Widespread refertilization of cratonic and circum-cratonic lithospheric mantle

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ABSTRACT

Studies of mantle xenoliths have confirmed that Archean subcontinental lithospheric mantle (SCLM) is highly depleted in basaltic components (such as Al, Ca and Na) due to high-degree extraction of mafic and ultramafic melts and thus is refractory and buoyant, which made it chronically stable as tectonically independent units. However, increasing studies show that ancient SCLM can be refertilized by episodic rejuvenation events like infiltration of upwelling fertile material. The North China Craton is one of the most typical cases for relatively complete destruction of its Archean keel since the eruption of Paleozoic kimberlites, as is evidenced by a dramatic change in the compositions of mantle xenoliths sampled by Paleozoic to Cenozoic magmas, reflecting significant lithospheric thinning and the change in the character of the SCLM. The compositional change has been interpreted as the result of refertilization of Archean SCLM via multiple-stage peridotite-melt reactions, suggested by linear correlations between MgO and indices of fertility, covariations of Al_2O_3 with CaO, La/Yb, $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{187}Os/^{188}Os$ and Re-depletion ages (T_{RD}), high Re abundances, scatter in Re–Os isotopic plot, variable in situ T_{RD} ages of sulfides, and correlation between T_{RD} ages and olivine Fo of peridotite xenoliths in Paleozoic kimberlites and Cenozoic basalts on the craton.

By integrating major and trace element, Sr, Nd and Os isotopic compositions of peridotite xenoliths and orogenic massif peridotites from the continents of Europe, Asia, America, Africa and Australia, together with previous studies of petrology and geochemistry of global peridotites, we suggest that (1) refertilization of cratonic and circum-cratonic lithospheric mantle is widespread; (2) Archean SCLM worldwide has experienced a multi-stage history of melt depletion and refertilization since segregation from the convecting mantle; (3) cratonic SCLM may be more susceptible to compositional change caused by refertilization than is generally assumed; (4) the original character of much Archean cratonic mantle has been partly overprinted, or even erased by varying degrees of refertilization, which may play a key role in the rejuvenation and erosion of the SCLM beneath the Archean cratons.

Due to the refertilization of ancient SCLM, (1) many published whole-rock Re-depletion ages cannot represent the formation ages of peridotites, but the mixtures of different generations of sulfides. Thus, the chronological significance of the Re–Os isotopic composition in individual peridotite should be cautiously interpreted; (2) many kimberlite- and intraplate basalt-borne lherzolite xenoliths, with major element compositions close to primitive mantle, may be the fragments of the ancient SCLM, strongly refertilized by infiltration of asthenosphere-derived melts, rather than newly-accreted SCLM. Consequently, new accretion of SCLM beneath ancient cratons such as the North China Craton may be less than was previously assumed.

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1. Introduction

The formation and evolution of subcontinental lithospheric mantle (SCLM) is critical to understanding the processes responsible for the development of Earth's continents. The SCLM is depleted in basaltic components owing to high degrees of partial melting (extraction of basaltic melt) of mantle peridotites (Frey and Green, 1974; Jordan, 1975, 1988; Boyd et al., 1985; Frey et al., 1985; Pollack, 1986; King, 2005; Griffin et al., 2009; Aulbach, 2012; Herzberg and Rudnick, 2012). Cratonic mantle most likely formed as residues after about 30% melting of ambient mantle at potential temperatures of 1500–1600 °C in the Archean. These conditions compare with about 7% melting to produce modern mid-ocean ridge basalt (MORB) at a potential temperature of 1350 °C. When melting is hot and extensive, the primary magmas are FeO-rich and these leave behind residues that are FeO-poor. Extensive melting also depletes the residues in CaO and Al_2O_3, and the combined effects of low FeO, CaO and Al_2O_3 makes them buoyant (Herzberg, 2004; Herzberg et al., 2010).

There is a secular evolution from depleted Archean mantle (Mg-rich), represented by the peridotite xenoliths in the African and Siberian kimberlites, to more fertile Phanerozoic mantle. Thus, newly formed SCLM, as represented by the peridotite xenoliths in some intraplate basalts, has become progressively less depleted from Archean, through Proterozoic to Phanerozoic time, in terms of Al, Ca and other basaltic components (Boyd, 1989; Boyd et al., 1997; Griffin et al., 1998a, 1999a, 2003a, 2009; O'Reilly et al., 2001). This is displayed by a large database of xenoliths and xenocrysts showing that the SCLM stabilizing during different geologic eons has distinctly different mean compositions that are broadly correlated with the tectonothermal ages of the crust (Griffin et al., 1998a, 1999a).

