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Differential destruction of the North China Craton: A tectonic perspective

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ABSTRACT

The North China Craton (NCC) provides one of the classic examples of craton destruction, although the mechanisms and processes of its decratonization are yet to be fully understood. Here we integrate petrological, geochemical, geochronological and geophysical information from the NCC and conclude that the destruction of the craton involved multiple events of circum-craton subduction, which provided the driving force that destabilized mantle convection and tectonically eroded the lithospheric mantle beneath the craton. Furthermore, subducted-slab-derived fluids/melts weakened the subcontinental lithospheric mantle and facilitated thermo-mechanical and chemical erosion of the lithosphere. The more intense destruction beneath the eastern part of the NCC reflects the crucial contribution of Pacific plate subduction from the east that overprinted the mantle lithosphere modified during the early subduction processes. Our study further establishes the close relationship between lithospheric modification via peridotite–melt reactions induced by oceanic plate subduction and cratonic destruction.

1. Introduction

Cratons are ancient continental nuclei and many of the ancient cratons on the Earth are underlain by thick subcontinental lithospheric mantle. The thickness of the lithospheric mantle varies from a few tens of kilometers beneath rift zones to more than 250 km beneath some of the ancient continents (Griffin et al., 2009). The relationship of the lithospheric mantle to denser asthenosphere beneath is considered to be like that of an iceberg, buoyant but partly submerged (Boyd, 1998). Knowledge of the evolution of ancient cratons is essential to understand continental dynamics and the long-term stability of ancient continental landmasses.

Early continental crust is generally considered to have formed from partial melts derived from the primitive mantle and the residue settled down to build the subcontinental lithospheric mantle. Thus, the lithospheric mantle beneath ancient cratons should be highly depleted in basaltic components (such as Fe, Ca and Al) due to the high-degree of magma extraction, resulting in a lower density (about 3.31 mg/m^3) and higher viscosity than those of the asthenosphere beneath (about 3.35 mg/m^3; O'Reilly et al., 2001). The density and viscosity differences help explain why most cratons have remained chronically stable in the scheme of global tectonics.

Archean cratons (such as the Kaapvaal craton and Siberian craton) are characterized by ancient, cool (lower geotherms than the adjacent mantle) and thick lithospheric mantle, mainly composed of high-refractory harzburgites and lherzolites (Boyd, 1998; Griffin et al., 2009; Herzberg et al., 2010). Moreover, typical cratons are dormant, in the absence of active magmatism except for some eruptions of kimberlites due to their thick lithosphere and low geotherms. However, the North China Craton (NCC; Fig. 1) has lost most of the typical characteristics of other Archean cratons (Zhu et al., 2012a and references therein), accompanied widespread deformation, magmatism and the formation of abundant gold deposits (Yang et al., 2003; Li et al., 2013). The NCC has become the most striking example of cratonic destruction over the world because the eastern NCC experienced much stronger destruction than any other cratons (Carlson et al., 2005; Tang et al., 2013a). Therefore, an evaluation of the tectonic history of the NCC destruction bears global significance and helps us to understand continental evolution and the related effects.

Many studies have addressed the mechanism and processes associated with cratonic destruction in the NCC (Wu et al., 2008; Zhang et al., 2009a; Zhu et al., 2011, 2012a; and references therein). One of the salient features is that the destruction of the craton was coincident with inward subduction of circum-craton plates and collision with the NCC, which led to the destabilization of the craton and intensive hydration and refertilization of the subcontinental lithospheric mantle by crust-derived water and melt (e.g., Zheng, 1999, 2009; Zhang et al., 2002, 2003, 2007, 2009b;

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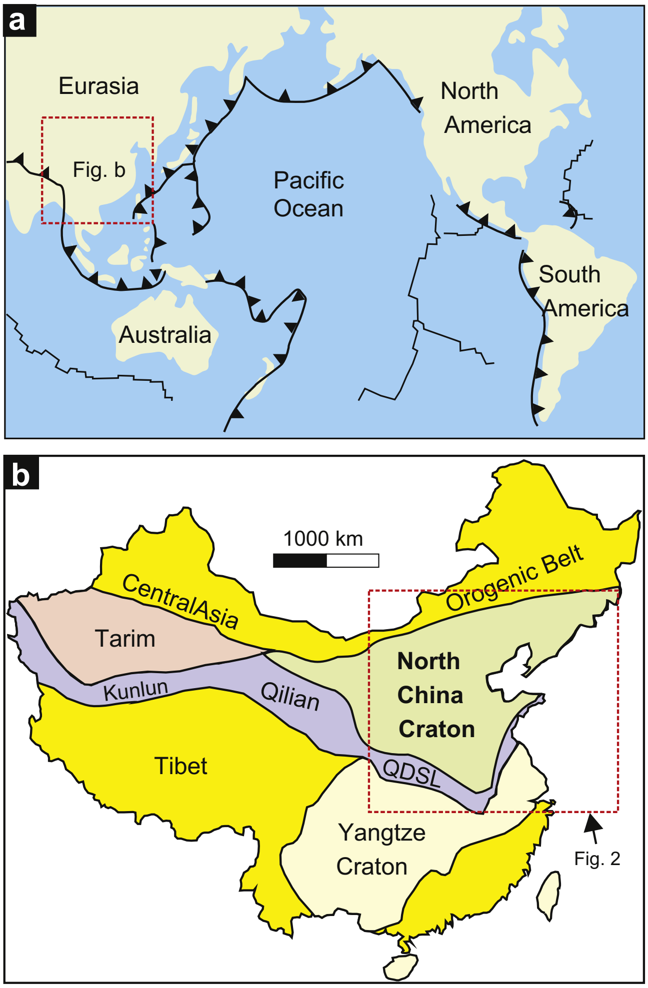

Fig. 1. (a) Location of the North China Craton (NCC) in the global plate tectonic system, and (b) location of the NCC relative to other blocks and fold belts in China (Zhao et al., 2001; Santosh, 2010). QDSL = Qinling-Dabie-Sulu fold belt.

Zhang, 2005, 2009; Zheng et al., 2008a, 2008b, 2012; Xu et al., 2009, 2012b; Zheng and Wu, 2009; Windley et al., 2010; Yang et al., 2012; Zhu et al., 2012a). The destruction processes may have been related to high mantle temperatures in the Early Cretaceous, lithospheric modification by peridotite–melt/fluid interaction (addition of volatiles) and lithospheric extension (Zhang, 2009). The subduction of Pacific slab has been considered as a crucial factor to destabilize mantle convection beneath the eastern NCC (Xu et al., 2009; Zheng and Wu, 2009; Zhu and Zheng, 2009; Santosh, 2010; Zhu et al., 2011, 2012a, 2012b), which likely caused the delamination (Gao et al., 2009) and/or thermal–mechanical–chemical erosion of the lithospheric mantle (Xu, 2001; Zheng et al., 2007; Zhang et al., 2009a; Santosh, 2010; Huang et al., 2012). However, the various models remain equivocal, and the reason why the eastern part of the NCC was almost completely destroyed whereas the thick lithospheric mantle is still preserved beneath the western part of the craton remains enigmatic. Particularly given the scenario that all the margins of the craton were disturbed by the subduction of oceanic plates, including Paleo-Asian ocean and Mongol–Okhotsk ocean on the northern side, Paleo-Tethyan ocean on the southern and western sides, and Paleo-Pacific ocean on the eastern side of the craton since the Paleozoic (Windley et al., 2010). Another problem concerns the dominant ages of lithospheric mantle beneath the eastern NCC, represented by peridotite xenoliths in Cenozoic basalts, which show age variation from Paleoproterozoic to the present, but are not as young as newly-accreted lithosphere since Cretaceous, leading to the question on how the subduction of the Pacific plate affected the craton. The main aim of this paper is to briefly review geophysical, geochemical and geochronological evidence for the destruction of the NCC, and to address the relationship between oceanic plate subduction and cratonic destruction.

