Oxygen Fugacity Evolution of the Mantle Lithosphere Beneath the North China Craton

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Abstract

Oxygen fugacity controls the behavior of multivalent elements and compositions of C-O-H fluids in Earth's mantle, which further affects the cycling of materials between the deep interior and surface of Earth. The redox state of mantle lithosphere of typical stable cratons has been well documented, but how oxygen fugacity had varied during craton destruction remains unclear. This study estimates the oxygen fugacity of peridotite xenoliths entrained in Mesozoic and Cenozoic basalts on North China Craton (NCC), a typical destroyed craton. The results reveal that the mantle lithosphere beneath the NCC experienced three stages of evolution in terms of oxygen fugacity. First, the refractory and oxidized peridotite xenoliths indicate the lithospheric mantle experienced a high degree of melt extraction and later long-term and complicated metasomatism before craton destruction. Then, the variations of olivine Mg-number in peridotites and oxygen fugacity reveal significant metasomatism by melts originated from the shallow asthenosphere during the destruction of the NCC since the Mesozoic. The third stage may have occurred when mantle peridotites interacted with silica-undersaturated melts stemmed from the mantle transition zone where the stagnant Pacific slab underlies. This study further verifies that the asthenospheric convection induced by the roll-back of the subducted paleo-Pacific slab played a crucial role in the destruction of the NCC and helps understand the oxygen fugacity variability during the later life of the craton.

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Key Words: Oxygen fugacity, Peridotite, Lithospheric mantle, Metasomatism, North China Craton.

Key Points:

- Peridotite xenoliths in Meso-Cenozoic basalts from the North China Craton fall into four groups and record different oxygen fugacities
- The oxygen fugacity variability of the peridotites results from mantle processes associated with the destruction of the North China Craton

Abstract

Oxygen fugacity controls the behavior of multivalent elements and compositions of C-O-H fluids in Earth's mantle, which further affects the cycling of materials between the deep interior and surface of Earth. The redox state of mantle lithosphere of typical stable cratons has been well documented, but how oxygen fugacity had varied during craton destruction remains unclear. This study estimates the oxygen fugacity of peridotite xenoliths entrained in Mesozoic and Cenozoic basalts on North China Craton (NCC), a typical destroyed craton. The results reveal that the mantle lithosphere beneath the NCC experienced three stages of evolution in terms of oxygen fugacity. First, the refractory and oxidized peridotite xenoliths indicate the lithospheric mantle experienced a high degree of melt extraction and later long-term and complicated metasomatism before craton destruction. Then, the variations of olivine Mg-number in peridotites and oxygen fugacity reveal significant metasomatism by melts originated from the shallow asthenosphere during the destruction of the NCC since the Mesozoic. The third stage may have occurred when mantle peridotites interacted with silica-undersaturated melts stemmed from the mantle transition zone where the stagnant Pacific slab underlies. This study further verifies that the asthenospheric convection induced by the roll-back of the subducted paleo-Pacific slab played a crucial role in the destruction of the NCC and helps understand the oxygen fugacity variability during the later life of the craton.

Plain Language Summary

The sub-continental lithospheric mantle is one of the most important reservoirs of carbon. Thus its oxygen fugacity controls the stability of diamond and the compositions of C-O-H fluids. Previous studies have revealed how the oxygen fugacity changes with depth in the upper mantle beneath stable craton. However, cratons are not forever and capable of being destroyed and the North China Craton is one of the most typical destructed cratons globally, as evidenced by extensive magmatism and tectonic deformation since the Mesozoic. The variation of oxygen fugacity during the destruction of the craton, as yet, remains unclear. We estimated the oxygen fugacity of peridotite xenoliths in Mesozoic and Cenozoic basalts on the North China Craton to solve this problem. The oxygen fugacities of the xenoliths record the three-stage evolution of the mantle lithosphere. The evolution process involves complicated secular oxidation before the craton destruction, the widespread reduction by asthenosphere-derived melts, and more oxidized

metasomatism by melts derived from the mantle transition zone, where the subducted Pacific plate is stagnant.

1 Introduction

Oxygen fugacity (f_{O_2}) is a critical parameter that controls the oxidation state of multi-valence elements, such as vanadium, carbon, and iron. (Frost & McCammon, 2008). The variation of f_{O_2} affects the species of C-O-H bearing fluids and melts, which in turn change the solidus and the nature of derived melts (Foley, 2011). For example, as a typical igneous rock that outcropped in stable craton, volatile-rich kimberlites, are generally believed to be the product of interaction between CO_2 and deep upper mantle under an oxidized condition (Sun & Dasgupta, 2020). However, diamond-bearing xenoliths captured by kimberlites imply a reduced background in the lithospheric mantle of the stable craton (Lazarov et al., 2009; McCammon & Kopylova, 2004).

Based on kimberlite-borne peridotite xenoliths, previous studies have established a P-logf_{O_2} profile of stable craton lithospheric mantle (e.g., Creighton et al., 2010; Goncharov et al., 2012; Lazarov et al., 2009). On the one hand, the oxygen fugacity decreases with increasing pressure, proving that diamond is stable in the lower lithospheric mantle (e.g., Creighton et al., 2010; Goncharov et al., 2012; Lazarov et al., 2009). On the other hand, the oxygen fugacity of the stable craton is higher than the ambient asthenosphere, suggesting that oxidized metasomatism may have also influenced the stable craton (Creighton et al., 2009; Foley, 2011).

However, cratons are not forever and capable of being destroyed. The North China craton (NCC) is one of the typical destroyed cratons, as evidenced by extensive magmatism, deformation, and metamorphic core complex during Meso-Cenozoic (Wu et al., 2019). Although numerous studies have been carried out to understand this catastrophic change, the exact cause and detailed mechanism leading to the craton destruction is still hotly debated. Primarily, few investigations are from a perspective of mantle redox state. So, it is valuable to figure out the redox state of the upper mantle beneath the NCC at different geological times, how oxygen fugacity varied and clues that f_{O_2} of peridotite xenoliths bears to unravel the geological processes during the craton destruction.

This paper collects numerous published geochemical data of peridotite xenoliths entrained in Mesozoic and Cenozoic basalts on North China Craton (NCC) and estimates their oxygen fugacity. The yielded data reveal the redox state of the mantle lithosphere beneath the NCC and how it has changed during the craton destruction and factors affecting such variations.

2 Geological Setting

The NCC is one of the oldest cratons in the world with Archean crustal remnants as old as 3.8 Ga (Liu et al., 1992). It can be divided into the Eastern Block, the Trans-North China Orogen (TNCO), and the Western Block based on geology, tectonic evolution, and P–T–t paths of metamorphic basement rocks (Figure 1) (Zhao et al., 2005). It is generally reckoned that the Eastern and Western blocks evolved independently from late Archean to early Paleoproterozoic times before colliding into a coherent craton and final cratonization along the Trans-North China Orogen belt at ca. 1.85 Ga (Zhao et al., 2005). Since then, the NCC had essentially remained stable until the Mesozoic.

