Archean-Paleoproterozoic Lithospheric Mantle at the Northern Margin of the North China Craton Represented by Tectonically Exhumed Peridotites

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Abstract: Tectonically emplaced peridotites from North Hebei Province, North China Craton, have retained an original harzburgite mineral assemblage of olivine (54%–58%) + orthopyroxene (40%–46%) + minor clinopyroxene (<1%)+spinel. Samples with boninite-like chemical compositions also coexist with these peridotites. The spinels within the peridotites have high-Al end-members with Al2O3 content of 30 wt%–50 wt%, typical of mantle spinels. When compared with experimentally determined melt extraction trajectories, the harzburgites display a high degree of melting and enrichment of SiO2, which is typical of cratonic mantle peridotites. The peridotites display variably enriched light rare earth elements (REEs), relatively depleted middle REEs and weakly fractionated heavy REEs, which suggest a melt extraction of over 25% in the spinel stability field. The occurrence of arc- and SSZ-type chromian spinels in the peridotites suggests that melt extraction and metasomatism occurred mostly in a subduction-related setting. This is also supported by the geochemical data of the coexisting boninite-like samples. The peridotites have 187Os/188Os ratios ranging from 0.113–0.122, which is typical of cratonic lithospheric mantle. These 187Os/188Os ratios yield model melt extraction ages (TRD) ranging from 981 Ma to 2054 Ma, which may represent the minimum estimation of the melt extraction age. The Al2O3-18Os-proxy isochron ages of 2.4 Ga–2.7 Ga suggest a mantle melt depletion age between the Late Archaean and Early Paleoproterozoic. Both the peridotites and boninite-like rocks are therefore interpreted as tectonically exhumed continental lithospheric mantle of the North China Craton, which has experienced mantle melt depletion and subduction-related mantle metasomatism during the Neoarchean- Paleoproterozoic.

Key words: harzburgite, boninite, Re-Os isotopes, lithospheric mantle, Paleoproterozoic, North China Craton

1 Introduction

The North China Craton (NCC) is an Archean craton with a complicated geological evolution. Crustal rocks within the NCC record nearly all major global geological events in the early geotectonic history of the Earth (Zhai, 2011; Kusky et al., 2007; Wan et al., 2016; Zhao et al., 2016). In addition, a large set of petrological, geochemical, and Re-Os isotopic data of mantle-derived peridotite and pyroxenite xenoliths suggest a complex history for the lithospheric mantle below the NCC, particularly during the Archaen and Phanerozoic (e.g. Zheng et al., 1999; Gao et al., 2002; Li and Wang, 2002; Chu et al., 2009; Wu et al., 2006; Zhang et al., 2008; Tang et al., 2013). Due to their small size and limited occurrence however, these mantle xenoliths are incapable of providing the full picture surrounding the extent, all the timing of mantle melt depletion and past metasomatic processes of the NCC. In this study, we report for the first time, the discovery of a series of tectonically exhumed Archean to Paleoproterozoic mantle peridotites as well as
metamorphosed boninite-like rocks in the north margin of the NCC. We report a series of new data, including: (1) electron microprobe chemical analyses of minerals (olivine, orthopyroxene and spinel) that survived metasomatic alteration; (2) whole rock major element data and trace element data; and (3) whole rock Re-Os data. Using these data, we have characterized the early accretion history of the lithospheric mantle at the north margin of the NCC. Our findings also provide new temporal constraints for the initiation of subduction below the NCC.

2 Geological Background and Sampling

The northern margin of the NCC (Fig. 1) is bounded by the Xianghuangqi–Duolun–Chifeng fault belt to the north and by the Jining–Shangyi–Chicheng–Pingquan fault belt to the south (Hu et al., 2003). The key Precambrian geological units in this area include: (1) a series of Neoarchean tonalite-trondhjemite-granodiorite (TTG) gneisses and low grade metamorphosed volcanic-sedimentary rocks, which record the cratonization of the NCC (Zhai et al., 2011; Zhao et al., 2005; Peng et al., 2012); (2) Paleoproterozoic high pressure granulites and retrograde eclogites: the result of Proterozoic orogenic events in the NCC (Zhai et al., 1992; Zhai et al., 1995; Guo et al., 2001); and (3) a Paleoproterozoic khondalite belt (Wan et al., 2009; Liu et al., 2016) containing local ultra-high temperature metamorphic rocks (Guo et al., 2006) and basic intrusive rocks indicative of excess mantle potential temperatures (Peng et al., 2010). These samples together suggest a reworking process likely accompanied by a mantle plume event (Zhai et al., 2011).