2. Geological background

The NCC is one of the world's oldest continental nuclei, containing crustal remnants as old as 3800 Ma (Liu et al., 1992; Zhai and Santosh, 2011). The craton includes Archean keels beneath the Eastern and Western Blocks, which were amalgamated along the Central Zone (Fig. 2), also known as the Trans-North China Orogen, at about 1850 Ma (Zhao et al., 2000, 2001, 2005, 2008, 2010; Santosh, 2010). The basements of the Eastern and the Western Blocks mainly consist of Archean tonalitic, trondhjemitic and granodioritic (TTG) gneisses (Zhao et al., 2000, 2001, 2005). The Western Block is composed of the Yinshan Block and the Ordos Block which were linked by the east–west trending Inner Mongolia Suture Zone at ~1.95 Ga (Fig. 2; Santosh, 2010; Zhao et al., 2010). The dominant lithology within the suture zone is graphite-garnet-sillimanite gneiss, garnet quartzite, felsic paragneiss, calc–silicate rock and marble, and has been termed the Khondalite Belt (Zhao et al., 2010). Paleoproterozoic ultrahigh temperature metamorphism has been reported in the Western Block (e.g., Santosh et al., 2007a, 2007b, 2009; Tsunogae et al., 2011; Zhang et al., 2012a). The Central Zone consists of a series of 2.5–2.7 Ga granitoid (TTG) gneisses, greenschist facies mafic rocks, amphibolites, high-pressure granulites and retrograded eclogites (Kröner et al., 1988; Zhao et al., 2000, 2001, 2005; Guo and Zhai, 2001; Zhang et al., 2006; Zhai and Santosh, 2011).

The Western Block remains relatively stable after its cratonization and its lithosphere is about 200 km thick. In contrast, the Eastern Block of the craton experienced significant tectonothermal reactivation and decratonization in its eastern part (Yang et al., 2008a) since the Mesozoic, as manifested by the extensive emplacement of voluminous Mesozoic granites, mafic intrusions and volcanic rocks (Zhang et al., 2002, 2003, 2004, 2005; Yang et al., 2003; Wu et al., 2005; Zhang, 2007), as well as Cenozoic basalts (Fig. 2; Zhou and Armstrong, 1982; E and Zhao, 1987; Chi, 1988; Lu et al., 1991; Fan et al., 2000; Zeng et al., 2011; Zhang et al., 2011; Xu et al., 2012b). The contrasting composition of mantle xenoliths in the Paleozoic diamondiferous kimberlites (Dobbs et al., 1994; Chi and Lu, 1996; Zheng, 1999; Zheng and Lu, 1999) and Cenozoic basalts in the Eastern Block suggests that a thick lithosphere (about 200 km) existed until the Paleozoic, but was substantially thinned (about 60–120 km) in the Late Mesozoic and Cenozoic (Fan and Menzies, 1992; Menzies et al., 1993, 2007; Griffin et al., 1998; Menzies and Xu, 1998; Xu et al., 1998; Zheng et al., 1998, 2001, 2006; Zheng, 1999; Fan et al., 2000; Xu, 2001; Gao et al., 2002; Rudnick et al., 2004; Zhang et al., 2008a, 2009a; Tang et al., 2011). The large-scale thinning of the lithosphere (up to 80–120 km), as well as the dramatic change in the physical and chemical properties of the lithospheric mantle (from old, cool and highly refractory to relatively young, hot and fertile) since the Paleozoic, indicates an intensive lithospheric modification and even destruction of the eastern NCC (e.g., Menzies et al., 2007; Zhang et al., 2010, 2011; Zhu et al., 2012a).

3. Evidence for the destruction of eastern NCC

The geological phenomenon that a craton lost its stability has been defined as cratonic destruction (Yang et al., 2008a; Zhu et al., 2011). The surface features of cratonic destruction include

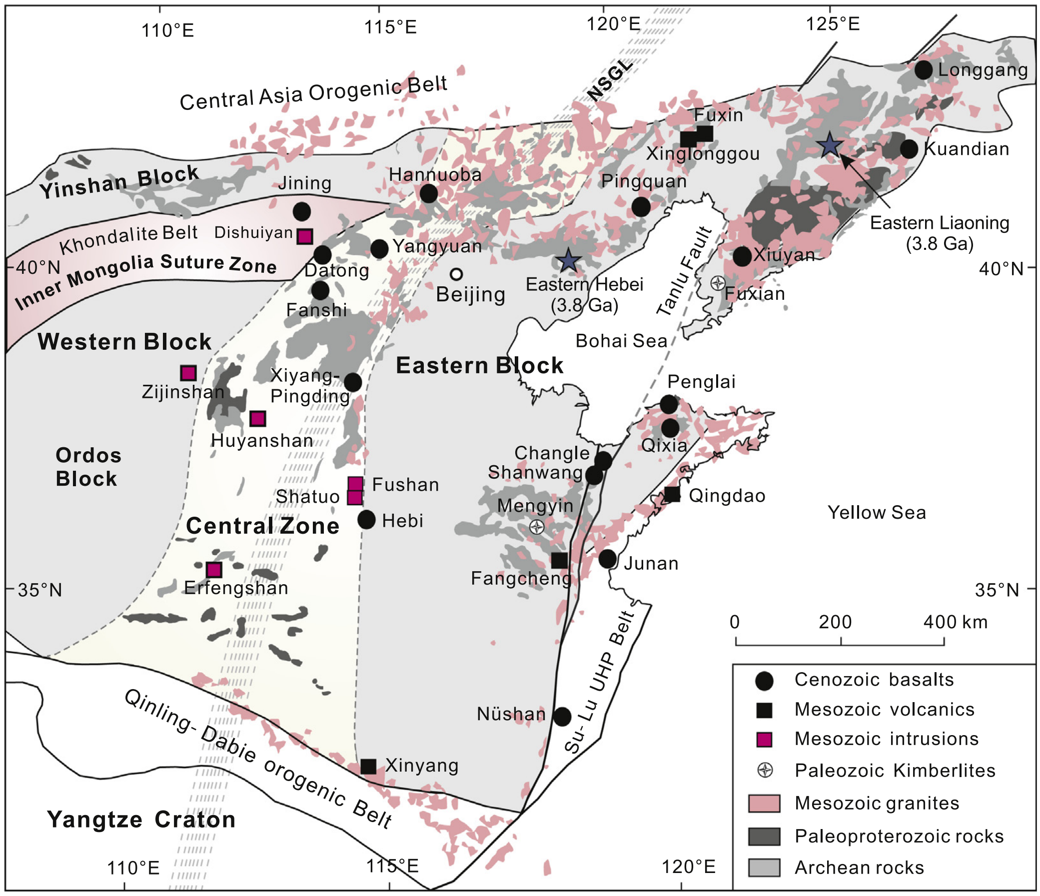

Fig. 2. Geological map of the NCC, revised after Zhao et al. (2000, 2008) and Santosh (2010), showing the distributions of the tectonic subdivisions, rocks of different ages and mantle xenoliths localities mentioned in the text. NSGL = North–South Gravity Lineament.

intense modification of the lithosphere, widespread magmatism, metallogeny and tectono-thermal events. Cratonic destruction can result in even complete loss of ancient lithospheric root.

