}Os$ =0.17432±0.55%, respectively.

4. Results

4.1 Major and trace elements

Whole rock geochemical data are listed in Table 1 and a brief summary is presented here. Al_2O_3 and CaO are negatively correlated with MgO (Fig. 3). The most fertile lherzolite sample (e.g., FS-1) is compositionally similar to the primitive mantle (Jagoutz et al., 1979; Hart and Zindler, 1985). Specifically, harzburgites have higher MgO contents and lower Al_2O_3 and CaO contents than lherzolites indicating a higher degree of partial melting for the harzburgites (Table 1; Fig. 3). The MgO content of the most refractory sample (YG-19) is 50%. Al_2O_3 and CaO contents in this sample are down to 0.36% and 0.12%, respectively.

Similar compositional distinction between lherzolites and harzburgites is also reflected in mineral chemistry (Table 2). For example, Cr# values of spinel (0.096-0.22) in lherzolites are lower than those in harzburgites (0.23-0.58). As $Cr\#_{Sp}$ is positively proportional to the degrees of partial melting, this implies that harzburgites underwent a higher degrees of melt extraction compared with lherzolites. Equilibrium temperatures for the Yangyuan peridotites, estimated using Ca-in-Opx thermobarometer of Brey and Kohler (1990), range from 916°C to 1050°C (Table 2). No difference in equilibrium temperature is observed between harzburgites and lherzolites.

The Yangyuan and Fansi peridotites exhibit substantial variations in both absolute concentration of trace elements (Table 1) and chondrite-normalized REE patterns. Three REE patterns for Cpx separates can be distinguished (Fig. 4). The first type is characterized by a flat HREE [$(Ho/Yb)_n$=1.03-1.15] pattern and a LREE-depleted pattern [$(La/Yb)_n$=0.34-0.58]. Primitive mantle-normalized element abundances gradually decrease from MREE to Rb forming a smooth trend line. This pattern shows a pronounced negative Ti anomaly but no Nb and Ta anomalies (Fig. 4a, b). The second type pattern is characterized by relatively flat REE pattern (Fig. 3c). YYB-5 and YYB-7 possess a weak HREE fractionation with the apex at Nd. YYB-8 exhibits a weak LREE-enrichment. These samples exhibit negative Zr, Hf and Ti anomalies but no Nb and Ta anomalies (Fig. 3d). The third type pattern is characterized by LREE-enrichment [$(La/Yb)_n$ = 2.7-110] and pronounced negative HFSE anomalies (Fig. 4e, f).

4.2 Sr-Nd isotope

$^{87}Sr/^{86}Sr$ ratio of Cpx in the Yangyuan peridotites ranges from 0.7031 to 0.7047. $^{143}Nd/^{144}Nd$ ratios have a wide variation from 0.5121 to 0.5136 (Table 2). These isotopic compositions are distinctly different from that of the host basalts (Fig. 5a). ε_{Nd} values of the LREE-enriched samples YYB-3 and YYB-9 are –10.6 and -6.9, respectively. However, their $^{87}Sr/^{86}Sr$ ratios are only moderately enriched (0.7044-0.7047). This may indicate a contribution from an EMI-type component (Fig. 5a). Although YYB-1 is also LREE-enriched, it has a positive ε_{Nd} value, and plots well within the Nd isotopic range of the LREE-depleted samples (ε_{Nd} = +5 to +8). The ε_{Nd} values of the samples with the second type of REE pattern (ε_{Nd} = 1.2) are between those of the LREE-depleted and the LREE-enriched samples. Nd model ages range from future ages to older than that of the Earth (Table 2). However, most of LREE-depleted samples have Nd model ages between 2.0-2.8 Ga.

4.3 Os concentration and isotopic composition

Osmium concentrations in all but one sample range between 0.3 ppb and 2.8 ppb (Table 2; Fig. 6). These Os concentrations are similar to off-cratonic spinel peridotites from around the world (Handler et al., 1997; Meisel et al., 2001; Peslier et al., 2000a; Pearson et al., 2004; Reisberg et al., 2005), but are lower than Os concentrations in peridotite massifs. The most refractory sample YG-19 is characterized by anomalously high Os content (9 ppb). No clear correlation is found between $^{187}Os/^{188}Os$ and Os and La/Yb for the whole suite (Fig. 7a, b).