A mafic-ultramafic intrusion belt, which consists of nearly three hundred intrusions, is distributed along the northern margin of the NCC (Chen et al., 1996; Tian et al., 2007). In the vicinity of Chicheng County, more than 120 ultramafic intrusions were tectonically emplaced into the Hongqiyingzi Complex, a metamorphosed complex mainly composed of amphibolite facies metavolcanic and metasedimentary rocks with Neoarchean to Paleoproterozoic ages (2535–2480 Ma, Liu et al., 2007). Retrograde eclogites can be found along the Jining–Chicheng–Pingquan major fault (Ni et al., 2004 and 2006). Recently Zhang et al. (2016) reported ca. 1.95 Ga U-Pb age for metamorphic zircons from the Hongqiyingzi Group, the country rock which hosts the retrograde eclogite. This metamorphic age places a Paleoproterozoic age constraint on the subduction to eclogite facies of our study area.

Fig. 1. (a), Location of the study area in the North China Craton. Distribution of Archean-Early Proterozoic geological units after Peng et al. (2010); (b), Simplified geological map of mafic-ultramafic bodies around Chicheng Country, North Hebei Province, China.

(1), Quaternary alluvium; (2), Yanshanian alkaline granite; (3), Jurassic volcanic rocks; (4), granitic gneiss-mylonite; (5), Early Proterozoic Hongqiyingzi complex; (6), Dantazi complex; (7), major fault; (8), ultramafic intrusions; (9), sample location and sample name.
The studied peridotites as well as boninite-like rocks occur as small blocks with outcrop lengths ranging from several hundreds of meters to five kilometers (Chen et al., 1996). No contact-metamorphic aureoles have been found between the peridotites and their wall rocks, implying that they are tectonically emplaced, ultramafic diapirs rather than intrusive magmatic bodies. Two boninite-like samples are from outcrops close to the Zhenningpu County, which are closely related to the peridotites (Fig. 1).

All the samples have experienced alteration due to post-emplacement hydrothermal reactions and surface weathering. Most of the olivine and orthopyroxene within the peridotites has been replaced by serpentine or talc, with the exception of sample LHPX01 (Fig. 2a–b). The undulating extinction of some of the large orthopyroxene porphyroclasts suggests that the peridotites have experienced ductile deformation (Fig. 2c).

In contrast to the olivine and opx, the spinel within the peridotites is well preserved. Most spinels are small, anhedral grains occurring along the boundaries of the major minerals (Fig. 2d). Clinopyroxene is absent in all peridotite samples. The boninite-like samples have the metamorphic mineral assemblage of tremolite+quartz+chlorite+minor apatite (Fig. 2e–f).

### 3 Analytical Methods

We conducted mineral chemistry, major and trace element analyses, and Re-Os isotope analyses for the samples as described below.

#### 3.1 Mineral chemistry

Mineral chemical compositions were analyzed using a JXA-8100 electron probe microanalyzer (EPMA) at Peking University in wavelength dispersive mode with 15 kV acceleration potential, 10 nA beam current and a beam diameter of 1 μm. Matrix corrections were applied using the PRZ correction program. 53 analytical standard minerals from American company SPI were used for external accuracy quantification, and mineral formulae were calculated based on stoichiometry. The analyzed olivine, orthopyroxene and spinel data are listed in Table 1–3, respectively.

#### 3.2 Major and trace element analysis

Major element analyses of bulk rock powers were conducted by X-Ray Fluorescence Spectrometry on fused glass disks using a Philips Avant (No.6735) + XRF-1500 instrument at the Laboratory of Orogenic and Crustal Evolution, Ministry of Education, Peking University. Trace element concentrations were determined using a PerkinElmer Sciex ElAN 6000 ICP-MS. The USGS and Chinese National standards BHVO-2 and GSR-2 were chosen for element concentration calibration. Analytical uncertainties of REE and other incompatible element analyses are generally better than 5%.

All analyzed data are listed in Table 4.