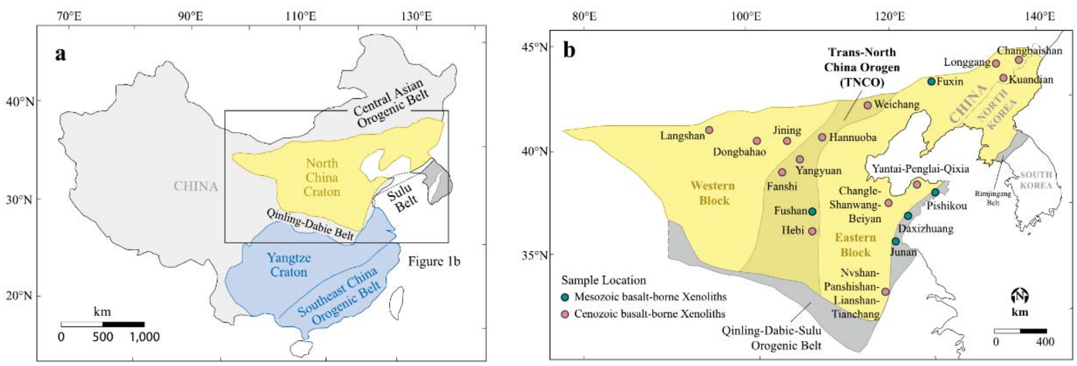

Figure 1. (a) Tectonic subdivision of the Chinese continent and the location of the NCC (modified after Wu et al., 2019). (b) Schematic geological map of the NCC, showing the three-fold tectonic subdivision (modified after Wu et al., 2019) and the localities of peridotites xenoliths entrained by Mesozoic and Cenozoic mafic rocks.

Since the Mesozoic, deformation and extensive magmatism triggered by circum-craton subduction suggest the NCC, except the Western Block, has lost its stability (Wu et al., 2019). From the view of peridotite xenoliths, the thick refractory lithospheric keel was removed and replaced by fertile peridotites (Zheng et al., 2012). Meanwhile, the geotherm of the lithosphere underneath the eastern part of the NCC soared from 40 mW/m2 in Paleozoic to >80 mW/m^2 in Mesozoic (Menzies & Xu, 1998). Likewise, geophysical imagining verifies that the thickness of the lithosphere of the Eastern Block is drastically thinned to about 70-80 km from greater than

200 km in Paleozoic. In contrast, the Western Block keeps almost intact (Chen et al., 2009). Accompanied by the NCC destruction are the widespread Meso-Cenozoic basaltic rocks, especially in the Eastern Block and the TNCO, which captured a large amount of mantle peridotite xenoliths. Previous investigations on these xenoliths have yielded an enormous amount of geochemical data, making it possible to draw a whole picture of the redox state of the mantle lithosphere beneath the NCC.

3 Data, or a descriptive heading about data

Thanks to previous studies, ample mineral compositions of peridotite xenoliths entrained in both Mesozoic and Cenozoic basalts are available to date, which gives us an excellent chance to do the research comprehensively. All the available peridotite xenoliths captured by basalts of different ages and locations are all compiled in Figure 1. After collecting 605 peridotite xenoliths, we estimate each sample’s equilibrium temperature and oxygen fugacity before performing subsequent statistical analysis. The reference of each sample is listed in Text S1.

The abovementioned peridotite xenoliths are mainly harzburgite and lherzolite, with a few amounts of wehrlite (Figure 2). We divide them into four groups based on the modal abundance and the Mg-number of olivine. The first group consists of Fushan, Hebi, and other localities from the Western Block of the NCC. The first group consists of Fushan, Hebi, and other localities from the Western Block of the NCC. The first-group xenoliths likely represent the relics of the Archean mantle due to their high olivine modal abundance and Mg-number (Figure 3a), and the Archean ages revealed by osmium isotope (Liu et al., 2011; Xu et al., 2010; Zheng et al., 2001). Geophysical imaging has demonstrated that the lithosphere of the Western Block underwent insignificant thinning (Chen et al., 2009). Therefore, peridotites xenoliths from the Western Block can also represent the ancient lithospheric mantle. However, the mineral modal abundance and chemical composition are somewhat different from those of Fushan and Hebi. The second group of xenoliths are relatively high in olivine modal abundance and Mg-number and fall into the Proterozoic field (Figure 3b). Thus, we name them “High-Mg Peridotites”. The third group samples belong to “Low-Mg Peridotites” due to their lower modal abundance and Mg-number of olivine relative to the High-Mg ones. They follow the oceanic trend proposed by Boyd (1989) and dominantly fall into the Phanerozoic field (Figure 3c). As for the fourth group, the Mg-number of olivine is lower than 88, with the lowest value being as low as 80 (Figure 3d), which differs sharply from that of the sub-continental lithospheric mantle (Griffin et al., 1999). Hence, we call them "Anomalously Low-Mg Peridotite". Among these xenoliths, "Low-Mg Peridotites" and "High-Mg Peridotites" dominate our samples (~53% and ~28% respectively), while the first group and the fourth group take ~12% and 7% of the samples, respectively. We perform discriminant analysis for those without published modal abundance data to judge whether they belong to the "High-Mg" or "Low-Mg". In our case, the Mg-number of olivine equal to 90.5 as the group discrimination criteria is feasible. The peridotites whose olivine have Mg-number higher than 90.5 belong to "High-Mg Peridotites". In contrast, those with olivine Mg-number between 88~90.5 belong to "Low-Mg Peridotites".

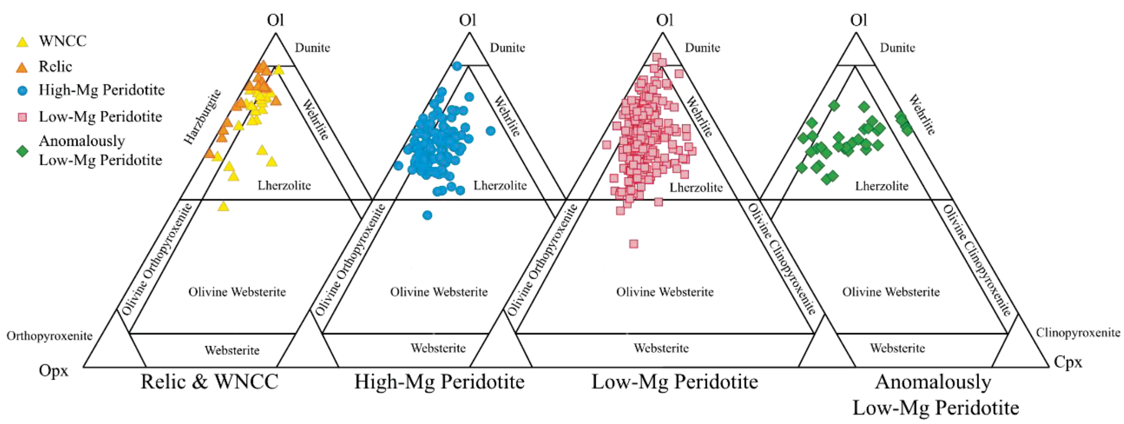

Figure 2. Petrological classification for peridotite xenoliths from the North China Craton (The detailed data are listed in **Table S1**). The brown and yellow triangle, circle, square, and diamond symbols represent the relics and those from the western NCC (WNCC), high-Mg, low-Mg, and anomalously low-Mg samples, respectively. The scheme for grouping is based on the Mg-number and modal abundance of olivine in each sample. Samples having olivine less than 50% are excluded.