3.1. Geochemical evidence

Fragments derived from the subcontinental lithospheric mantle are carried to the surface as xenoliths by kimberlites and basaltic rocks. Mantle xenoliths carry invaluable petrographic and geochemical information about the nature and evolution of lithospheric mantle. Studies of mantle xenoliths entrained in the Paleozoic diamondiferous kimberlites in the Mengyin and Fuxian regions of China (Fig. 2) suggest that the lithosphere in these localities was ancient (Archean ages), cool (geotherms 36–40 mW/m^2) and thick (>200 km) at the time of kimberlite eruption, with highly refractory compositions in mantle peridotites, implying that a typical Archean lithospheric keel existed beneath the eastern NCC at least until the kimberlite emplacement (Menzies et al., 1993; Griffin et al., 1998; Zheng et al., 2001, 2006; Gao et al., 2002; Wu et al., 2006; Zhang et al., 2008a). In contrast, the Cenozoic basalts sampled a younger (Proterozoic-present ages), thinner (<80 km) and hotter (50–105 mW/m^2) lithosphere, with predominantly fertile compositions in mantle peridotites (Griffin et al., 1998; Fan et al., 2000; Zheng et al., 2006; Xiao et al., 2010), consistent with the geophysical observation of a thin lithosphere (60–80 km) in this region (Chen, 2009). The voluminous magmatism, high surface heat flow, thin lithosphere and fertile compositions in the lithospheric mantle suggest that the eastern NCC has been completely destroyed (complete loss of typical characteristics of ancient craton) since the Paleozoic and the character of the subcontinental lithospheric mantle has changed from typical-craton to ocean-like (Xu et al., 1998; Zheng et al., 1998; Fan et al., 2000), which makes the NCC unique amongst ancient cratons of the world.

The salient characteristics of the lithospheric mantle beneath the NCC are summarized below.

(1) Olivine Fo of peridotite xenoliths (Fig. 3): Most of the peridotite xenoliths in the Paleozoic kimberlite from the eastern NCC are highly refractory harzburgites and dunites and have high Fo (>92) (Zheng and Lu, 1999; Zhang et al., 2008a; Chu et al., 2009), typical of cratonic lithospheric mantle. However, the peridotite xenoliths in the Cenozoic basalts from the eastern NCC (Xu et al., 1998; Zheng et al., 1998; Fan et al., 2000; Wu et al., 2003, 2006; Chu et al., 2009; Xiao et al., 2010) and those from the northern margin of NCC (Fan and Hooper, 1989; Song and Frey, 1989; Fan et al., 2000; Chen et al., 2001; Rudnick et al., 2004; Ma and Xu, 2006; Tang et al., 2007; Zhang et al., 2009a, 2012b; Liu et al., 2011) are dominantly fertile lherzolites with low Fo (<92 and most <91), showing the character of oceanic lithospheric mantle. The peridotite xenoliths from the Hebi and Fanshi regions, central NCC (Zheng et al., 2001; Tang et al., 2008, 2011; Xu et al., 2008b; Liu et al., 2011) are composed of refractory harzburgites (Fo > 92) and relatively fertile lherzolites (Fo < 92). The high-Mg# (Fo > 92) harzburgites are interpreted as relics of the Archean lithosphere, preserved locally at relatively shallow levels (<100 km) (Zheng et al., 2001, 2005; Tang et al., 2008, 2011; Xu et al., 2008b;

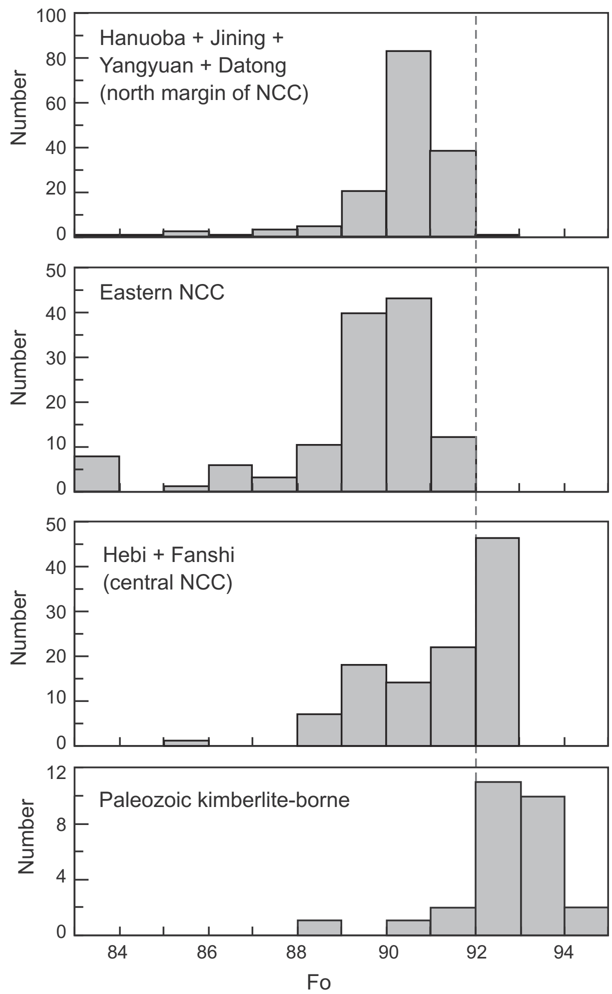

Fig. 3. Histograms showing olivine Fo distribution of the peridotite xenoliths from the NCC. Data sources: North margin of NCC (Fan and Hooper, 1989; Song and Frey, 1989; Fan et al., 2000; Chen et al., 2001; Rudnick et al., 2004; Ma and Xu, 2006; Tang et al., 2007; Zhang et al., 2009a, 2012b; Liu et al., 2011); Eastern NCC (Xu et al., 1998; Zheng et al., 1998; Fan et al., 2000; Wu et al., 2003, 2006; Chu et al., 2009; Xiao et al., 2010); Central NCC (Zheng et al., 2001; Tang et al., 2008, 2011; Xu et al., 2008b; Liu et al., 2011); Paleozoic kimberlite-borne xenoliths (Zheng and Lu, 1999; Zhang et al., 2008a; Chu et al., 2009).