<table>
<thead>
<tr>
<th>Table 1 Composition of olivine from peridotite samples</th>
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<tr>
<td>Sample</td>
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</tr>
<tr>
<td>SiO₂</td>
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</tr>
<tr>
<td>Al₂O₃</td>
</tr>
<tr>
<td>FeO</td>
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<td>MnO</td>
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<td>MgO</td>
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<td>K₂O</td>
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<tr>
<td>Cr₂O₃</td>
</tr>
<tr>
<td>Mg²⁺/Fe³⁺</td>
</tr>
<tr>
<td>XOl/Fe²⁺</td>
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</tbody>
</table>
3.3 Re-Os isotope analysis

Rhenium and Os isotope analyses were performed on bulk rock powders at the Institute of Geology and Geophysics, Chinese Academy of Science (IGGCAS) as per Shiry and Walker (1995). About 2 g of whole rock powder was added to a spike of mixed $^{185}$Re and $^{190}$Os, along with approximately 9ml of aqua regia. This was sealed inside Carius tubes, and heated at 240°C for 48–72 hours. After opening the tubes, the Os was extracted from the aqua regia solution into CCl$_4$ (Cohen et al., 1996) and

Fig. 2. Microphotographs of the North Hebei peridotites and boninitic rocks.

(a), Slightly serpentinized peridotite LHPX01, showing unserpentinized olivine (II to III interference) and orthopyroxene (I grey interference); (b), Cartoon color illustration of (a) under single polar: pale green represents olivine, yellow represents orthopyroxene, black represents chromian spinel and white represents serpentine; (c), unaltered orthopyroxene porphyroclast surrounded by serpentine under cross polar; (d), the same area of (c) under single polar, note the slightly reddish color of orthopyroxene and yellowish green color of serpentine. The serpentine grains are surrounded by opaque chromian spinels, which preserve the outline of the olivine grains before serpentinization. (e), metamorphic mineral assemblage (tremolite + quartz + chlorite + minor apatite) of ZNP-1, a sample with boninite-like chemical compositions, under cross polar; (f) single polar image of ZNP-1, showing the color and cleavage of chlorites.
then back-extracted into HBr, followed by purification via microdistillation (Birk et al., 1997). Rhenium was separated from the matrix and purified by anion exchange chromatography using 2 ml resin. The Re was further purified using a small anion exchange column packed with 0.1ml resin at the University of Maryland (UMD). All the collected fractions were dried down and redissolved in 1ml of 0.8 M HNO₃ for ICP-MS measurement.

Both Re and Os were corrected for blanks. Total blank levels were 8±2 and 3±2 pg for Re and Os respectively, and the blank ¹⁸⁷O⁸/¹⁸⁸O⁸ ratio was 0.191±0.025. Precision of ¹⁸⁷O⁸/¹⁸⁸O⁸ measurements, based on analysis of an in-house standard over a period of several months, was better than 0.4% (2σ). The analyzed data are listed in Table 5.

4 Results

4.1 Mineral chemistry

Compositions of olivine, orthopyroxene and spinel (Table 1–3) are described as below.

4.1.1 Olinine

The olivines from the peridotite samples have forsterite content ranging from Fo₉₁ to Fo₉₂ and NiO content from 0.35wt%–0.41wt%, typical of mantle peridotites (Frey et al., 1978). CaO content of the olivine ranges from 0.01wt%–0.08wt%.

4.1.2 Orthopyroxene

The enstatite proportion of orthopyroxene ranges from 92.3% to 93.6%, with Al₂O₃, CaO and TiO₂ contents ranging from 0.14wt%–0.58wt%, 0.07wt%–0.14wt% and 0.02wt%–0.07wt%, respectively.

4.1.3 Spinel

In the spinel prism classification diagram (Deer et al., 1992), the spinels within the peridotites are plotted over the chromite, Al-chromite, picotite and hercynite areas (Fig. 3b). In the Cr₂O₃ vs. Al₂O₃ diagram (Fig. 4), the samples are distributed along a linear array from a high Cr chromite end member (Cr₂O₃ = 45wt%–60wt%) to a high Al chromite end member (Al₂O₃>25wt%). This is typical in chromite of magmatic origin (Zhou et al., 2014) and residual mantle spinels (Morten et al., 1989; Hao et al., 2013; Himmelberg et al., 1973), respectively. The TiO₂ content of the spinels ranges from 0.02 wt%–0.76wt%. Fluid alteration can increase the Fe³⁺ and decrease the Al³⁺ of chromite (Baumgartner et al., 2013), so hydrothermally altered spinel will plot in the low-Al₂O₃ area, as shown in Fig. 4. Our spinel samples have no overlap with the “altered spinel” field in Fig. 4, confirming that they remain unaltered hydrothermally.