Whole rock $^{187}Os/^{188}Os$ isotopic compositions measured by ICP-MS at WHOI range from 0.1106 and 0.1325, with a large number of samples having very unradiogenic Os isotopic ratios (<0.12; Table 2). The sample YYB-7 has an $^{187}Os/^{188}Os$ ratio of 0.1106, which is among the lowest values measured so far for the Chinese mantle xenoliths in Cenozoic basalts (Wu et al., 2006; X. Xu et al., this volume). The most refractory sample YG-19 and a LREE-enriched sample YYB-3 have $^{187}Os/^{188}Os$ higher than that of the present-day primitive upper mantle (PUM) value (0.129±1, Meisel et al., 2001). In the plot of $^{187}Os/^{188}Os$ against Al_2O_3, these two samples and another very refractory sample (YYB-1) plot off the positive correlation defined by remaining samples (Fig. 7a). All three samples show evidence for melt percolation given their high La/Yb (Table 1) and LREE-enriched pattern (Fig. 4). According to the $^{187}Os/^{188}Os$-Al correlation trend, the Os composition of the fertile lherzolite at 4.2 wt% Al_2O_3 is 0.128, which agrees well with the PUM values of Meisel et al. (2001).

5. Discussion

5.1 Depletion and enrichment events

Modal compositions (Fig. 2) reveal that the Yangyuan-Fansi peridotite xenoliths range from primitive lherzolite via clinopyroxene-poor lherzolites to strongly refractory harzburgites. Such modal variation is accompanied by mineral and whole rock composition changes. In particular, the inverse correlations between CaO (and Al_2O_3) and MgO (Fig. 3) are similar to those observed for xenoliths from worldwide occurrences (Frey and Prinz, 1978; Xu et al., 1998; Takazawa et al., 2000). This indicates that the Yangyuan-Fansi peridotites represent the refractory residues left after extraction of the basalts by variable degrees of partial melting. Applying the method of Norman et al. (1998), we have estimated the degrees of partial melting for the Yangyuan samples. Comparison of Y and Yb contents in lherzolite cpx and the modeled melting trend (Fig. 8) further indicates that the degrees of melting for the Yangyuan lherzolites and harzburgite varied between 0-5% and 6-20%, respectively. Nd model ages of LREE-depleted samples (2.0-2.8 Ga) suggest that melt extraction took place during late Archean and early Proterozoic.

LREE-enrichment associated with some moderately to highly refractory samples indicates mantle metasomatism. Chromatographic-type migration of LREE-enriched melts/fluids through LREE-depleted peridotites is an efficient metasomatic mechanism (Navon and Stolper, 1987; Bodinier et al., 1990). This type of melt-rock interaction produces REE patterns with extremely variable LREE enrichment and almost intact HREE, which is typical of that observed in the cpx studied in this paper (Fig. 4). Incipient metasomatism is associated with the samples with relatively flat REE patterns (YYB-5, 7, 8; Fig. 3c). High Nb abundance in cpx from YYB-8 indicates that the metasomatic agent was capable of carrying this element. This, the positive ε_{Nd} values and relatively low Sr/Nd and Ba/La ratios suggest that the metasomatism in these samples was probably related to small degree melts from an asthenospheric source during intraplate volcanism.

A different metasomatic agent for LREE-enriched samples (YYB-1, 3, 9) could be invoked given the strong HFSE depletion (Fig. 4e, f). Carbonatite, subduction-released fluid/melt and evolved asthenosphere-derived melt (Menzies, 1990; Ionov et al., 1993; Bedini et al., 1997) are potential agents because they can all produce a high La/Yb and a marked HFSE depletion. Discrimination between these alternatives is not an easy task. Nevertheless, carbonatite metasomatism is not favored given the lack of the features typical of carbonate metasomatism in the xenoliths (e.g., presence of apatite, high Na in cpx, Yaxley et al., 1998). With the exception of YYB-1, the Yangyuan samples define a roughly positive correlation between ε_{Nd} and Sm/Nd (Fig. 5b). This can be explained either by mixing between a depleted endmember and an enriched component or by time-integrated radiogenic decay.