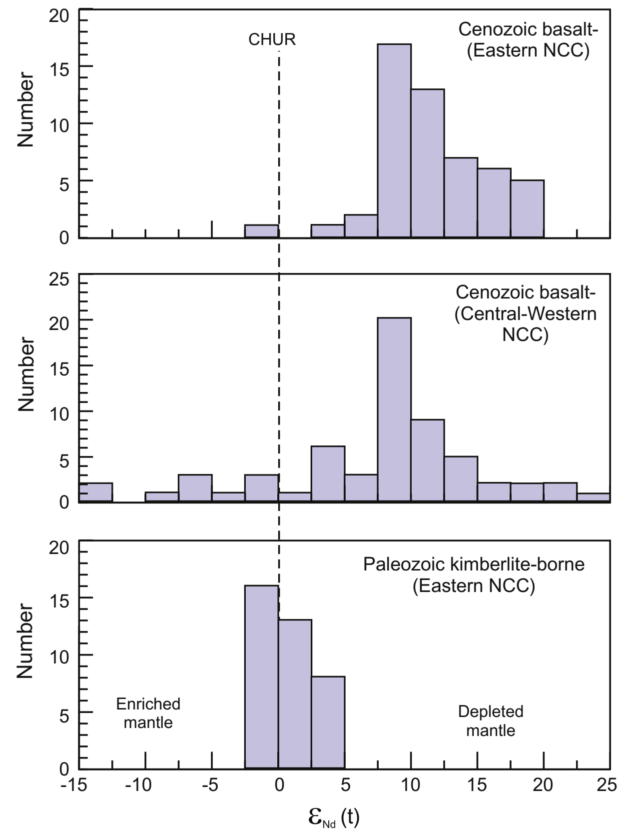

Fig. 4. Histograms showing $\varepsilon_{Nd}(t)$ distribution of the peridotite xenoliths from the NCC. The $\varepsilon_{Nd}(t)$ were recalculated to 20 Ma. CHUR represents the chondritic uniform reservoir (Rollinson, 1993). Data sources: Eastern NCC (Xu et al., 1998; Fan et al., 2000; Wu et al., 2006; Chu et al., 2009; Xiao et al., 2010); Central-Western NCC (Song and Frey, 1989; Tatsumoto et al., 1992; Fan et al., 2000; Rudnick et al., 2004; Ma and Xu, 2006; Tang et al., 2008, 2011; Xu et al., 2008b; Zhang et al., 2009a, 2012b); Paleozoic kimberlite-borne xenoliths (Zhang et al., 2008a; Chu et al., 2009; Yang et al., 2009b).

Liu et al., 2011). In contrast, the low-Mg# lherzolites might represent modified lithospheric mantle beneath the central NCC, with characteristic radiogenic isotopic systematics in most of the peridotites (Tang et al., 2008, 2011, 2013b) and/or newly accreted lithospheric mantle beneath the eastern NCC as suggested by its fertile composition (Zheng et al., 1998, 2005, 2007; Fan et al., 2000; Xu, 2001; Xu et al., 2004; Ying et al., 2006) and young Re–Os isotopic ages (Zhi et al., 2001; Wu et al., 2003, 2006; Chu et al., 2009; Xiao et al., 2010). The Fo variation may reflect different degrees of modification of the lithospheric mantle beneath the craton by peridotite–melt reaction, which is known to lower the Fo of mantle peridotites (Griffin et al., 1999, 2009; Zhang, 2005). The peridotites from the eastern NCC and the northern margin of the craton have lower Fo than those from the central NCC, likely reflecting higher-degree modification of the lithospheric mantle beneath the margin than that beneath the central NCC (Tang et al., 2008, 2011, 2013b; Zhang, 2009).

(2) The change of ε_{Nd} in mantle peridotites (Fig. 4): The Paleozoic kimberlite-borne peridotite xenoliths are relatively enriched in Nd isotopic composition, with ε_{Nd} ranging from −2.5 to +5 (Zheng, 1999; Zhang et al., 2008a; Chu et al., 2009; Yang et al., 2009b). In contrast, most of the peridotite xenoliths in the Cenozoic basalts are depleted in Nd isotopic composition, with ε_{Nd} > +5 (Xu et al., 1998, 2004; Fan et al., 2000; Wu et al., 2006; Chu et al., 2009; Xiao et al., 2010). The peridotite xenoliths from the Central Zone and the Western Block show a large variation in isotopic composition, with ε_{Nd} ranging from −10 to +25 (Song and Frey, 1989; Tatsumoto et al., 1992; Fan et al., 2000; Rudnick et al., 2004; Ma and Xu, 2006; Tang et al., 2008, 2011; Xu et al., 2008b; Zhang et al., 2009a, 2012b). The depleted Nd isotopic compositions of the Cenozoic basalt-borne peridotite xenoliths can be interpreted as those of newly accreted lithospheric mantle (Zheng et al., 1998; Fan et al., 2000). Alternately, the depleted Nd isotopic composition can also indicate the modification of the lithospheric mantle by melts with depleted isotopic compositions (e.g., asthenosphere-derived melts; Xu et al., 2003; Tang et al., 2006, 2011; Zhang, 2009). This inference is well supported by the broadly positive correlation between ε_{Nd} and Al_2O_3 contents (Fig. 5). The refractory peridotites, with low ε_{Nd} values, became fertile and high in ε_{Nd} values with the reaction between peridotites and melts with depleted isotopic compositions (Tang et al., 2013b).

(3) H_2O contents of lithospheric mantle (Fig. 6): Water played an important role during the modification of the subcontinental lithospheric mantle of the NCC (Windley et al., 2010 and references therein; Santosh, 2010). The Cenozoic

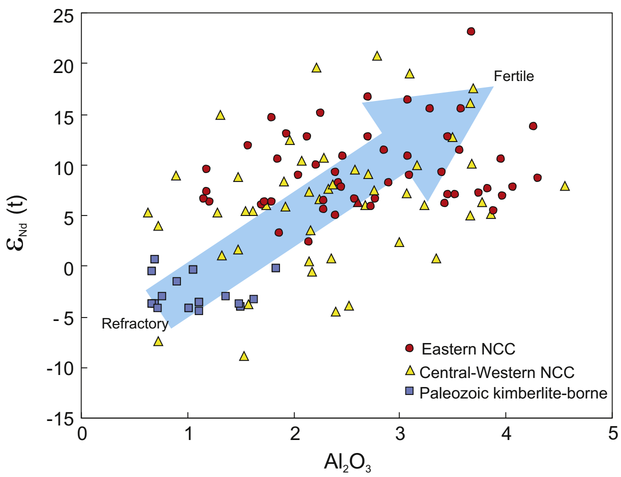

Fig. 5. Variation diagram of $\varepsilon_{Nd}(t)$ versus Al_2O_3 (wt.%) for the peridotite xenoliths from the NCC. Data sources are the same as in Fig. 4.

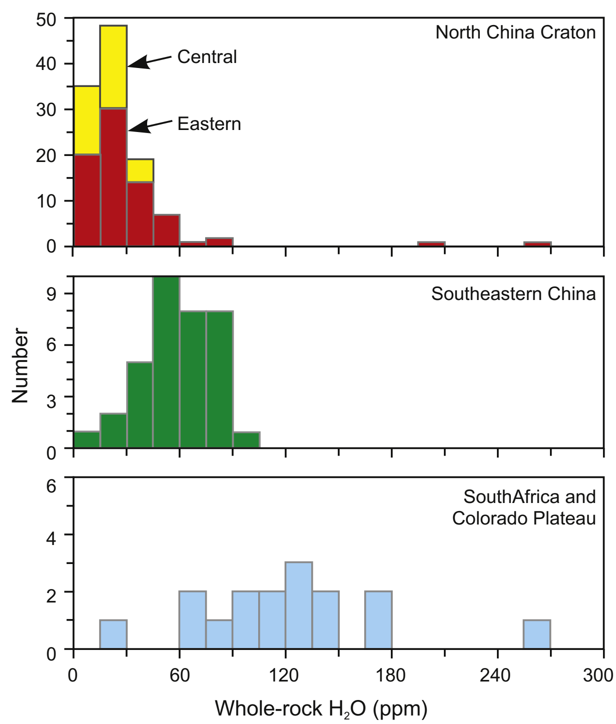

Fig. 6. Comparison of H_2O contents of whole rock of the NCC peridotite xenoliths with those of cratonic peridotites. Data sources: the NCC (Yang et al., 2008b; Xia et al., 2010, 2013); the Cathaysia Block of Southeastern China (Yu et al., 2011); South Africa and Colorado Plateau (Bell and Rossman, 1992a,b; Grant et al., 2007; Li et al., 2008).