One analysis of spinel from the boninite-like sample is characterized by high Cr₂O₃ (54.63wt%), low Al₂O₃ (12.28wt%), and low TiO₂ (0.05wt%), thereby falling into the “Hercynite” field (Fig. 3c).

4.2 Major element geochemistry of whole rock

Major element compositions of whole rock samples are listed in Table 4. The peridotite samples are characterized by high loss-on-ignition (LOI) from 13.08wt% to 14.00wt%, due to pervasive serpentinization. When normalized to exclude volatile elements, the peridotites have Al₂O₃ (1.30wt%–2.07wt%), CaO (0.0–0.28wt%) and FeO (5.57wt%–7.21wt%) lower than fertile peridotite, while MgO (41.9wt%–43.3wt%) and SiO₂ (46.7wt%–47.4wt%) are higher than fertile peridotite (Fig. 5). The boninite-like samples have high SiO₂ (53.91wt%–57.18wt%) and extremely low TiO₂ (0.059wt%–0.067wt%), typical of arc boninites.

4.3 Rare earth and trace elements

The REE abundances of the peridotites (Table 4) are plotted in a chondrite-normalized diagram and compared with modeled residual mantle peridotites at variable depth and melt fraction (Fig. 6). The peridotite samples display a small Eu anomaly (dEu), ranging from 0.70 to 1.70. Based on the variation in LREE enrichment, the REE patterns of the peridotites can be divided into two types: the “U-shape” patterns that are characterized by enrichment of La and

<table>
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molecular formula (based on six oxygens and Fe³⁺ corrected)

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Table 3 Composition of spinel from peridotite samples

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<tr>
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<td>MgO</td>
<td>Fe₃O₄</td>
<td>Al₂O₃</td>
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</table>

Molecular formula (based on four oxygens) and Fe³⁺ corrected:

- TiO₂: 0.57
- Cr₂O₃: 0.49
- Fe₂O₃: 0.50
- MgO: 0.50
- Fe₃O₄: 0.49
- Al₂O₃: 0.50
- TiO₂: 0.80
- Cr₂O₃: 0.80
- Fe₂O₃: 0.80
- MgO: 0.80
- Fe₃O₄: 0.80

Note: TiO₂ and Fe₃O₄ compositions of melts in equilibrium with the spinel(s) are calculated according to the regression of Kamikusa et al. (2001). mgO is an average Mg/Mg(Fe²⁺) of coexisting olivine from Table 1; T₁ and T₂ are temperatures after the calibrations of Ballhaus et al. (1991) and O'Neill and Wall (1987), respectively; fO₂ values were calculated after Ballhaus et al. (1991).
Ce, with a trough at Nd and Sm; and the “sinusoidal type” patterns which are characterized by highly enriched light and middle REE up to Dy (Fig. 6).

The boninite-like samples have low Nb/La ratios (0.09–
0.42) and low (Zr/Sm)$_{pm}$ ratios (0.05–0.80)- typical of arc boninites- and their Ti/Zr ratios (12–184) and Zr contents are similar to the Archean second stage melts (Smithies et al., 2004). The Sc abundance of the boninite-like samples is much lower than that of the Archean second stage melts; however, Sc is easily lost during submarine alteration (Staudigel and Hart, 1983). Therefore, the low Sc abundance may not be a characteristic of the magma but the fingerprint of later alteration. REEs in boninitic rocks however, are relatively immobile and would not be greatly affected by post magmatic alteration. In Fig. 7, the boninite-like samples are compared with different types of the Archean second-stage melts (Whundo- and Whitney-type from Smithies et al., 2004). Their low La/Yb and La/Gd ratios are identical to the subduction-related Whundo-type boninites, but higher than the plume-related Whitney-type.

4.4 Re-Os isotopical geochemistry

Rhenium and Os isotopic data are reported in Table 5. The abundance of Osmium in the peridotites varies from 2.9 ppb to 4.6 ppb, while the boninite-like samples have a smaller range from 1.5 ppb to 2.1 ppb. The $^{187}$Os/$^{188}$Os ratios of the peridotites range from 0.113 to 0.122, yielding $T_{RD}$ from 981Ma to 2054 Ma (Table 5). The boninite-like samples also have low $^{187}$Os/$^{188}$Os ratios of 0.1164 and 0.1220.