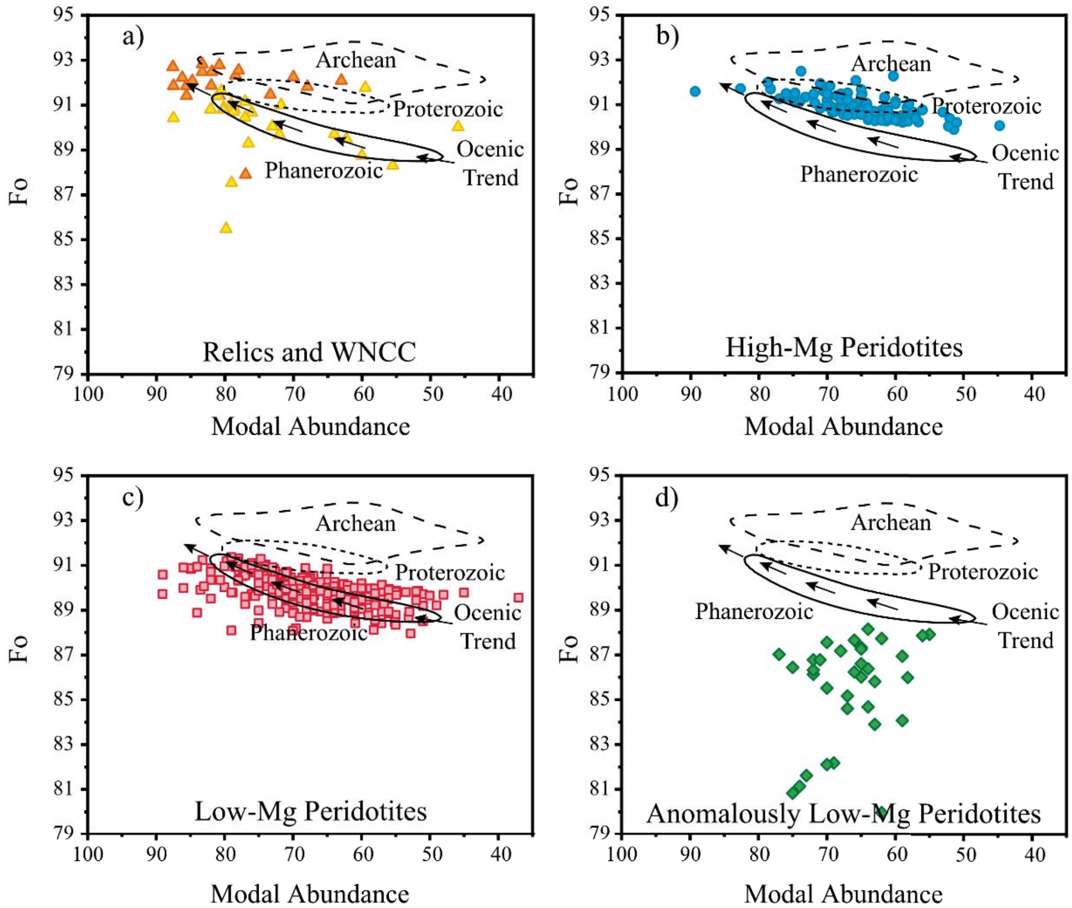

Figure 3. Olivine Mg-number vs. modal abundance for peridotite xenoliths from the North China Craton (The detailed data are listed in **Table S1**). The oceanic trend is after Boyd (1989). The Archean, Proterozoic, and Phanerozoic fields are from Griffin et al. (1999). Symbols are the same as in Figure 2.

4 Methods and Results

Since all samples compiled are spinel-facies peridotites, there are no suitable geobarometers that can be used to yield reasonable pressure estimation to date. Therefore, we assume an equilibrium pressure of 1.5 GPa for subsequent calculations of temperature and oxygen fugacity.

4.1 Equilibrium Temperature

Many geothermometers have been calibrated to date, but not all are applicable in our study, primarily because lacking raw data for the calculation of key parameters. Therefore, we choose the two-pyroxene thermometers (Brey & Kohler, 1990; Taylor, 1998) or the enstatite-in-Cpx thermometer (Nimis & Taylor, 2000) to estimate the equilibrium temperatures of these xenoliths. For samples that are Cpx-poor or devoid of chemical compositions of Cpx, their equilibrium temperatures are calculated based on the Ol-Sp thermometer (Coogan et al., 2014).

As all above mentioned pyroxene-related thermometers are developed based on the similar enstatite-exchange between Opx and Cpx (Nimis & Gruetter, 2010), they yield nearly consistent outcomes within errors (Table S2). By contrast, the Ol-Sp thermometer usually gives slightly higher temperatures (Table S2).

The statistical results show that no matter where the peridotites are from or which group the xenoliths belong to, they all have similar temperatures (Table 1). Compared with those from the other tectonic units of the NCC, peridotites from the Trans-North China Orogen (TNCO) appear more homogeneous in temperature. Furthermore, if we project the average temperature to the geotherm of North China Craton in Mesozoic (> 80mW/m^2), an estimation of ~1.5 GPa can be inferred, confirming the reasonability of our assumption of an equilibrium pressure of 1.5 GPa for these xenoliths.

4.2 Oxygen Fugacity

Oxygen fugacity of spinel-facies peridotites is recorded by the thermodynamic equilibrium of Olivine-Orthopyroxene-Spinel assemblages (O'Neill & Wall, 1987):

$$\underset{Ol}{6Fe_2SiO_4} + O_2 \leftrightarrow \underset{Opx}{3Fe_2Si_2O_6} + \underset{Sp}{2Fe_3O_4} \quad (1)$$

Previous experiments have proposed two types of oxybarometers, one of which relies on the activity of Fe_3O_4 (e.g., Davis et al., 2017; Mattioli & Wood, 1988) and another requires $Fe^{3+}/\sum Fe$ by calculation assuming perfect stoichiometry (Ballhaus et al., 1991). Compared with the former equation, the advantage of the latter is that it directly links f_{O_2} to mineral compositions analyzed by EPMA, especially when Mössbauer spectroscopy is unavailable, and thus avoids correction of spinel and errors introduced during the calculating activity of magnetite end-member. Therefore, we choose the equation proposed by Ballhaus et al. (1991) to estimate the f_{O_2}.

The calculated oxygen fugacities of the peridotite xenoliths are shown in Figure 4 and Table 2 and S2. The Ni precipitation curve reaches nearly FMQ-4 under 1.5 GPa (Frost & McCammon, 2008; O'Neill & Wall, 1987), implying the appearance of Ni-bearing peridotite. Nevertheless, no Ni-bearing peridotites are reported on the NCC yet. Therefore, samples with f_{O_2} lower than FMQ-4 are excluded for further discussion. The results show that for peridotites falling into SCLM fields, f_{O_2} decreases along with lowering Mg-number (Figure 4). However, the "Anomalously Low-Mg Peridotites" have relatively higher f_{O_2}, which is between the "High-Mg Peridotites" and peridotites being regarded as Archean relics and from the Western Block (Figure 4).