Despite the contrast in ε_{Nd} (Table 2), YYB-1 (ε_{Nd}=+5), YYB-3 and YYB-9 (ε_{Nd} =-6~-10) have similar trace element compositions. It is thus possible that the associated metasomatic agents were likely derived from the asthenosphere by small degrees of partial melting, but metasomatism took place at a different time. The LREE enrichment associated with YYB-1 is a recent event so that the time elapsed was not sufficiently long to create low, unradiogenic $^{143}Nd/^{144}Nd$. In contrast, those associated with YYB-3 and YYB-9 must be old. The calculation suggests that the enrichment must have taken place at least 1000 Ma ago so that radiogenic decay subsequent to LREE enrichment can produce low ε_{Nd} observed in these samples. A weakness with this interpretation comes from Os data. As will be discussed later, YYB-3, which is only moderately depleted in terms of Al_2O_3, likely contains a mixture of primary and secondary sulfides, whereas highly refractory YYB-1 is likely dominated by metasomatic sulfides. If both samples were metasomatized by a similar melt, then a higher $^{187}Os/^{188}Os$ ratio is expected for YYB-1 that has relatively higher Os abundances (1.6 ppb) compared to YYB-3 (~0.5 ppb). However an opposite is observed (Table 2).

Although the above mentioned problem can be explained if the enrichment of lithophile elements and the introduction of Os took place by separated processes, a more plausible interpretation is that LREE-enriched samples with negative ε_{Nd} were affected by a metasomtatic agent that is different from the asthenospheric melts invoked for the samples with positive ε_{Nd}. Subduction-related melts are the likely candidate. This suggestion is consistent with the fact that studied area is located within the Central Orogenic belt of the NCC, formed as a result of collision between the western Block and eastern Block during the Proterozoic (Zhao et al., 2001).

5.2 Effect of metasomatism on Re-Os system

A number of the Yangyuan-Fansi samples show signs of mantle metasomatism (e.g., LREE-enrichment). However, only three of them plot off the general trend in the $^{187}Os/^{188}Os$-Al plot (Fig. 7a) due to their relatively high $^{187}Os/^{188}Os$, whereas remaining metasomatized samples and unmetasomatized define a coherent correlation between $^{187}Os/^{188}Os$ and Al_2O_3. This correlation may be of age significance (see next section for age determination), or represent a mixing line reflecting refertilisation of the lithosphere (Beyer et al. 2006) and/or by metasomatism of a sulfide-saturated silicate melt that introduced silicate phases (Pearson et al., 2004). However this interpretation is problematic for the following reasons: (a) There is no correlation between $^{187}Os/^{188}Os$ and Os for the studied samples, as would be expected with a mixing trend. Moreover, Os addition through lithospheric refertilisation or metasomatism would produce a curved array (Reisberg and Lorand, 1995), rather than the linear correlation observed in Yangyuan-Fansi samples; (b) Metasomatic enrichment tends to be involved to a greater degree in more refractory samples than in more fertile samples (Frey and Prinze, 1978; Xu et al., 1998; this study), which is the opposite required to explain the positive $^{187}Os/^{188}Os$-Al_2O_3 correlation. There is no petrographic and geochemical evidence for a large-scale metasomatism that affected the whole sample suite, as the presence of LREE-depleted and high ε_{Nd} peridotites (Table 1 and Fig. 4-5) reflects a long-term isolation from the convecting mantle since the melting event. In fact, Al_2O_3 contents in peridotites, which are negatively correlated with MgO, are most likely controlled by depletion event; and (c) the extension of the $^{187}Os/^{188}Os$-Al_2O_3 correlation overlaps with the PUM Os isotopic composition of Meisel et al. (2001). Similar trends have been observed in peridotite xenoliths worldwide (e.g., Meisel et al., 2001; Peslier et al., 2001a; Handler et al., 2003; Wu et al., 2003, 2006; Reisberg et al., 2005), and in peridotite massifs (Reisberg and Lorand, 1995, 2005). These trends most likely resulted from radiogenic ingrowth of ^{187}Os subsequent to an ancient melt extraction event during which different degrees of melt extraction led to different degrees of Re-Os fractionation.