5 Discussion

5.1 Mantle melt depletion and metasomatism of peridotites

The presence of high-Al residual mantle spinels in peridotite samples (Fig. 4) suggests that the peridotites come from the lithospheric mantle. This means we can use these peridotites to make inferences about melting in the NCC lithospheric mantle. Partial melting will preferentially remove the clinopyroxene component from the mantle source into a melt (Walter, 2003), and therefore the mineral proportions of peridotites can be used to evaluate the degree of mantle melt depletion. Unfortunately, most of our peridotite samples have experienced alteration, and most
primary minerals have been replaced by secondary minerals such as serpentine, talc, and bastite. As a result, the original mineral compositions of the peridotites must be estimated by modal mineral calculations from bulk rock compositions. We use the volatile-free major element data to calculate the modal mineral composition of the peridotites using the thermodynamic simulation software THERMOCALC ver.3.33. The specified mineral activity models used in the calculation are as follows: (1) Clinopyroxene from Green et al. (2007); (2) Garnet from...
White et al. (2007); (3) Orthopyroxene from Powell and Holland (1999); (4) Spinel from Powell and Holland (1998), and an ideal mixing model is used for the olivine activity. The modal mineral compositions calculated at the spinel and garnet stability depth are listed in Table 6. It is clear that the peridotites are extremely low in modal clinopyroxene abundance. If calculated at the spinel stability depth, the modal clinopyroxene ranges from 0.06wt%–1.13wt%; however, if calculated at the garnet stability depth, the modal clinopyroxene decreases to 0.04wt% –0.64wt %. These extremely low modal clinopyroxene abundances suggest that the peridotites were highly refractory harzburgites before serpentinization. The absence of clinopyroxene in petrographic observation (as shown in Fig. 1) also suggests that the peridotites from North Hebei Province were likely to be harzburgites.

The major element compositions of the peridotites were plotted in FeO, Al₂O₃ and SiO₂ V.S. MgO diagrams (Fig. 5a, b and c) and compared with experimentally determined melt depletion trajectories (Herzberg, 2004). It is clear that the peridotite samples have MgO contents much higher than primitive fertile mantle as represented by KR-4003 (Fig. 5). Actually, the olivine Fo contents (91–92) of the peridotites correspond to melt depletion rates of ~30% or higher (Fig. 5a). In terms of Al₂O₃, the peridotite samples plot close to the melt depletion trajectory of ~20%, although their MgO contents are slightly lower. This can be explained by the addition of SiO₂ (orthopyroxene), which may lower the MgO contents of the bulk rock compositions. If we take the addition of orthopyroxene into account, the original melt depletion ratios can be constrained by connecting the orthopyroxene endmember, the peridotite samples, and the melt depletion trajectories. As shown in Fig. 5a and 5b, the “melt-peridotite interaction” lines passing through the orthopyroxene field and the North Hebei peridotite samples will intersect the ~20% to ~30% melt depletion trajectories. This is consistent with the nearly clinopyroxene-absent petrography and the extremely low clinopyroxene modal compositions (Table 6). Actually, the fertile mantle source KR-4003 contains over 27wt% clinopyroxene at garnet stability pressures (Walter, 1998), and therefore forming harzburgites within the garnet stability field would require the complete removal of the ≥27wt% clinopyroxene. In the spinel stability field the clinopyroxene abundance should be higher because decomposition of garnet will yield new clinopyroxene (Johnson et al., 1990) and a higher degree of melting would be required for generating harzburgites.

In Fig. 5a–b the addition of orthopyroxene is evidenced by the shifting of peridotite sample points from the melt-residue area toward the orthopyroxene field. In the MgO-SiO₂ co-variation diagram (Fig. 5c), the peridotites form a remarkable SiO₂-enrichment trend. Orthopyroxene-rich peridotites are found in cratonic mantle and active subduction zones (Herzberg, 2004), both of which can be
interpreted as reaction products of residual mantle with a silica-rich melt (Kelemen et al., 1992, 1998). These two types can be distinguished using MgO–FeO T systematics: orthopyroxene-rich cratonic mantle peridotites are FeO-depleted, while modern forearc peridotites with excess orthopyroxene often form FeO enrichment trends (Herzberg, 2004). In this case, the North Hebei peridotites display an FeO-depletion trend (Fig. 5a), suggesting a cratonic mantle origin rather than a modern arc-type origin.