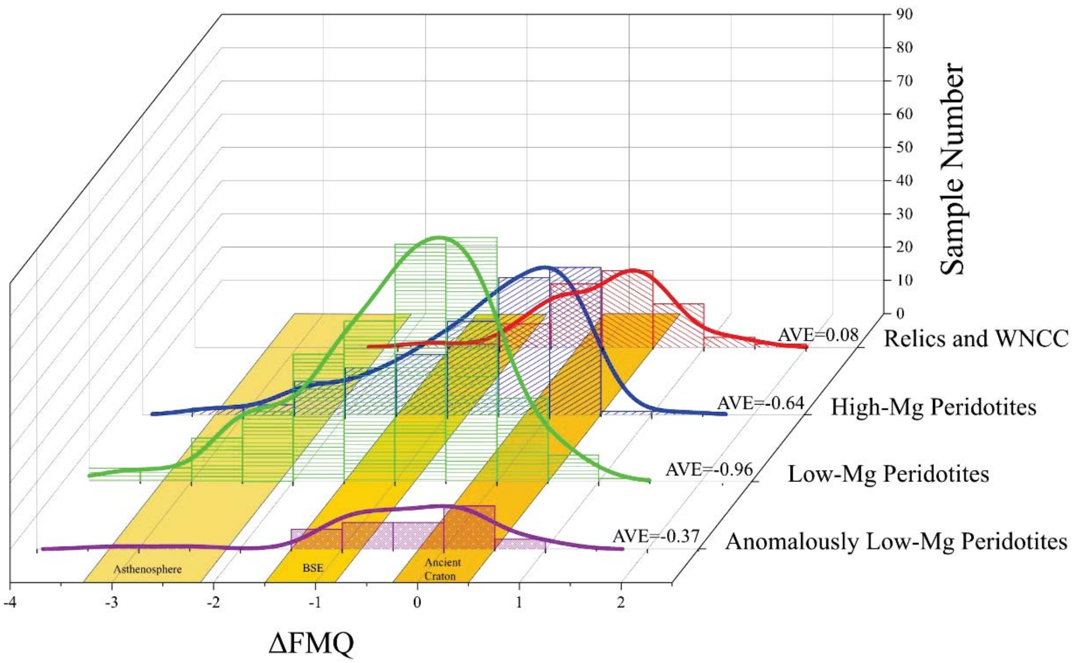

Figure 4. The oxygen fugacity of peridotites from the North China Craton. The grouping scheme follows that in Figure 3. The data of each group shows in the form of the histogram and corresponding kernel density estimation (**the detailed data are listed in Table S2**). The oxygen fugacity of the ancient craton is extrapolated from other stable cratons (Slave Craton: Creighton et al., 2010, McCammon and Kopylova, 2004; Siberia Craton: Goncharov et al., 2012, Yaxley et al., 2012; Kaapvaal Craton: Lazarov et al., 2009, Woodland and Koch, 2003) to 1~2 Gpa, under which only spinel-facies peridotites are stable. The oxygen fugacity between 1~2 GPa of the Bulk Silicate Earth (BSE) mantle is calculated via methods proposed by Stagno et al. (2013). As the Fe_2O_3 content of the asthenosphere ranges between 0.3 and 0.5 wt% (Cottrell & Kelley, 2011;

Sorbadere et al., 2018) and the primary melts record the same f_{O_2} to the equilibrated residues (Birner et al., 2018; Davis & Cottrell, 2018), we estimate the oxygen fugacity of hypothetical melts identical to the composition of the asthenosphere under 1~2 GPa and 950 °C. The average oxygen fugacity of the normal mantle decreases with decreasing Mg-number of olivine. However, the anomalously low-Mg peridotites are slightly more oxidized than the high-Mg and low-Mg ones.

Table 1. Temperature estimations for peridotites from the North China Craton (the detailed data are listed in **Table S2**)

Group	Archean relics (n=47)	WNCC (n=21)	High-Mg			Low-Mg			Anomalously Low-Mg		
			TNCO (n=82)	ENCC (n=80)	Total (n=162)	TNCO (n=101)	ENCC (n=205)	Total (n=306)	TNCO (n=10)	ENCC (n=30)	Total (n=40)
Temperature (°C)	951.68	882.43	973.93	923.93	949.24	952.73	939.05	943.56	1031.69	948.36	969.19
S.D.	150.52	109.00	86.62	132.25	114.28	84.74	127.66	115.45	74.44	108.37	107.22

Table 2. Oxygen fugacity estimations for peridotites from the North China Craton (the detailed data are listed in **Table S2**)

Group	Archean relics (n=47)	WNCC (n=21)	High-Mg			Low-Mg			Anomalously Low-Mg		
			TNCO (n=82)	ENCC (n=80)	Total (n=162)	TNCO (n=101)	ENCC (n=205)	Total (n=306)	TNCO (n=10)	ENCC (n=30)	Total (n=40)
ΔFMQ	0.13	-0.07	-0.61	-0.67	-0.64	-1.01	-0.93	-0.96	-0.17	-0.43	-0.37
S.D.	0.59	0.64	0.83	0.91	0.87	0.93	0.89	0.90	0.87	0.77	0.80

5 Discussion

5.1 Oxygen fugacity of cratonic mantle

Before discussing how f_{O_2} of lithospheric mantle evolved during craton destruction, it is crucial to test if the peridotites of Archean relics and those from the Western Block can be treated as starting points, namely, whether their f_{O_2} resemble that of typical stable cratonic mantle lithosphere. As previous studies mainly focused on kimberlite-borne garnet-facies peridotites rather than spinel-facies ones (e.g., Lazarov et al., 2009; Woodland & Koch, 2003; Yaxley et al., 2012), to extrapolate P- logf_{O_2} curves to 1~2 Gpa, under which spinel-facies peridotites are stable (e.g., Till et al., 2012; Ziberna et al., 2013) is a prerequisite. In theory, when coexisting spinel and garnet reach thermodynamic equilibrium, they record consistent oxygen fugacity (Miller et al., 2016). Besides, studies of Siberia Craton also support that pressure and f_{O_2} of spinel-facies and garnet-facies peridotites fit well in the same curve (Goncharov et al., 2012). McCammon and Kopylova (2004) found more reduced spinel peridotites that deviate from the P-logf_{O_2} curve in Slave Craton. Notwithstanding, this is usually interpreted to be the result of a high degree of depletion. Therefore, the extrapolation of f_{O_2} of mantle lithosphere from garnet to spinel facies is reasonable and appropriate.

Extrapolation of P-logf_{O_2} that combined data from Slave Craton, Siberia Craton, and Kaapvaal Craton follows the equation (Figure 5):

$$\Delta FMQ=1.37-0.86*P \qquad (2)$$

The gradient of the P-logf_{O_2} is similar to those reported in previous studies (Slave Craton: -0.59 log/GPa, McCammon and Kopylova, 2004; Siberia Craton: -0.83 log/GPa, Goncharov et al., 2012; -1.0 log/GPa, Yaxley et al., 2012; Kaapvaal Craton: -1.0 log/GPa, Lazarov et al., 2009; and -0.86 log/GPa, Woodland and Koch, 2003). Under 1~2 GPa, the extrapolation of stable cratons' P-logf_{O_2} curve is nearly consistent with the oxygen fugacity of the first group samples, which represent relics of the Archean lithospheric mantle (Figure 4). Thus, we propose that peridotites of the first group reflect the redox state of the mantle lithosphere before the destruction of the NCC. Furthermore, similar to typical stable craton around the world, peridotites from the first group have higher f_{O_2}, which could be the outcome of oxidized, sometimes multi-stage metasomatism, as evidenced by trace elements and in-situ Sr isotope of clinopyroxene (Creighton et al., 2010; Creighton et al., 2009; Dai et al., 2019; Wu et al., 2017; Xu et al., 2010; Zheng et al., 2001).