If the positive $^{187}Os/^{188}Os$-Al_2O_3 correlation is not a mixing line, it follows that the major Os modification affected only three samples (YYB-1, YYB-3 and YG-19) that deviate from the trend (Fig. 7a). Because of the extremely high partition coefficients for Os in sulfides, metasomatic sulfides can contain 1-10 ppm Os. Consequently, addition of metasomatic sulfides to mantle residues is an effective way to disturb both the Os abundance and Os isotopic ratios of the host peridotites. Recent investigation using the in-situ techniques revealed multiple generations of sulfides in mantle peridotites. For instance, Alard et al.

(2002) reported two types of sulfides in peridotite xenoliths: the “original” type was included in silicate phases and the secondary type was interstitial along silicate boundaries. Osmium abundances in interstitial sulfides are significantly lower than those of the primary sulfides (Alard et al., 2002). The whole rock analyses integrate these different generations of sulfides. Whether its Re-Os composition is affected by metasomatism depends upon the proportion between primary sulfides and secondary sulfides. Specifically, the effect of such metasomatic sulfide addition on the whole rock Os isotopic systematics is only significant when the primary sulfides have been completely removed in the peridotites (Handler et al., 2003).

The fact that LREE-enriched samples (YYB-5, YYB-7, YG-5) do not display high $^{187}Os/^{188}Os$ ratio and plot along the correlation suggests that not all metasomatism can affect Re-Os isotopic system of the mantle. Such a decoupling between enrichment of lithophile and siderophile elements may be due to the relatively high proportion between primary sulfides and metasomatic sulfides in these samples. As indicated previously, these samples were affected by chromatographic metasomatism at very low melt/rock ratio. In this case, the percolating melts may be evolved thus having high concentration of LILE but low contents of siderophile elements due to sulfide segregation during precedent evolution. As a consequence, metasomatism cannot introduce a significant amount of siderophile elements, consequently the residual primary sulfides in these peridotites still dominate the Os budget.

YYB-3 has Os abundances (0.55 ppb) that are significantly lower than those of the other peridotites from the same locality, making it more susceptible to metasomatic Os addition. Hence, a straightforward explanation is that the high $^{187}Os/^{188}Os$ ratios in YYB-3 could have developed as a result of addition of a radiogenic Os component to the peridotites. The measured high $^{187}Os/^{188}Os$ reflects the mixing between primary sulfide and a metasomatic component which has more radiogenic composition. So far, radiogenic Os combined with low Os abundances has been documented in peridotite xenoliths from subduction setting (Brandon et al. 1996) and peridotites that have been modified by plume-derived melts (Handler et al., 2003). Given the Nb-Ta depletion and negative ε_{Nd} value for YYB-3, an interpretation involving supra-subduction zone processes is likely. Alternatively, high $^{187}Os/^{188}Os$ ratio was developed as a result of radiogenic ingrowth subsequent to metasomatic enrichment of Re/Os.

A similar explanation may be put forward for YYB-1, but the positive ε_{Nd} observed in this sample requires a different and recent metasomatic event. YG-19 and YYB-1 are highly refractory with Al_2O_3 of 0.36 and 0.63%, respectively. It is possible that the original Os component in these rocks may have been largely removed during melt extraction, allowing the secondary Os to dominate its current Os budget. Lithophile element compositions suggest that the metasomatic agent has a geochemical affinity with asthenospheric melts. Asthenosphere-derived melts are generally more radiogenic than most peridotites, thus accounting for the high $^{187}Os/^{188}Os$ ratios observed in these two refractory samples. The effect of radioactive decay is negligible given the recent melt infiltration processes. YG-19 has anomalously high Os concentration (>9 ppb), while the Os concentration in YYB-1 (1.6 ppb) is typical of those observed in other samples from the same localities. This may be related to the sulfide saturation of percolating melt during its passage in the lithosphere. The percolating melt associated with YG-19 probably deposited sulfides in peridotites, whereas the melts percolating YYB-1 may be relatively depleted in Os due to previous loss of sulfides.

5.3 Ages of the lithospheric mantle beneath the western NCC

The Re-depletion ages (T_{RD}) for the Yangyuan samples (except for YG-19), assuming a Re/Os of zero (Walker et al., 1989), range from 0.33 to 2.69 Ga (Table 1). Because Re-contents in peridotites are certainly higher than zero after melt extraction, T_{RD} may underestimate the true ages of melting events, and are considered as minimum model ages (Walker et al., 1989). Only the Re-depletion age of the most refractory samples may approach that of the true age. In this sense, 2.7 Ga may represent the age of melt extraction although this is still a minimum estimate given the presence of more refractory samples.