### 5.3 Trace element systematics

The variable enrichment of light to middle REEs of the North Hebei peridotites is indicative of a post-melt depletion alteration event. Mantle metasomatism is common in peridotite xenolith samples which can result in enrichment of the light to middle REEs (e.g., Bodinier et al., 1990; Ionov et al., 2002; Chen et al., 2014). Before the possibility of mantle metasomatism can be discussed however, the influence of serpentinization on the trace element systematics of the North Hebei peridotites must be determined.

Remarkable compositional variations of REEs and trace elements have been reported in modern sea floor abyssal peridotites, which have a predominantly serpentine mineral assemblage. Based on the positive correlation between Th and REE, Niu (2004) and Paulick et al. (2006) suggest that the serpenitized peridotites can preserve their original REE systematics in high T regimes, and therefore the REE patterns can be used to evaluate the extent of mantle melt depletion and melt-peridotite interaction. More recent studies, however, have revealed that LREEs are mobile during interactions between hydrothermal fluids and serpentinites (Allen and Seyfried, 2005; Menzies et al., 1993). Based on a detailed review of global serpentinite geochemical data, Deschamps (2013) suggested that HREEs of serpentinized peridotites are poorly mobile and therefore they can retain the geochemical signature of the original protolith. In light of this we suggest that the highly immobile elements, like Nb, Th and HREEs, may be more reliable than other trace elements when making geochemical inferences about the mantle protolith.

In the Nb-La diagram (Fig. 8a), the North Hebei peridotites plot at the intersection of the fluid/rock and melt/mantle trajectories. This means that the processes that are responsible for the LREE enrichment of the peridotite samples cannot be identified. When the more immobile elements Th, Gd and Lu (Fig. 8b) are used, however, the North Hebei peridotites plot off the fluid/rock trend and close to the melt/mantle interaction trend. This proves that the HREEs were poorly mobile during serpentinization of the peridotites and their signatures have been preserved at high temperatures.

![Fig. 8. Nb-La (a) and Th-Gd/N/LuN(b) diagrams for the North Hebei peridotites, showing comparisons with deviating trends for melt–mantle interaction and hydrothermal fluid/rock interaction.](image)

PM Nb/La ratio is calculated using primitive mantle data from Sun and McDonough (1989). The grey squares are global abyssal peridotites compiled by Niu, (2004). The open squares are serpentites that have experienced fluid/peridotite interaction from Paulick et al. (2006).
In chondrite-normalized rare earth element diagrams (Fig. 6), the HREEs of the peridotites are much lower than PM values with flat to slightly left-dipping distributions. This suggests that the North Hebei peridotites have not experienced melt depletion in the garnet stability field, as existence of garnet in the melting residue would result in an elevation of HREE abundances, as well as a steeply left-dipping HREE distribution (Fig. 6b). Absence of an Eu anomaly also rules out the existence of plagioclase in the mantle source. Following the melt extraction model proposed by Johnson et al. (1990), we estimated that the studied peridotites have experienced melt extraction of more than 25% in the spinel stability field (Fig. 6a), while melting in the garnet stability field cannot match the HREE patterns of any of the samples (Fig. 6b). Although the stability of HREEs during serpentinization cannot be completely guaranteed, this melt extraction rate is consistent with the petrographic observation that clinopyroxene is absent, and major element constraints which show extremely low values of CaO and TiO2.

It should be noted that the starting mantle composition in the REE modelling is fertile primitive mantle (Johnson et al., 1990), and consists of nearly 30% clinopyroxene at spinel and garnet stability pressures (Walter, 1998). For generating MORBs, the depleted mantle source peridotites were estimated to have experienced ~10% (Langmuir et al., 1992) to 15% melting (Niu and Batiza, 1991) at dry condition. A rather lower melting ratio was proposed (<6.5%) by Asimow and Langmuir (2003) when they assume that the solidus of peridotites was "dampened" by H2O in nominally anhydrous minerals. However, the anhydrous solidus used in their parameterization has recently been disproved because earlier partial melting experiments failed to avoid H2O adsorption onto starting materials (Sarafian et al., 2017). Therefore, a 10%–15% melting extent at the mid-ocean ridge area can be assumed.