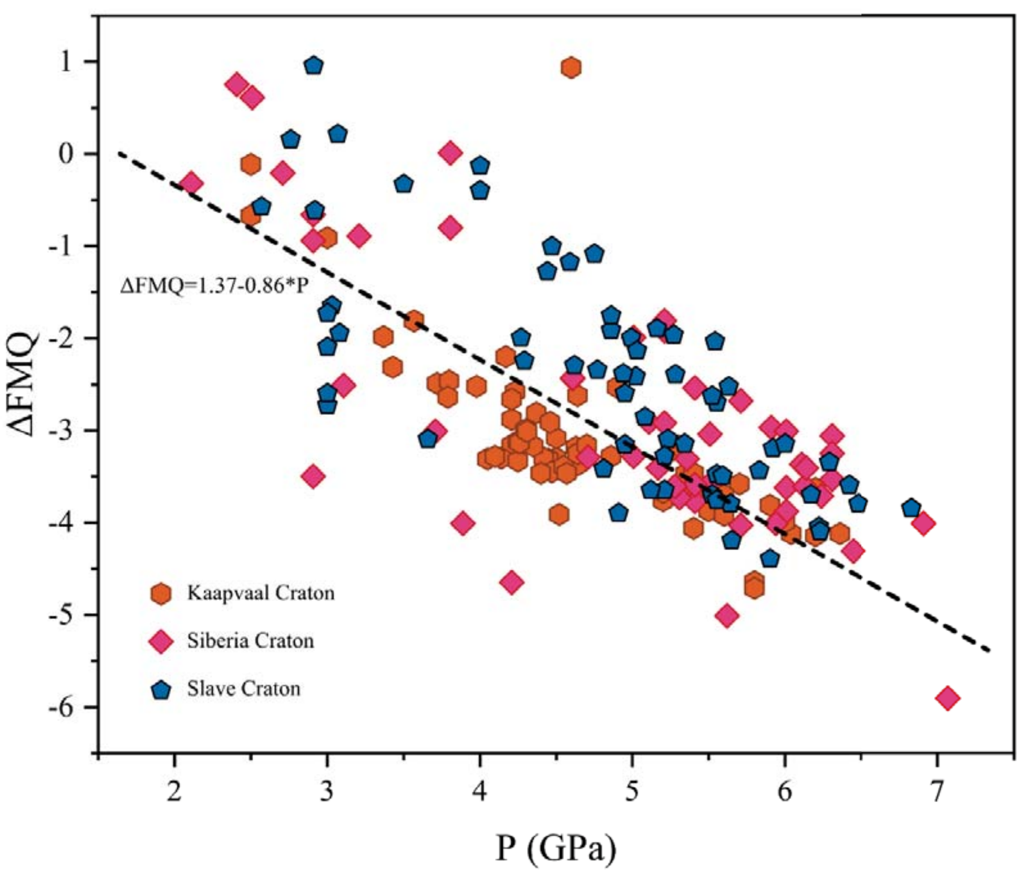

Figure 5. Correlation between the oxygen fugacity and equilibrium pressure of peridotites from Kaapvaal Craton, Siberia Craton, and Slave Craton. The dashed line fitting these data serves for the oxygen fugacity extrapolation from garnet facies to spinel facies mantle. Data source: Kaapvaal Craton: Lazarov et al. (2009), Woodland and Koch (2003); Siberia Craton: Goncharov et al. (2012), Yaxley et al. (2012); Slave Craton: Creighton et al. (2010), McCammon and Kopylova (2004) (the detailed data are listed in **Table S3**).

5.2 Variation of oxygen fugacity during craton destruction

Craton destruction resulted from the removal or replacement of the ancient refractory lithospheric keels by fertile materials (Tang et al., 2008; Xiao et al., 2010; Ying et al., 2006), which is also clearly demonstrated by our observation as more than 50% of samples fall into Phanerozoic fields (Figure 3). Along with craton destruction, the oxygen fugacity of peridotites tends to be more reduced (Figure 4). Potential mechanisms leading to the reduction of lithospheric mantle include: 1) a higher degree of melt extraction (Gaillard et al., 2015), 2) metasomatism by reduced fluids (Griffin et al., 2018), and 3) metasomatism by reduced melts (Creighton et al., 2010; Goncharov et al., 2012).

In theory, the higher degree of melt extraction the mantle peridotites suffer, the lower $\boldsymbol{f_{O_2}}$ the peridotite residues will record (Gaillard et al., 2015). However, the studied samples with a lower degree of melt extraction, as reflected by low Mg-numbers, commonly have lower oxygen fugacity (Figure 4), indicating that partial melting cannot account for the reduction during craton destruction.

When reduced fluids (mainly CH_4+H_2O) interact with the ambient mantle, methane can be oxidized to diamond (e.g., Smit et al., 2016; Thomassot et al., 2007), and the lithospheric mantle will get reduced correspondingly (Griffin et al., 2018). However, three lines of evidence argue against that CH_4+H_2O fluids reduced the mantle lithosphere underneath the NCC. First, under the circumstance of ~950 °C and 1.5 GPa, only when $\boldsymbol{f_{O_2}}$ is lower than FMQ-3.25, the dominant species in the fluids is CH_4 (Figure 6). By contrast, the $\boldsymbol{f_{O_2}}$ of most peridotites from the NCC are above FMQ-2 with only minor equilibrating with CH_4-dominated fluids (Figure 4). Furthermore, if fluids and peridotites had reached an equilibrium, what can be predicted is that the proportion of water caused by the oxidation of methane will increase with increasing $\boldsymbol{f_{O_2}}$, which will likely lead to an increase of water content in peridotite. However, no such correlation exists in our dataset (Figure 7). Moreover, the interaction of the mantle peridotites with reduced fluids would produce materials that reflect reduced conditions, such as diamond, SiC, and metal-alloy (Griffin et al., 2018). However, no such materials havebeen reported yet in peridotites entrained by Mesozoic and Cenozoic mafic rocks. Therefore, we argue that reduced fluids are highly unlikely to be the primary driving force reducing the mantle.