lithospheric mantle beneath the eastern China, as represented by the available data on H_2O content from the NCC, Yangtze Craton and Cathaysia block in southeastern China, is quite dry (most samples <60 ppm) relative to typical cratonic mantle of South Africa and Colorado plateau (>80 ppm) (Yu et al., 2011 and references therein). The extremely low water content of the NCC mantle has been interpreted as a relict feature of the Archean–Proterozoic constitution, possibly due to heating by an upwelling asthenospheric flow during the lithospheric thinning of the NCC since the Late Mesozoic (Yang et al., 2008b; Xia et al., 2010, 2013). In contrast, the water content of Mesozoic lithospheric mantle beneath the eastern NCC, represented by clinopyroxene phenocrysts in the Feixian basalts (210–370 ppm; Xia et al., unpublished data), is much higher than the MORB (50–200 ppm). This observation suggests that the Mesozoic lithospheric mantle beneath the NCC experienced strong modification by hydration before the large-scale lithospheric thinning. The hydration of the Mesozoic lithospheric mantle could enhance heat conductivity, facilitate mineral deformation and lower the solidus and viscosity of peridotites (Peslier, 2010 and references therein), which facilitated the large-scale melting and thinning of the lithospheric mantle.

3.2. Geochronological evidence

The T_{RD} ages of the peridotite xenoliths (Fig. 7): The peridotites in the Paleozoic kimberlite from the eastern NCC have Paleoproterozoic–Archean T_{RD} ages, suggesting the existence of Archean lithospheric mantle beneath the eastern NCC (Gao et al., 2002;

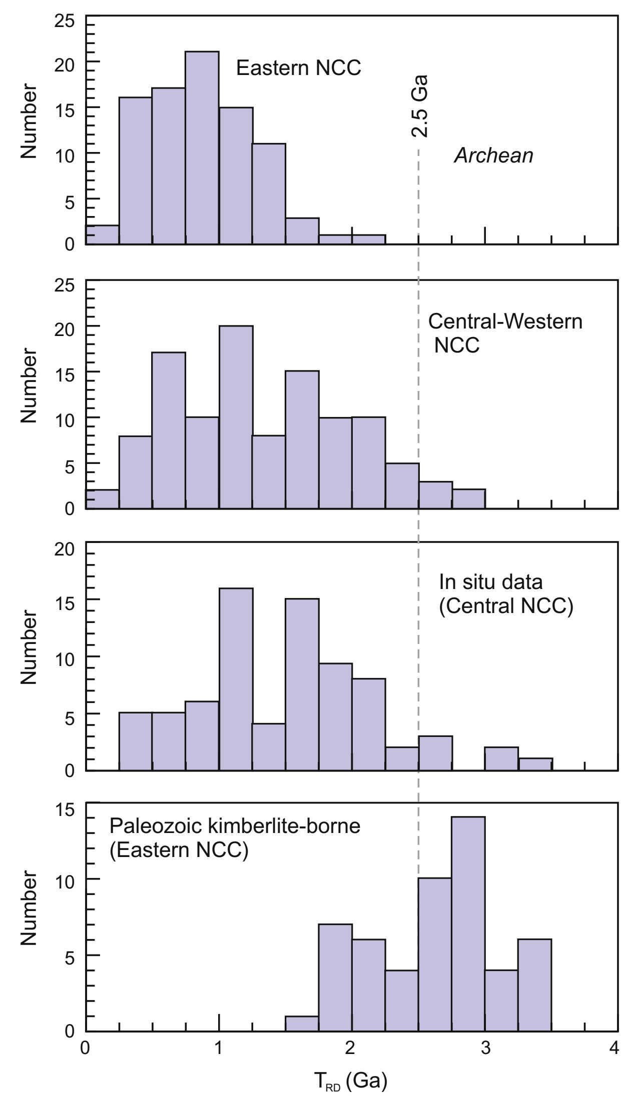

Fig. 7. Histograms showing T_{RD} (Re-depletion model age) distribution of the peridotite xenoliths from the NCC. Data sources: Eastern NCC (Zhi et al., 2001; Gao et al., 2002; Wu et al., 2003, 2006; Chu et al., 2009; Xiao et al., 2010); Central-Western NCC (Gao et al., 2002; Xia et al., 2004; Xu et al., 2008b; Zhang et al., 2009a, 2012b; Liu et al., 2011); In situ data of sulfides in peridotites (Zheng et al., 2007; Xu et al., 2008a); Paleozoic kimberlite-borne xenoliths (Gao et al., 2002; Zhang et al., 2008a; Chu et al., 2009; Yang et al., 2009b).

Zhang et al., 2008a; Chu et al., 2009; Yang et al., 2009b). However, all of the peridotites from the eastern NCC (Zhi et al., 2001; Gao et al., 2002; Wu et al., 2003, 2006; Chu et al., 2009; Xiao et al., 2010) and most of the samples from the Central Zone and the Western Block (Gao et al., 2002; Xia et al., 2004; Xu et al., 2008b; Zhang et al., 2009a, 2012b; Liu et al., 2011) show T_{RD} ages ranging from Proterozoic to present. Only a few samples from the central NCC have whole-rock Archean T_{RD} ages. In situ data of sulfides in the peridotites from the Hannuoba and Hebi localities in the Central Zone of the NCC (Yu et al., 2007; Zheng et al., 2007; Xu et al., 2008a) show a very large variation of T_{RD} ages, ranging from Archean to Cenozoic. The relatively young and variable T_{RD} ages of the peridotite xenoliths in the Cenozoic basalts also suggest different degrees of modification of the lithospheric mantle beneath the NCC by melt additions (Xu et al., 2008a,b; Zhang, 2009; Xiao and Zhang, 2011; Tang et al., 2013b). The fact that the relics of Archean lithospheric mantle, as demonstrated by both in situ and whole rock age data, is observed only beneath the central NCC further indicates lower-degree modification of the mantle beneath the central region than that beneath the eastern NCC. Based on the above observations, we illustrate that spatial variation of the lithospheric architecture of the NCC in Fig. 8. From west to east of the craton, the lithospheric mantle becomes thin, young and fertile (Griffin et al., 1998; Xu, 2001; Gao et al., 2002; Chen, 2009; Zhang et al., 2009a) due to stronger modification and destruction of the mantle beneath the east relative to that beneath the west. Some of the new lithospheric mantle beneath the Tanlu fault in the eastern NCC might have formed through asthenospheric accretion due to their fertile composition (Zheng et al., 1998; Xu, 2001; Xiao et al., 2010) and very young Re–Os isotopic ages (Xiao and Zhang, 2011).