Another method to obtain the melt-depletion age is to use Al_2O_3 as proxy of Re/Os because Al_2O_3 are positively correlated with Re/Os (e.g., Reisberg and Lorand, 1995). The $^{187}Os/^{188}Os$-Al_2O_3 correlation is interpreted as a result of radiogenic ingrowth of ^{187}Os subsequent to an ancient melt extraction event. The age of this event can be estimated by comparing the *y*-intercept of the correlation with the mantle evolution curve assuming the

Re/Os of the PUM (Meisel et al., 2001). Because in refractory peridotites, Al_2O_3 contents rarely reach zero, consequently the Al-model age may overestimate the true depletion age (Pearson, 1999; Peslier et al., 2000). Handler and Bennett (1999) argued that extrapolation to of 0.7 wt% is warranted because in most peridotite suites worldwide Re/Os approaches zero at that approximate level of depletion. YG-19, YYB-1 and YYB-3 are not used in model age determination because their Os isotopic compositions have been modified during melt percolation processes. The remaining samples define a positive $^{187}Os/^{188}Os$-Al_2O_3 correlation with the *y*-intercept (at Al_2O_3 = 0.7 wt%) at ~0.110, yielding a model age of 2.8 Ga (Fig. 7c). This age is in agreement with the T_{RD} of the most refractory samples and the Nd model ages of the LREE-depleted samples (2.0-2.8 Ga, Table 1), suggesting a long-term isolation of the lithospheric mantle from the convective asthenosphere. All the model ages (2.4-2.6 Ga) of melt extraction are virtually identical to the Nd model age of overlying crust (Wu et al., 2005), suggesting an essentially coupled crust-mantle in the western NCC.

The antiquity of the lithospheric mantle under the western NCC is also consistent with the unusual EM1 type Sr-Nd isotope composition of some LREE-enriched samples. Similar isotopic characteristics have been observed in garnet inclusion from south Africa and xenoliths and megacrysts from Outer Hebrides from Scotland, which have been interpreted as a result of radiogenic decay after a LREE-enrichment (Richardson et al., 1984; Menzies and Halliday, 1988).

5.4 Lateral variation in age structure of the upper mantle beneath the NCC

A number of Os isotope studies are now available on mantle xenoliths from eastern China, thus enabling us to gain insights into the lateral variation in the age structure of the upper mantle in this region. In the following, we compare the mantle domains across the DTGL as this lineament may represent a fundamental boundary in eastern China and its formation may be genetically related to the lithospheric removal (Xu, 2007).

Gao et al. (2002) reported a Re-Os isochron age of 1.9 Ga for selected xenoliths from Hannuoba, which is also located to the west of the DTGL. This age is significantly younger than the Nd model age of the overlying crust, suggesting a decoupled crust and mantle at

Hannuoba. These authors suggested that some portion of the original Archean lithospheric mantle underlying Hannuoba was removed during the Proterozoic, and was replaced with new lithosphere derived from the convective mantle. The decoupled crust-mantle at Hannuoba contrasts with the coupled crust-mantle at Yangyuan although the two localities are geographically proximal (Fig. 1). It is interesting to note that both Hannuoba and Yangyuan xenoliths define the same trend in the $^{187}Os/^{188}Os$-Al_2O_3 plot (Fig. 7b). We thus suggest that the mantle xenoliths from western NCC record the same stabilization age (i.e., very early Proterozoic). The assessment of the Early Proterozoic mantle at Yangyuan and Fansi suggests that fertile mantle can persist for a prolonged time (Lee et al., 2001). The contrast in composition between Archean and Proterozoic mantle implies a dramatic change in thermal condition from the Archean to the Proterozoic (Menzies, 1990; Griffin et al., 1998).