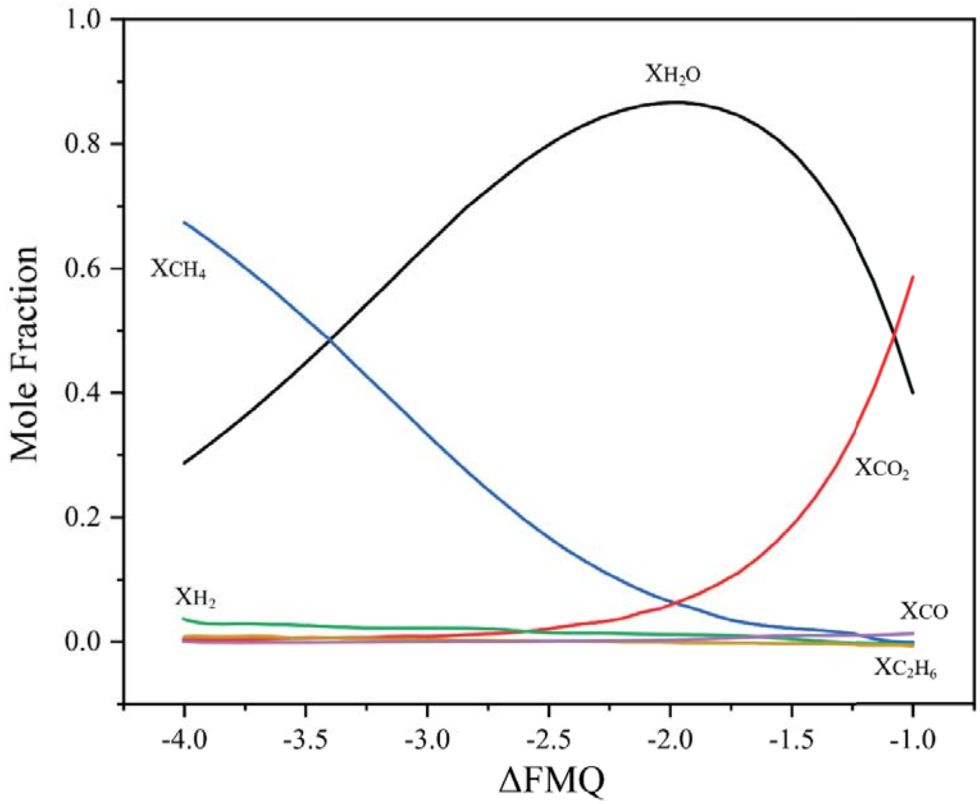

Figure 6. Variation of fluids species vs. oxygen fugacity under 950 °C and 1.5 GPa. The composition of fluids is calculated via GFluid (Zhang & Duan, 2009, 2010; The detailed data are listed in **Table S4**). The proportion of CH_4 increases with decreasing f_{O_2}, while CO_2 decreases with decreasing f_{O_2}. With lowering f_{O_2}, the proportion of H_2O rises and reaches the peak at ΔFMQ=-2 at first and then declines. When f_{O_2} reaches ΔFMQ=-3.46, the fractions of CH_4 and H_2O are identical. Other minor species (H_2, CO, and C_2H_6) show negligible variation.

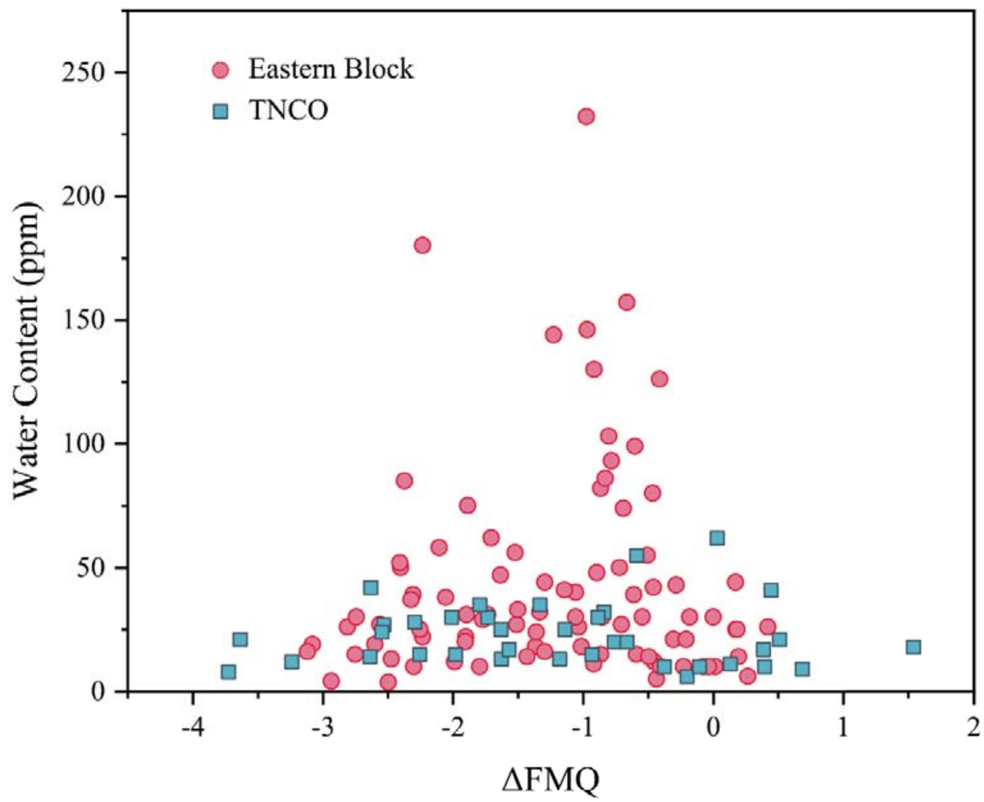

Figure 7. Whole-rock water content vs. the oxygen fugacity of peridotite from the North China Craton. Both peridotites from the Trans-North China Orogen (TNCO) and the Eastern Block (EB) show no correlation between water content and f_{O_2}. Data source: Hao et al. (2016), Li et al. (2015), Wang et al. (2014), Xia et al. (2010), Xia et al. (2013), Yang et al. (2008). The detailed data are listed in **Table S5.**

5.3 Origin of the Anomalously Low-Mg Peridotite

Some samples from Yangyuan, Beiyan, Fuxin, Daxizhuang, and Longgang have very low Mg-number (generally lower than 88), inconsistent with a typical craton mantle. They are higher in $\boldsymbol{f_{O_2}}$ than all other peridotites but those of the first group (Figure 4). Therefore, an alternative process rather than metasomatism by asthenospheric materials is required to account for this anomaly.

Wehrlite and Cpx-rich lherzolite are preponderant in the Anomalously Low-Mg Peridotite group (Figure 2). Two modes of origin have been proposed for wehrlite, including mafic-ultramafic cumulate (e.g., Mattielli et al., 1996) and product of metasomatism (e.g., Gervasoni et al., 2017; Ionov et al., 2005). The wehrlite studied here cannot be mafic-ultramafic cumulate because they have no cumulate texture. Experiments have demonstrated that Opx-poor lherzolite and wehrlite could result from the interaction between rock and silica-undersaturated basaltic melts or silicate-carbonate melts. The peridotite-melt reaction could dissolve orthopyroxene while generating olivine and clinopyroxene (Gervasoni et al., 2017; Kelemen et al., 1990). This interpretation is reasonable because silica-undersaturated alkali basalts, which are also oxidized, outcrop extensively on the NCC after ~100 Ma (Hong et al., 2020; Li et al., 2017). More convincingly, Zhang et al. (2007) reported a hand-specimen scale phenomenon that a wehrlite rim formed between a lherzolite and its host alkali basalt. Therefore, the metasomatism of silica-undersaturated melts could lower the Mg-number but raise the oxygen fugacity of the peridotites.

5.4 Tectonics implication

Peridotites have weak buffer capacity, implying their oxygen fugacity is easily reset and thus only record the influence of the last metasomatism (Luth & Stachel, 2014). From the view of $\boldsymbol{f_{O_2}}$, different groups of spinel-facies peridotites from the NCC jointly record multi-stage metasomatism during its evolution.

The first stage of evolution (Figure 8a), corresponding to the time period since the final cratonization of the NCC and before the craton destruction, is recorded by the first group of peridotites. Their higher Mg-number of olivine and $\boldsymbol{f_{O_2}}$ are similar to those of typical stable craton (Goncharov et al., 2012), implying a high degree of melt extraction and subsequent oxidized metasomatism by fluids or melts that might be released during the amalgamation of the Eastern and Western Block at ca. 1.85 Ga.

The second stage of evolution is craton destruction (Figure 8b~e). The relics, High-Mg, and Low-Mg peridotites, primarily record the interaction between the asthenosphere and shallow craton lithospheric mantle, with minor direct accretion of the asthenosphere. Multiple subductions, especially the Paleo-Pacific subduction and subsequent slab roll-back, eroded the above lithosphere, facilitating upwelling melts' infiltration and creating chemically weak zones (Foley, 2008; Wu et al., 2019). In addition, the Tan-Lu fault zone, a lithosphere deep fault, also facilitates the development of a physically weak zone (Xiao et al., 2010). Therefore, along with the slab roll-back, the asthenosphere laterally convected to the base of the lithosphere and then infiltrated and interacted with the shallow lithospheric mantle (Zheng et al., 2018), resulting in the observed trend that f_{O_2} decreases with decreasing Mg-number of olivine. The ancient lithospheric mantle loses its stability after being eroded or even dismembered by the asthenosphere, which led to the destruction of the NCC.