Another important question is why the dominant ages of peridotite xenoliths in the Cenozoic basalts from NCC are Proterozoic and variable from Archean to the present. It has been well established that the chemical erosion (Xu, 2001; Zheng, 2009) and/or peridotite–melt reactions (Gao et al., 2009; Zhang, 2009; Zhang et al., 2009b; Zheng and Wu, 2009) played an important role in the transformation of the lithospheric mantle beneath the NCC. The different degrees of mantle lithospheric refertilization could explain the continuity of T_{RD} ages (Fig. 7) although most of the

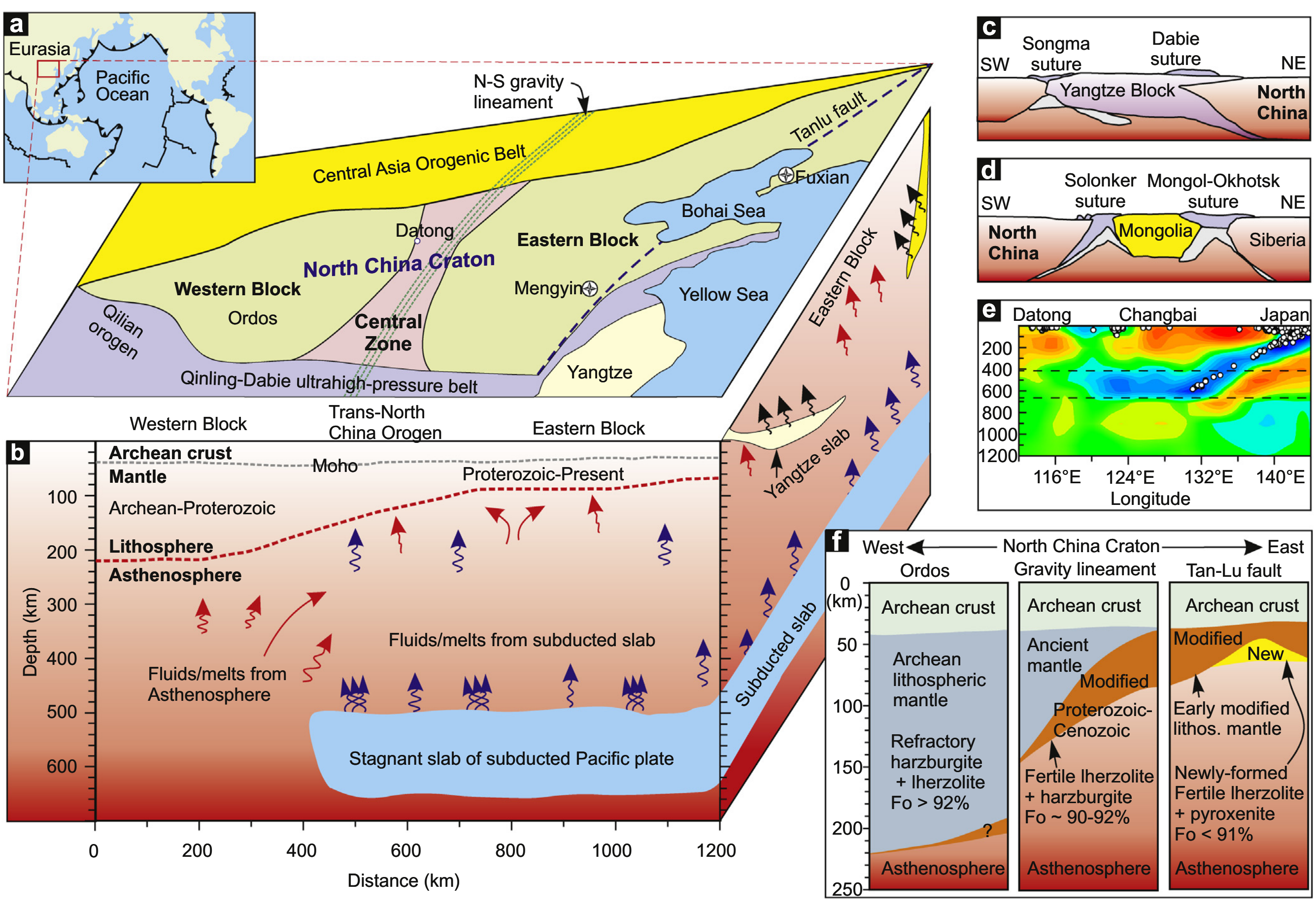

Fig. 8. (a) Simplified map showing the tectonic setting of the North China Craton (Zhao et al., 2001), (b) schematic diagram showing the variation of lithospheric thickness from the Eastern Block to the Western Block (Ordos block) (Chen et al., 2006; Chen, 2009) and the stagnant slab of subducted Pacific plate (Huang and Zhao, 2006). The lithospheric mantle beneath the southern and northern margins of the craton was metasomatized by fluids/melts derived from subducted slabs during early circum-craton plate collision (Gao et al., 2002; Zhang et al., 2002, 2003, 2009a; Zheng et al., 2006; Zhang, 2007). The lithospheric mantle beneath the Eastern Block subsequently experienced further refertilization by fluids/melts derived from subducted Pacific plate (Huang and Zhao, 2006; Zhang et al., 2008b; Zhao and Ohtani, 2009; Tang et al., 2012) and those from the asthenosphere (Zhang et al., 2009a; Xiao et al., 2010; Tang et al., 2011; Xiao and Zhang, 2011). The thickness of lithosphere dramatically decreases from west (Ordos block) to east (Baohai Sea Bay), and the apparent ages of lithospheric mantle beneath the craton become younger from west (Archean–Proterozoic) to the east (Proterozoic-Present). (c and d) Schematic maps showing the formation of Dabie suture (orogen) on the southern side and Solonker suture on the northern side of the NCC as a result of collisional events between the NCC and Yangtze Block with the closure of Paleo-Tethyan ocean and between the NCC and Mongolian plate with the closure of Paleo-Asian ocean since the Paleozoic (Zhang et al., 2003; Windley et al., 2010). (e) E–W directed vertical cross section of P-wave velocity perturbations at 41°N showing stagnant Pacific slab in the mantle transition zone under eastern China (Huang and Zhao, 2006), (f) schematic map showing the lithospheric architecture of the NCC. From west to east of the craton, the lithospheric mantle becomes thin, young and fertile (Griffin et al., 1998; Xu, 2001; Gao et al., 2002; Chen, 2009; Zhang et al., 2009a), reflecting stronger modification and destruction of the mantle beneath the east relative to that beneath the west. The previously modified lithospheric mantle beneath the Eastern Block was further thinned due to the subduction of Pacific plate and some new lithospheric mantle may be formed through an asthenospheric accretion due to thermal loss (Xu, 2001).