At subduction zones, the already depleted mantle wedge can be melted by a flux of slab-derived fluids. The melting extent at subduction zones was estimated to be ~10% by different parameterization melting models (e.g., Katz and Langmuir, 2003; Kimura et al., 2014). This means that if the first-stage melt depletion at ridges and second-stage flux melting of highly depleted mantle at subduction zones are combined, a total of 25% melt extraction is reasonable.

5.3 Mantle-derived melts in an arc setting

The magmatic spinels, including chromites, Al-chromites, and picotites, are resistant to weathering and alteration. Their mineral chemical compositions can be used to constrain the composition of their parental magma, which should represent the melt end-member during metasomatic processes. We calculated the Al2O3 and TiO2 composition of melts (Table 3) in equilibrium with chromite spinel using the regressions of Zaccarini et al., (2011), which are:

\[
\begin{align*}
(\text{Al}_2\text{O}_3_{\text{melt}}) &= \frac{5.2253\ln(\text{Al}_2\text{O}_3_{\text{spinel}})}{1.1232} \\
(\text{TiO}_2_{\text{melt}}) &= \frac{1.0897(\text{TiO}_2_{\text{spinel}}) + 0.0892}{1}
\end{align*}
\]

As listed in Table 3, the melts parental to the spinels have Al2O3melt ranging from 9.48wt%–15.07wt%, and TiO2melt ranging from 0.05wt%–0.92wt%, which is similar to that of the Troodos boninites (Cameron et al., 1985; Flower et al., 1987) and Thetford boninites (Page et al., 2008) respectively. This suggests that the North Hebei peridotites have been metasomatized by boninite-like melts.

In the classification diagram proposed by Kamenetsky et al., (2001) (Fig. 9), the spinel compositions of peridotite samples QL02, DYG01, 05LHP02, 05LHP04 and LHPX02 plot in the “arc” and “SSZ peridotite” field, implying a genesis related to subduction. The compositions of samples LHPX01, LHPX02, 05LHP01 and 05LHP02 plot in the “MORB-SSZ peridotite” overlapping area, and spinel sample 05LHP01 plots in the “MORB peridotite” field, suggesting a genesis within the mantle beneath an ocean spreading center.

The silica-rich rocks (ZNP01 and ZNP02) have trace element patterns similar to Archean Whundo-type boninites (Smithies et al., 2004), suggesting a subduction-related origin. It is noted that the boninite-like samples have very high Yb/Sc (Fig. 7b) contrasting to the low Yb/Sc (Fig. 7a) of the peridotites. As Sc is preferentially hosted in mafic minerals (Doe, 1997), the compensative Yb-Sc distributions of the peridotites and the boninitic rocks (Fig. 7a–b) strongly suggest that the silica-rich rocks were originally mantle melts. Kelemen et al., (1998) suggest that subduction-related melts would react with mantle peridotites to produce silica-rich peridotites. The coexistence of peridotites and boninite-like rocks in the
study area indicates that the mantle peridotites have reacted with the boninite-like melts within a subduction-related setting. It is noteworthy that high-Cr spinels and high-Al spinels occur in a same peridotite sample O5LHP02. This may reflect the effect of late stage metasomatism of a peridotite that was located within a fluid-magma-flow channel during the ascent of the subduction-related magma.

5.4 Ages of peridotites based on the Re-Os isotopes

Rhenium depleted model ages (TRD) can provide the minimum constraints on the timing of mantle melt depletion events by assuming that a single melting event removes all of the Re from a peridotite and can therefore “freeze” the evolution of the isotopic composition of the mantle source along a chondritic path prior to that time (Walker et al., 1989; Shirey and Walker, 1998). As listed in Table 1, the peridotites from North Hebei Province have TRD ages ranging from 748 Ma to 2055 Ma, indicating that the peridotites experienced melt depletion during the Precambrian. This age range is too large to represent the timing of one single melt depletion event for the studied peridotites, however these peridotites are unlikely to be the products of several different melt extraction events for the following reasons: Firstly, they have similar normative mineral compositions and similar chemical compositions; secondly, they are found together in a limited outcrop area; and thirdly, the peridotites from North Hebei Province both have >1wt% Al₂O₃ and as such are not highly refractory.