The third stage of evolution is not a ubiquitous phenomenon and probably a locally occurred process (Figure 8e). The lowering of Mg-number of olivine with increasing f_{O_2} is likely attributed to the metasomatism by silica-undersaturated basaltic melts. Silica-undersaturated basaltic melts that host and interact with xenoliths could originate from the deep upper mantle metasomatized by melts from the stagnant Pacific slab (Xu et al., 2018). The asthenosphere was involved in the metasomatism of both the second and the third stages. However, the source depth of the metasomatic agents ultimately determined the different outcomes. The shallow asthenosphere could not have been oxidized by melts derived from the stagnant slabs, whereas the deep part has. This phenomenon justifies the mantle lithosphere's vertical heterogeneity (Xu et al., 2018). Moreover, the f_{O_2} profile of a reduced shallow and an oxidized deep upper mantle of the NCC is in sharp contrast to typical stable cratons.

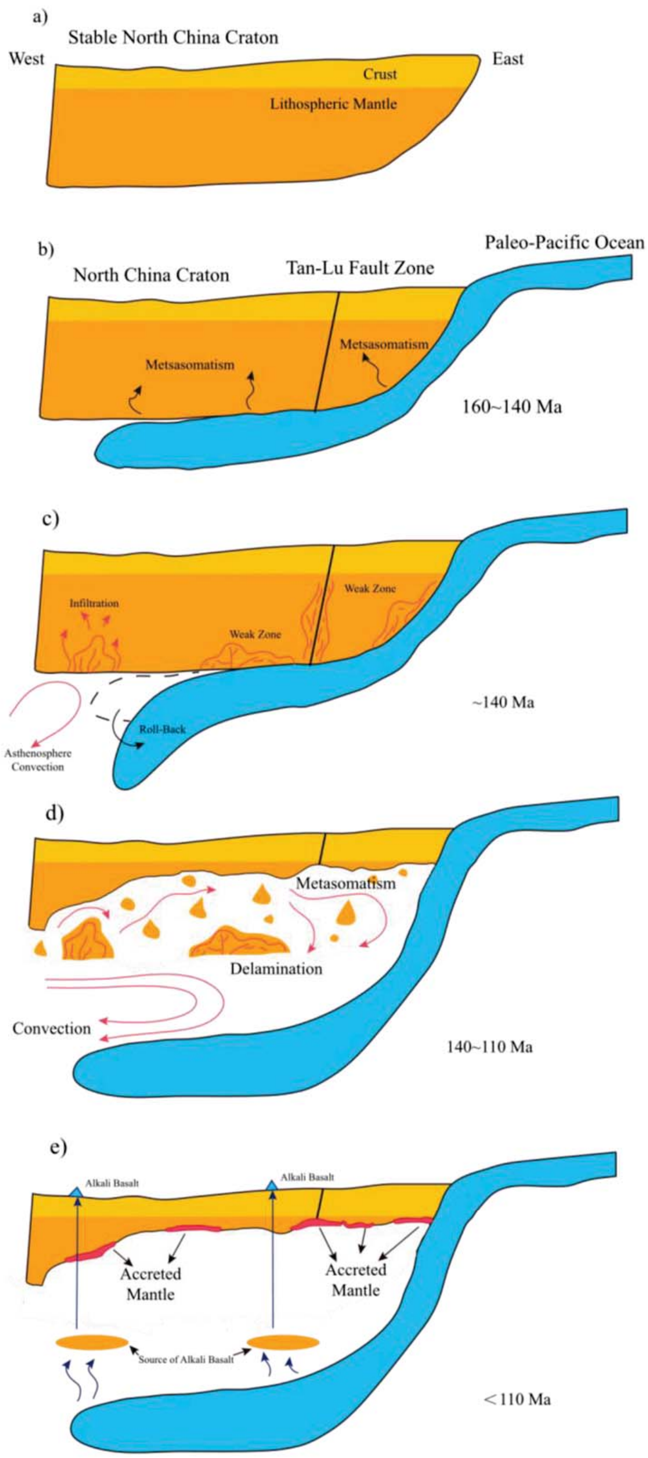

Figure 8. Schematic tectonic evolution of the North China Craton (not in scale). (a) Fluids and melts derived from adjacent plates oxidized the NCC lithospheric mantle before craton destruction. (b) Fluids released by flat subduction of the Paleo-Pacific metasomatized and weakened the lithospheric mantle. (c) The subducted plate rolled

back, inducing mantle convection, and weak zones facilitated the infiltration of the asthenospheric melts. (d) Intensive asthenosphere convection dismembered the lithospheric mantle with erosion and local delamination. (e) Metasomatism of asthenosphere-derived melt lowered the oxygen fugacity of the mantle lithosphere, associated with minor accretion. During the Cenozoic, silica-unsaturated melts from the mantle metasomatized by stagnant slab interacted with xenoliths, forming the Cpx-rich lherzolites and wehrlites.

6 Conclusions

1. Peridotite xenoliths captured by Meso-Cenozoic basalts on the NCC record the variation of oxygen fugacities in the mantle lithosphere beneath the destroyed craton.

2. Peridotite xenoliths from the Western Block of the NCC are relics of the Archean mantle and representative of the mantle lithosphere before the craton destruction. Their high $\boldsymbol{f_{O_2}}$ could result from the long-term and complicated metasomatism since its cratonization and before the craton destruction.

3. A trend displayed by the majority of peridotite xenoliths of lowering $\boldsymbol{f_{O_2}}$ with decreasing Mg-number of olivine might have resulted from extensive metasomatism by melts derived from shallow asthenosphere, rather than melt extraction or metasomatism by reduced fluids.

4. The Anomalously Low-Mg Peridotites exhibit higher $\boldsymbol{f_{O_2}}$ relative to those of the Low-Mg Peridotites, suggesting that the former are probably the products of metasomatism by silica-undersaturated basaltic melts derived from deep asthenosphere, impinged by melts from the stagnant Pacific slab.

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the cited references, tables, and supporting information. These data are also accessible in Mendeley data https://data.mendeley.com/datasets/k5nvgspkmf/draft?a=3863ec55-0280-49f0-9f39-8b5d2c2e7fd9.Any real or perceived financial conflicts of interests for any author

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Supporting Information for

Oxygen fugacity evolution of the mantle lithosphere beneath the North China craton

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Additional Supporting Information (Files uploaded separately)

Introduction

This supporting information contains specific references of our research (Text S1) and histograms that show the modeled partial melting degree the Low-Mg peridotites had experienced (Figure S1). The detailed major elemental compositions for peridotite minerals (Ol, Opx, Cpx, and Sp) are listed in Dataset S1. Tables S1 to S7 compile the data for Figure 2 to 7 in the main text.