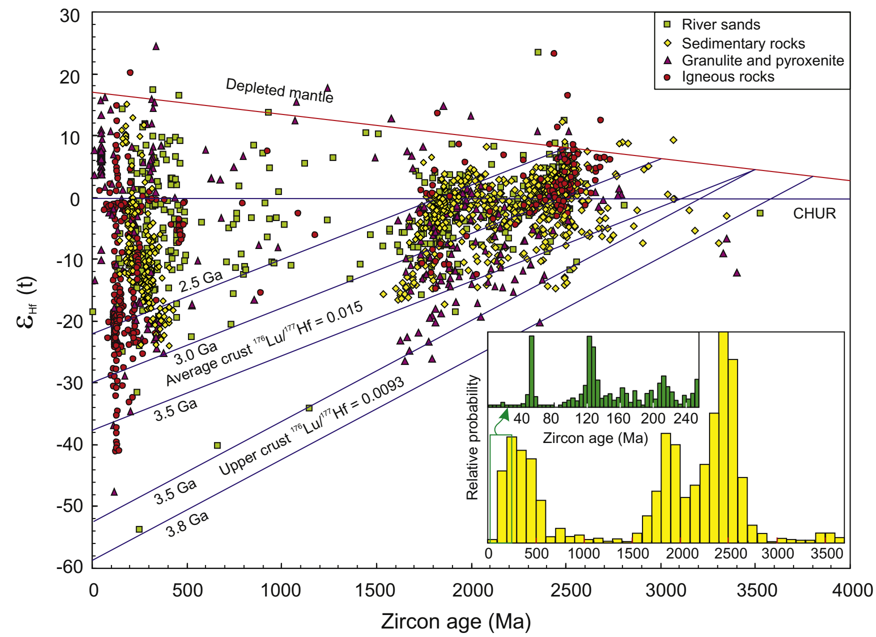

Fig. 9. $\varepsilon_{Hf}(t)$ Versus U–Pb age plot of zircons from river sands (Yang et al., 2009a), sedimentary rocks (Yang et al., 2006b; Ying et al., 2011b), granulite and pyroxenite xenoliths (Zheng et al., 2004, 2008a, 2009, 2012; Liu et al., 2010; Ying et al., 2010, 2011a; Zhang, 2012; Zhang et al., 2012c, 2012d, 2013) and igneous rocks (Yang et al., 2006a, 2007, 2008a; Zhang et al., 2011). Inset histogram shows relative probability plots of U–Pb ages for zircons, including zircon data for igneous rocks in Wu et al. (2005).

younger ages are apparent ages due to metasomatism and do not represent actual melt-extraction events. The relics of Archean lithospheric mantle beneath the Central Zone still possess Archean T_{RD} ages due to the very weak modification by the peridotite–melt reaction. In contrast, the peridotite xenoliths with Proterozoic ages might have experienced relatively strong refertilization (Tang et al., 2013a). Some peridotites with very young ages from the Tanlu fault in the eastern NCC may also represent newly-accreted lithosphere since Cretaceous (e.g., Xu et al., 1998; Zheng et al., 1998, 2001; Zheng, 1999; Fan et al., 2000; Ying et al., 2006; Xiao et al., 2010).

3.3. Geophysical evidence

The lateral thickness of the lithosphere beneath the NCC is highly variable. It is about 80 km in the Bohai basin in the east and changes from about 90 to 120 km within a lateral distance of 100 km at around the boundary between the Bohai basin and the Central Zone to the west (Chen, 2009), spatially coincident with the distinct gravity decrease of more than 100 mGal across the North–South Gravity Lineament (Fig. 2). The gravity lineament parallels the Pacific subduction margin for 3500 km and roughly overlaps the Central Zone. To the east of the gravity lineament, the Eastern Block is characterized by a thin lithosphere (60–80 km), high heat flow (50–106 mW/m^2) and weak negative to positive regional Bouguer anomalies. To the west of the gravity lineament, the Ordos Block has a thick lithosphere (>200 km), low heat flow (35–72 mW/m^2; Hu et al., 2000) and strong negative Bouguer anomalies. The geophysical image of lithosphere once again confirms that the destruction mainly occurred in the eastern NCC (Chen, 2009) as also previously suggested mainly based on geological and geochemical data (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Zheng et al., 2001).

4. Effects of circum-craton collision/subduction

The NCC experienced multiple events of circum-craton collision and subduction since the Paleozoic, such as the Paleozoic northward subduction of Tethyan ocean and Yangtze Craton, and the intense collision between Yangtze Block and North China in Triassic that formed the Qinling–Dabie ultrahigh-pressure belt in the south (Li et al., 1993). Further collisions include the Late Paleozoic southward subduction of Paleo-Asian ocean and collision with the NCC, Early Mesozoic closure of Paleo-Asian ocean and Okhotsk ocean that formed the huge accretionary-type Central Asian Orogenic Belt in the north (Xiao et al., 2003, 2013), and the Mesozoic–Cenozoic subduction of Pacific plate in the eastern part of the craton (Huang and Zhao, 2006). These events could provide not only the driving force that triggered the instability of convective mantle beneath the craton by mechanical collision and erosion, as well as thermal perturbation (Lin et al., 2005; Zhao et al., 2007; Zhu et al., 2011), but also fluids/melts derived from the subducted slabs that intensively refertilized the overlying subcontinental lithospheric mantle. The episodes of circum-craton collision/subduction eventually led to extensive modifications in chemical compositions via peridotite–melt/fluid interactions (Fig. 8) and physical properties including the thickness, thermal state and viscosity, which induced the large-scale thinning and dramatic transformation of the lithospheric mantle beneath the NCC (Gao et al., 2002; Zhang et al., 2002, 2003, 2008b, 2009b; Zheng et al., 2006, 2012; Windley et al., 2010; Tang et al., 2011, 2012; Yang et al., 2012; Li et al., 2013). Numerical simulations of two-dimensional anisotropic medium indicate that complex upper mantle deformation has occurred in the NCC (Zhao and Xue, 2010). The anisotropy pattern beneath the NCC imaged in high-resolution seismic tomography was considered as the result of a regional upwelling beneath the Central Zone and a mantle wedge flow beneath the Eastern Block (Zhao et al., 2007; Zhao and Xue, 2010).

The effects of the subducted Pacific plate on the eastern part of China have been confirmed from geological, geophysical and geochemical studies. Since the Late Mesozoic, eastern China was an important part of the circum-Pacific tectonic–magmatic zone (Wu et al., 2005; Sun et al., 2007). High-resolution seismic tomographic images show that the stagnant slabs of subducted Pacific plate extend from Japan to Beijing in China for over 1000 km long, indicating that the arc-trench system covers the entire region from the Japan trench to East Asia (Huang and Zhao, 2006; Zhao et al., 2007). The westward subduction of the Pacific plate generated a large mantle wedge above the subducted oceanic slab and significantly affected the physical–chemical properties of lithospheric mantle beneath the eastern China (Huang and Zhao, 2006; Zhao et al., 2007; Zhu and Zheng, 2009; Zhu et al., 2011). Mesozoic–Cenozoic igneous rocks in eastern China provide petrological and geochemical records of modification of the lithospheric mantle by the fluids/melts derived from the subducted Pacific plate (Sun et al., 2007; Zhang et al., 2008b, 2009b; Tang et al., 2012; Xu et al., 2012a; Zheng, 2012; Zhu et al., 2012a). The Late Cretaceous mafic dikes in the Qingdao region, eastern China, show geochemical features similar to those of back-arc basalts from the Japan Sea (such as radiogenic Sr and Pb, but less radiogenic Nd isotopic compositions), suggesting the contribution of subducted Pacific slab in the mantle source (Zhang et al., 2008b). The petrologic and geochemical signatures of the Cenozoic continental basalts and their mantle peridotite xenoliths from eastern China also reflect the components of subducted oceanic crust in their mantle sources (Zhang et al., 2009b; Tang et al., 2012; Xu et al., 2012a). Remarkably, the Cretaceous large-scale orogenic lode gold minerlization and major tectonic change from extgension to transpression in eastern China occurred contemporaneously with an abrupt change of ~80 °C in the drifting direction of the subducting Pacific plate (Sun et al., 2007), indicating the importance of Pacific plate subduction in the lithospheric evolution of eastern China.