A complex age structure is found for the lithospheric mantle beneath the eastern NCC. For instance, some highly refractory samples from Longgang (Jilin Province) and Qixia (Shandong Province) have T_{RD} age of 1-1.2 Ga, suggesting a minimum Mesoproterozoic model age for melt depletion of the SCLM underlying some portions of the eastern NCC (Gao et al., 2002; Wu et al., 2003). Reisberg et al. (2005) reported Re-Os isotopic data on peridotite xenoliths from Subei basin (east Central China) and suggested the mantle underneath this region were affected by an early Proterozoic (~1.8 Ga) melt extraction event. More recently, Wu et al. (2006) obtained a model age of ~2.3 Ga for Kuandian peridotites. All these data point to the presence of ancient mantle residues in the eastern NCC. On the other hand, a number of samples from the eastern NCC show Os isotopic data overlapping that of the modern convecting upper mantle defined by abyssal peridotites and ophiolites, and their T_{RD} ages range from 0.4 to 0 Ga (Gao et al., 2002; Wu et al., 2003). This may indicate the presence of much younger portion of the lithospheric mantle. It is possible that the upper mantle beneath the eastern NCC comprises both ancient melting residues and newly accreted material (e.g., Gao et al., 2002; Wu et al., 2003, 2006), although their spatial resolution is unclear.

The Os model ages for the upper mantle from the eastern NCC are significantly younger than the formation age of the overlying crust (Wu et al., 2005), suggesting a decoupled crust-mantle system in this region. This contrasts with the coupled crust-mantle system in the western NCC, thereby outlining the lateral heterogeneity of the lithospheric mantle beneath the NCC. This is consistent with the view that lithospheric removal was largely limited to the eastern NCC. The different lithospheric structure in the western and eastern NCC could be due to the diachronous extension history that resulted from interaction of two tectonic regimes (Xu et al., 2004b). While the extension in the Shanxi graben was likely related to the Indo-Eurasian collision (Ye et al., 1987), the NNE-trending basins in the eastern NCC may be induced by subduction of the Pacific plate underneath the Asian continent (Griffin et al., 1998; Wu et al., 2003; Xu et al., 2004b), which started probably since the end of the Mesozoic (Engebretson et al., 1985). On the other hand, the co-existence of new and old mantle in the eastern NCC is not consistent with the delamination model in which the removal of the entire old mantle is expected (Reisberg et al., 2005).

Available Os isotopic data point to the presence of Archean mantle residues prior to the lithospheric thinning (Gao et al., 2002; Wu et al., 2006). If the thermal erosion model applies, the co-existence of Archean relicts and new mantle components is expected. However, Cenozoic basalts essentially sampled both Proterozoic mantle and newly accreted mantle with $^{187}Os/^{188}Os$ consistent with those of modern convecting mantle (Gao et al., 2002; Wu et al., 2003; 2006). A key issue needs to address why there is no sign of Archean mantle under the eastern NCC. This has been discussed in detail by Wu et al. (2006) who considered three possibilities: inverted age stratigraphy in the lithospheric mantle during the Paleozoic, preferential sampling of Proterozoic and modern age mantle by Cenozoic volcanism, and replacement of Archean mantle during thinning by Proterozoic-Phanerozoic mantle that formed underneath the Yangtze craton. Testing of these alternatives requires information about the spatial variation in age structure of the lithosphere prior to thinning. This is, however, hampered by limited and geographically restricted occurrences of pre-Mesozoic, xenolith-bearing volcanism. Nevertheless, the "exotic" Proterozoic mantle as implied by the third alternative is not consistent with the accumulating evidence for an intense and widespread Paleoproterozoic mantle melting event in the eastern NCC. For instance, the granulite xenoliths in the Fuxian kimberlites were formed at 2.5 Ga and represent underplates ($\varepsilon_{Hf}(t)$ = 2.4-8.4) of a significant magmatic event (Zheng et al., 2004). Similar 2.5 Ga zircons with positive Hf composition are preserved in the Mesozoic intrusions in Shandong province

(Xu et al., 2007), suggesting that the Proterozoic mantle is indeed an intrinsic component of the lithospheric mantle under the eastern NCC. It is likely that the upper mantle prior to the lithospheric thinning was composed of both Archean and Proterozoic residues, although the spatial relation of these two components is unclear yet. The Phanerozoic mantle may have formed as a result of conductive cooling of upwelled asthenosphere that emplaced at the space left by the thinning of pre-existing lithospheric keel (Xu, 2001).