Text S1. References of peridotites referred in this study

Location (Sample Number)	Age[1](Ma)	Reference
Trans-North China Orogen		
Hannuoba (n=53)	27~14 Ma	Chen et al. (2001)
		Hu et al. (2016)
		Liu et al. (2011)
		Rudnick et al. (2004)
		Tang et al. (2007)
		Wang et al. (2014)
		Yang et al. (2008)
		Zhao et al. (2010)
Yangyuan (n=94)	35~30 Ma	Hao et al. (2012)
		Liu et al. (2011)
		Liu et al. (2012)
		Wang et al. (2014)
		Wang et al. (2019)
		Xia et al. (2013)
		Yang et al. (2018)
		Zhao et al. (2015)
Datong (n=5)	~1 Ma	Liu et al. (2011)
Fanshi (n=37)	~25 Ma	Liu et al. (2011)
		Tang et al. (2008)
		Xia et al. (2013)
Hebi (n=35)	~4 Ma	Liu et al. (2011)
		Wang et al. (2014)
		Xia et al. (2010)
		Zhao et al. (2010)
		Zheng et al. (2001)
Fushan (n=10)	~125 Ma	Liu et al. (2011)
		Xu et al. (2010)
Weichang (n=12)	23~5.2 Ma	Zou et al. (2016)
Northeast China		
Longgang (n=17)	0.68~0.05 Ma	Chen et al. (2003)
		Tang et al. (2012)
		Xu et al. (2019)
Kuandian (n=10)	~0.6 Ma	Wu et al. (2006)
Changbaishan (n=12)	19.9~2.6 Ma	Xu et al. (2019)
Fuxin	~100 Ma	Zheng et al. (2007)

(n=25)		Zou et al. (2020)

Shandong-Talu Fault Zone

Penglai (n=20)	~8 Ma	Chu et al. (2009)
		Xia et al. (2010)
Shanwang (n=33)	~16 Ma	Chu et al. (2009)
		Zheng et al. (1998)
		Zheng et al. (2006)
Changle (n=24)	18~9 Ma	Deng et al. (2017)
		Xia et al. (2010)
Yantai (n=11)	~7.4 Ma	Hong et al. (2012)
Tianchang (n=15)	~9 Ma	Hao et al. (2016)
Junan (n=22)	~67 Ma	Li et al. (2015)
		Ying et al. (2006)
Daxizhuang (n=19)	~74 Ma	Li et al. (2015)
		Zhang et al. (2007)
		Zhao et al. (2020)
Pishikou (n=28)	~82 Ma	Li et al. (2015)
		Zhang et al. (2011)
Qixia (n=25)	~6 Ma	Rudnick et al. (2004)
		Xia et al. (2010)
		Zheng et al. (1998)
Nvshan (n=23)	~2 Ma	Wang et al. (2014)
		Xu et al. (2004)
		Yang et al. (2008)
Panshishan (n=10)	~9 Ma	Xia et al. (2010)
Lianshan (n=15)	~9 Ma	Xia et al. (2010)
Fangshan (n=13)	~9 Ma	Xia et al. (2010)
Beiyan (n=22)	18.8~10.8 Ma	Xiao et al. (2010)

Western North china Craton

Langshan (n=7)	~89 Ma	Dai et al. (2019)
Jining (n=11)	~32 Ma	Liu et al. (2011)
Dongbahao (n=6)	23.54~20.24 Ma	Wu et al. (2017)

[1] The age of the host rocks

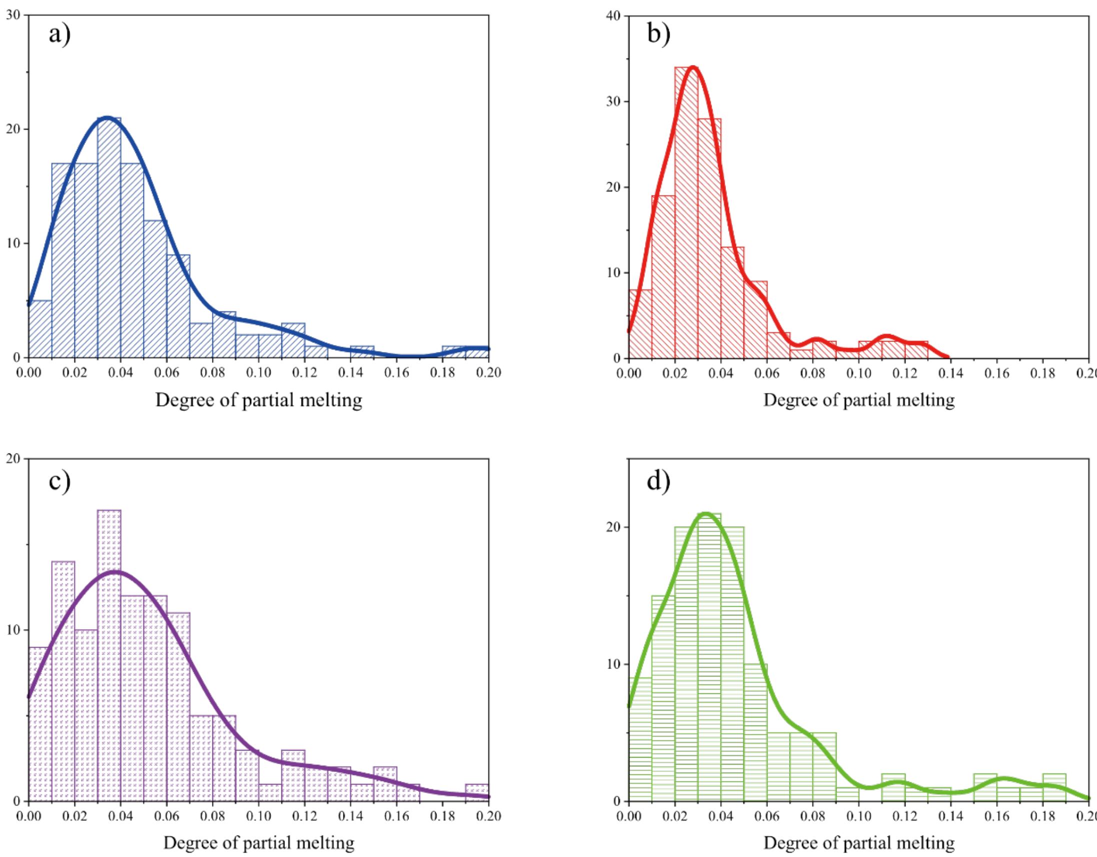

Figure S1. Histograms showing the modeled partial melting degree of the Low-Mg peridotite. a) and c) and b) and d) correspond to batch and fractional partial melting, respectively. The modeling follows the mode of Norman (1998). The initial compositions are assumed to be DMM of Workman and Hart (2005) and PM of McDonough and Sun (1995) for batch and fractional melting modeling, respectively.

Table S1. Modal abundance of Ol, Opx, Cpx, and Sp and Mg-number of peridotites from the North China Craton

Table S2. Temperature and oxygen fugacity estimations for peridotites from the North China Craton

Table S3. Oxygen fugacity of Kaapvaal, Slave, and Siberia craton

Table S4. Fluids species with oxygen fugacity ranging from ΔFMQ-1to -4 calculated via GFluids under 950 ℃ and 1.5 GPa

Table S5. Published water content of peridotite xenoliths from the North China Craton vs. the oxygen fugacity

Table S6. Partial melting degree of Low-Mg peridotites calculated via model proposed by Norman (1989) and assuming the initial composition of DMM of Workman and Hart (2005) and PM of McDonough and Sun (1995)

Table S7. Composition of primary melts derived from pMELTS simulation

Data Set S1. Major element of olivine, orthopyroxene, clinopyroxene, and spinel for each referred peridotite.