Circum-craton collision/subduction not only led to the intensive modification of the lithospheric mantle beneath the NCC, but also caused widespread magmatism and reworking of the crust throughout the NCC. U–Pb ages and Hf isotopes of zircons from river sands (Yang et al., 2009a), sedimentary rocks (Yang et al., 2006b; Ying et al., 2011b), granulite and pyroxenite xenoliths (Zheng et al., 2004, 2008a, 2009, 2012; Liu et al., 2010; Ying et al., 2010, 2011a; Zhang, 2012; Zhang et al., 2012c, 2012d, 2013) and igneous rocks including granites, granodiorites, monzogranites, dolerites, diorites and basalts (Wu et al., 2005; Yang et al., 2006a, 2007, 2008a; Zhang et al., 2011) revealed the long history of preservation, episodic growth and reworking of the Archean continental crust of the NCC (Fig. 9). The most striking age peak at 2.5 Ga (Fig. 9) was suggested to mark an important period for the evolution of the lower crust of the NCC and the cratonization of the Archean blocks in the NCC (at least for the Eastern Block). The 1.8–2.0 Ga age peak, coinciding with the timing of amalgamation of the Eastern Block and Western Block of the craton (Zhao et al., 2005, 2010; Santosh, 2010; Zheng et al., 2013), suggests the first significant modification of the whole lower crust after the cratonization of the Archean blocks of the NCC (Zhang et al., 2012d). The Phanerozoic episodic magmatic events recorded from the lower crustal xenoliths (Fig. 9) are linked to the tectonic movements of circum-craton blocks (see the review of Zhang et al., 2013). The early Paleozoic craton-wide event, as evidenced by the emplacement of Ordovician kimberlites and the widespread occurrence of Paleozoic zircons identified in the garnet-bearing lherzolites and pyroxenites, granites and eclogites (Zhang et al., 2013 and references therein), is the first phase of Phanerozoic magma underplating following the final cratonization of the NCC in the Paleoproterozoic, marking the initiation of the decratonization process. This coincided with the northward subduction of the Paleo-Tethyan ocean in the south and the southward subduction of the Paleo-Asian Ocean in the north of the NCC. The ~120 Ma age peak observed in the lower crustal rocks and igneous suites marks a major and significant magmatic event, likely associated with the geothermal overturn caused by the giant south Pacific mantle plume (Wilde et al., 2003). The Early Cretaceous Earth was characterized by upwelling of the mid-Pacific superplume, mantle avalanche related to the closure of Tethys and the breakup of Gondwana continent, which could have accelerated and changed the direction of the Pacific subduction (Sun et al., 2007; Zhu et al., 2011; and references therein). The geotherm elevated by the superplume induced large-scale melting of the NCC lithosphere and ultimately resulted in the complete destruction of the eastern NCC. The age peak at ~50–60 Ma likely reflects the episodic melt-peridotite interaction induced by juvenile input of probable asthenospheric origin because the 50–60 Ma zircons are remarkably enriched in rare earth elements, U and Th, absent in Ce anomaly, and have positive $\varepsilon_{Hf}(t)$ values, suggesting that the metasomatic melt at 50–60 Ma could be derived from the deplete mantle (Zheng et al., 2009; Liu et al., 2010; Zhang et al., 2012c). The occurrence of sapphirine in a mantle-derived xenolith from the Cenozoic Hannuoba basalts in the NCC also suggests magma underplating and interaction between the infiltration melts and the wall-rock peridotite (Su et al., 2012). These events, closely related to the subduction of circum-craton plates, resulted in the modification of the crust of the NCC (Xu, 2002; Liu et al., 2010; Zhang et al., 2011, 2012d, 2013; Zhang, 2012), similar to the transformation from the refractory lithospheric mantle to fertile one by the reaction between refractory peridotites and infiltrated melts (Zhang et al., 2013).

5. Contrasting cratonic destruction in the Eastern and Western Blocks

Experiments of volatile-bearing peridotite melting have proved that partial melting of mantle peridotite does not occur until at least one of the three factors are satisfied: addition of volatiles, temperature increase and decompression (see review of Zhang (2009)). The addition of volatile can significantly lower the melting point of peridotite. Temperature increase or depression will lead to the intersection of geothermal gradient and solidus of peridotite, resulting the partial melting of previously refractory peridotite. For the eastern NCC, large-scale melting of the lithospheric mantle occurred because all the above three factors could be sufficient in the Late Mesozoic (Zhang, 2009): volatile could be added into the lithospheric mantle by peridotite–melt/fluid interaction; temperature could be increased by elevation of regional thermal anomaly due to superplume; and decompression could have resulted from lithospheric extension and thinning.

Since the Cretaceous, the backarc expansion caused by westward subduction of Pacific plate has played a crucial role in the lithospheric extension and the formation of sedimentary basins in the eastern NCC, associated with asthenospheric upwelling. This resulted in the large-scale melting and further thinning of the overlying lithosphere by heating and chemical erosion (Xu, 2001, 2007; Xu et al., 2004). As discussed above, the destruction of the eastern NCC is ascribed to the combined effects of multistage circum-craton collision/subduction events (Xu et al., 2009; Zhang, 2009; Zheng et al., 2012). The earlier-stage subduction processes had already significantly transformed the chemical compositions and physical properties of the lithospheric mantle beneath the margins of the NCC (Gao et al., 2002; Zhang et al., 2002, 2003, 2009a; Zheng et al., 2006; Zhang, 2007; Xu et al., 2009; Zheng, 2009; Yang et al., 2012; Zhu et al., 2012b), and facilitated the lithospheric thinning and the intensive destruction of the craton.

In contrast, the Western Block of the NCC has been bound by orogens formed by continent–continent collisions since the Paleoproterozoic, which buffered and protected the block from further destruction caused by early subduction of palaeo-oceans. This is because the relatively "cold" subduction (low geothermal gradients) of the continental crust would result in crustal accretion and orogeny. The subducting crust cannot release significant amounts of aqueous fluids in cold subduction zones until a major dehydration reaction occurs at mantle depths, in contrast to the subduction of oceanic crust that occurs in both low and high geothermal gradients (Zheng, 2012 and references therein). Compared to the Western Block, the Eastern Block has been significantly and continuously affected by the subducted Pacific plate since the Mesozoic. The subduction of oceanic plate is commonly characterized by a significant release of aqueous fluids, which will be introduced into the overlying mantle-wedge peridotite. Partial melting of hydrated peridotites gives rise to oceanic and continental arc magmatism above oceanic subduction zones (Yogodzinski et al., 2001; Zheng, 2012 and references therein).Therefore, the effect of Pacific plate subduction overprinted the early modified lithospheric mantle, ultimately leading to the intensive destruction of the eastern NCC.

6. Summary

The destruction of the lithospheric mantle beneath the NCC is the net result of the evolution of continental lithosphere under specific tectonic settings (Zhu et al., 2011), and was related to the multiple events of circum-craton collision and subduction since the Paleozoic. These processes not only resulted in craton-scale tectono-thermal reactivation, but also caused substantial modification in the chemical composition and physical property of the lithospheric mantle via multiple additions of melts/fluids, thus significantly contributing to the lithospheric thinning through thermo-mechanical and chemical erosion and/or asthenospherisation, upwelling of asthenosphere and the destruction of the eastern part of the craton. The reactions between old peridotites and penetrated melts altered the metasomatized peridotites to younger, more fertile and depleted in Nd isotopic compositions than their precursors.

The early-stage circum-craton collision and subduction may have not only destabilized the whole NCC, but also resulted in mantle-wedge metasomatism. In the late stage, the prolonged subduction of Pacific plate further aggravated the modification of the lithospheric mantle beneath the eastern NCC and ultimately caused whole-scale destruction. In contrast, the Western Block remained relatively robust shielded on the margins by circum-craton continental orogens (Central Asian Orogenic Belt in the north, Qilian orogen in the west and Qinling-Dabie orogenic belt in the south).

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