Multi-stage metasomatism, or metasomatism of variable intensity, may be a better explanation of the variable TRD ages of the studied peridotites. Mantle-derived melt can transport several tens of ppt of Os (Shirey and Walker, 1998), and therefore repeated melt input during mantle metasomatism may introduce more radiogenic Os into the peridotites. This would result in the TRD of the metasomatized peridotites to appear younger than the actual melt depletion event, and as a result the oldest TRD (2055 Ma) may reflect the later limit of the melt depletion event.

Rhenium concentrations may be affected by later mantle metasomatism, so an “isochron age” cannot be obtained from the \(^{187}\text{Re}/^{188}\text{Os}-^{187}\text{Os}/^{188}\text{Os}\) plot for the studied peridotites (not shown in this paper). Conveniently, Al is less easily perturbed during metasomatism since Al₂O₃ remains in the peridotite after nearly all of the Re has been removed during partial melting (Reisberg and Lorand, 1995). By using the extrapolation from Al₂O₃(PUM) to a value of 0.7% as suggested by Handler and Bennett (1999), we draw three “proxy isochrones” which intercept the \(^{187}\text{Os}/^{188}\text{Os}\) axis at the values of 0.108, 0.111 and 0.117, corresponding to model ages of 2.7 Ga, 2.4 Ga and 1.4 Ga respectively (Fig. 10). When plotted on an \(\text{Al}_2\text{O}_3-^{187}\text{Os}/^{188}\text{Os}\) diagram, the most refractory (low Al) samples are close to the 2.4 Ga and 2.7 Ga “proxy isochrons”. This suggests that melt extraction may occur around the end of the Neoarchean. The fertile samples have younger proxy model ages of around 1.4 Ga, however this may not represent the actual timing of the mantle melt depletion event because their Al abundance and Os isotopes may have been highly altered during subsequent metasomatic processes.

In summary, Re depleted model ages (TRD) suggest that the peridotites experienced mantle melt depletion during the Precambrian; and Al proxy isochrons suggest minimum melt depletion ages of between 2.4 and 2.7 Ga. The apparently younger model ages of the more fertile peridotites may be the results of later metasomatism.

5.5 A lithospheric mantle and infiltrated melt suite formed in the North Hebei subduction zone

Petrological, geochemical, and mineral composition data suggest that the North Hebei peridotites were originally part of a residual mantle after melting at depth, implying that the peridotite belt from North Hebei Province was once part of the continental lithospheric mantle below the NCC. The peridotites differ from the cratonic mantle as represented by some high Mg² mantle xenoliths (eg. Gao et al., 2002; Chu et al., 2009; Wu et al., 2006; Zhang et al., 2008), however they are similar to the supra-subduction zone peridotite suite in the central orogenic belt of the NCC (Polat et al., 2005). A subduction-related origin is also supported by the coexistence of the boninite-like rocks and the peridotites, with the former having geochemical compositions similar to Archean Whundo-type boninites (Smithies et al., 2004). The peridotites from North Hebei Province do not seem to be a part of the accreted supra-subduction mantle of the central orogen, as they occur along the E-W striking
major fault and coexist with metamorphic lithologies from the Inner Mongolia–North Hebei Orogen near the northern margin of the NCC (Fig. 1a) (Kusky et al., 2007; Zhai and Santosh, 2011). In light of this, we suggest that the peridotites and boninite-like rocks distributed in the North Hebei Province represent part of the lithospheric mantle that was accreted to the NCC during Paleoproterozoic subduction along the North Hebei Orogen.

6 Conclusions

(1) The peridotites from North Hebei Province were originally harzburgites that experienced a high degree of melt extraction and subsequent mantle metasomatism in a subduction zone setting.

(2) Silica-rich samples coexisting with peridotites have protolithic compositions similar to Archean boninites.

(3) Re-Os isotopes of the peridotites yield melt extraction ages between the Late-Achaean to Early Paleoproterozoic.

(4) The peridotite-boninite suite from North Hebei Province may represent accreted continental lithospheric mantle after subduction-related melt extraction and metasomatic processes in the North Hebei Orogen at the northern margin of the NCC.

Acknowledgements

This study was financially supported by the NSFC(grant no. 41430207, 41602340) and China Postdoctoral Science Foundation (2016M591246). Guiming Shu is thanked for assistance on EPMA analysis.

References


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