6. Conclusions

(1) The lithospheric mantle sampled by the Yangyuan and Fansi Cenozoic volcanism (western NCC) is chemically and isotopically heterogeneous. Parts of the lithospheric mantle are characterized by moderately to strongly refractory mantle with variable enrichment in LILE. The Yangyuan samples show a wide range in Sr-Nd isotopic composition from DMM to EM-1 like component. The lithospheric mantle beneath the western NCC experienced multiple metasomatic enrichments involving small melt fractions derived from the asthenosphere and melts related to a supra-subduction setting.

(2) The Yangyuan-Fansi peridotites are characterized by a wide range in Os isotopic ratio (0.110-0.133). The unradiogentic Os isotopic ratios in some refractory samples provide evidence for the existence of ancient lithosphere under the western NCC. Correlations between $^{187}Os/^{188}Os$ and Al_2O_3 (and Lu) yield a model age of 2.4-2.8 Ga, suggesting that the lithospheric mantle beneath the western NCC was stabilized in the late Archean or very early Proterozoic. This model age overlaps the Nd modal age of overlying crust, reflecting a coupled crust-mantle beneath the western NCC.

(3) The coupled crust-mantle in the western NCC contrasts with the decoupled nature in the eastern NCC. This confirms that the notion that the lithospheric removal was largely limited to the eastern NCC. The co-existence of new and old mantle in the eastern NCC is not consistent with the delamination model in which the removal of the entire old mantle is expected. The different lithospheric structure in the western and eastern NCC could be due to the diachronous extension history that resulted from interaction of the Pacific subduction-controlled regime and Indo-Euroasian collision regimes.

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Figure captions

Fig. 1 (a) Simplified tectonic map of the North China Craton. Note that the North China Craton is cut by two major geological and geophysical linear zones – Tan-Lu fault zone (TLFZ) to the east and Daxinganlin-Taihangshan gravity lineament (DTGL) to the west. Two shaded and dashed lines outline the Trans North China Orogen which separates western and eastern Blocks of the North China Craton (after Zhao et al., 2001). The Shaanxi-Shanxi rift system occurs in the Trans-North China Orogen. (b) Distribution of the Cenozoic basalts in the western North China Craton.

Fig. 2 (a) Modal composition of the peridotite xenoliths from Yangyuan and Fansi. (b) Modal orthopyroxene *versus* forsterite content in olivine. Complied fields for xenoliths found in Archean, Proterozoic and Phanerozoic crust are from Menzies (1990).

Fig. 3 Plots of CaO and Al_2O_3 against MgO for peridotite xenoliths from Yangyuan and Fansi. Diagonally hatched areas are primitive mantle compositions (Jagoutz et al., 1979; Hart and Zindler, 1986).

Fig. 4 REE and trace element abundances in clinopyroxenes from Yangyuan peridotites. On the left, the REE patterns normalized by chondrite values (Sun and McDonough, 1989). On the right hand are spiderdiagrams with trace elements normalized to primitive mantle values (Sun and McDonough, 1989).

Fig. 5 (a) $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ of clinopyroxene separates from the Yangyuan peridotites. Isotope data of peridotite xenoliths from eastern China (Fan et al., 2000; Song and Frey, 1989; Tatsumoto et al., 1992; Xu et al., 1998, 2003; Rudnick et al., 2004) and of the host basalts (Ma, 2004) are shown for comparison. (b) ε_{Nd} versus Sm/Nd diagram.

Fig. 6 $^{187}Os/^{188}Os$ versus Os and La/Yb

Fig. 7 (a) Left: whole $^{187}Os/^{188}Os$ ratios plotted against Al_2O_3 and model age determination. (b) Right: whole $^{187}Os/^{188}Os$ ratios plotted against Lu and model age determination. Os mantle evolution curve is calculated using the Os isotopic composition of the present-day PUM of Meisel et al. (2001) and initial $^{187}Os/^{188}Os$ ratio (0.09531) used by Shirey and Walker (1998). The model ages obtained for Yangyuan and Fanxi peridotites range between 2.4-2.8 Ga.

Fig. 8 Comparison of Y and Yb contents of clinopyroxenes in peridotite xenoliths from south China with the calculated melting trend using fractional melting model within spinel stability field (Norman, 1998). The subscript n in (a) indicates that the Yb and Y concentrations are normalized to primitive mantle (Sun and McDonough, 1989).