Archean SCLM is distinctive in containing significant proportions of refractory harzburgites with minor lherzolites (Herzberg, 2004) and highly refractory dunites (Bernstein et al., 2006, 2007), marking the most significant difference between Archean SCLM and that beneath younger terranes (Griffin et al., 1999a). The compositional variations significantly contribute to the difference in the density of SCLM of different ages. Mean density increases significantly from Archean through Proterozoic to Phanerozoic SCLM (Griffin et al., 1998a, 1999a, 2003a, 2009; O'Reilly et al., 2001). Thus, Archean lithosphere is highly buoyant and cannot be delaminated through gravitational forces alone. The buoyancy, as well as the refractory nature of Archean SCLM, offers a simple explanation for the thickness and longevity of Archean lithospheric keels (Jordan, 1988).

Archean and Proterozoic SCLM is forever unless it is physically disrupted (e.g. rifting, thinning and displacement) with associated thermal and chemical erosion (metasomatism) (O'Reilly et al., 2001). Changes tracked in the SCLM in several regions, such as the Wyoming craton (Eggler and Furlong, 1991) and the North China Craton (Fan and Menzies, 1992), show that Archean mantle can be transformed by mechanical destruction (lithospheric thinning and rifting) and refertilized (chemical re-enrichment) by episodic infiltration of upwelling fertile material (O'Reilly et al., 2001; Foley, 2008; Griffin et al., 2009; Zhang et al., 2009a). The term "refertilization" is commonly used to describe a phenomenon occurring within the lithospheric mantle as metasomatic fluids/melts continually percolate through this layer and modify its composition (Griffin et al., 2009). Thus, refertilization means the chemical re-enrichment of originally depleted protoliths by

introduction of fluids/melts via metasomatism or peridotite-melt/fluid reactions. The percolating fluids/melts were rich in Fe, Ca, Al, Na and incompatible trace elements and derived from the asthenosphere or recycled crust. Refertilization of a depleted peridotite could be linked to heating, partial melting and melt migration on a scale of kilometers, related to asthenospheric upwelling (Griffin et al., 2009 and references therein).

Although cratons, the ancient continental nuclei characterized by tectonic inactivity, thick SCLM and low heat flow, are stable as tectonically independent units for at least the past 2 billion years, they have experienced episodic rejuvenation events throughout their history (Foley, 2008 and references therein). Is the process of refertilization of depleted Archean mantle identified in previous studies a common phenomenon? In other words, did most Archean SCLM around the world undergo the process of refertilization?

In order to answer these questions, we will summarize and analyze critical evidence for refertilization of cratonic and circum-cratonic lithospheric mantle worldwide by integrating the existing data, including major and trace element, Sr, Nd and Os isotopic compositions of mantle peridotite xenoliths and orogenic massif peridotites. Firstly, the North China Craton will be selected to represent the typical region for the destruction of its Archean keel and the critical evidence for refertilization of the SCLM beneath the craton will be analyzed in detail. Then, advances in petrology and geochemistry of mantle peridotites from other cratonic and circum-cratonic regions worldwide (Africa, America, Siberia, Australia and Europe; Fig. 1) will be reviewed and comprehensively compared with those of the North China Craton. The integrated results suggest that refertilization of ancient SCLM is widespread and that the original character of Archean cratonic mantle has been transformed by varying degrees of refertilization, leading to the rejuvenation and erosion of ancient mantle.

2. Refertilization of Archean mantle beneath the North China Craton

The North China Craton is one of the major continental blocks in eastern Eurasia (Fig. 1), preserving Archean crustal remnants as old as 3.8 Ga (Liu et al., 1992). The lithosphere of the craton was cold, thick (>200 km), refractory and typically Archean craton in chemical composition during the early Paleozoic, as is proved by extensive studies of peridotite xenoliths, mineral xenocrysts and diamond inclusions in the Mid-Ordovician diamondiferous kimberlites (Chi et al., 1992; Dobbs et al., 1994; Meyer et al., 1994; Chi and Lu, 1996; Wang et al., 1998; Wang and Gasparik, 2001; Zheng et al., 2001; Gao et al., 2002; Wu et al., 2006; Zhang et al., 2008a; Chu et al., 2009). In contrast, the Tertiary basalts on the craton sampled a hot, thin (<120 km), fertile and relatively young lithosphere, showing characteristics similar to "oceanic" mantle (Song and Frey, 1989; Fan and Menzies, 1992; Griffin et al., 1992, 1998b; Tatsumoto et al., 1992; Menzies et al., 1993; Menzies and Xu, 1998; Xu et al., 1998; Zheng et al., 1998, 2005, 2006a; Fan et al., 2000; Xu, 2001; Rudnick et al., 2004; Chu et al., 2009; Zhang et al., 2009a, 2010; Tang et al., 2012). These observations reflect a dramatic change in physical property and chemical composition of the SCLM beneath the North China Craton during the intervening time interval. Briefly, the Archean SCLM has been considerably destroyed and a relatively young SCLM has formed beneath the North China Craton since the Paleozoic (Griffin et al., 1992, 1998b; Menzies et al., 1993;
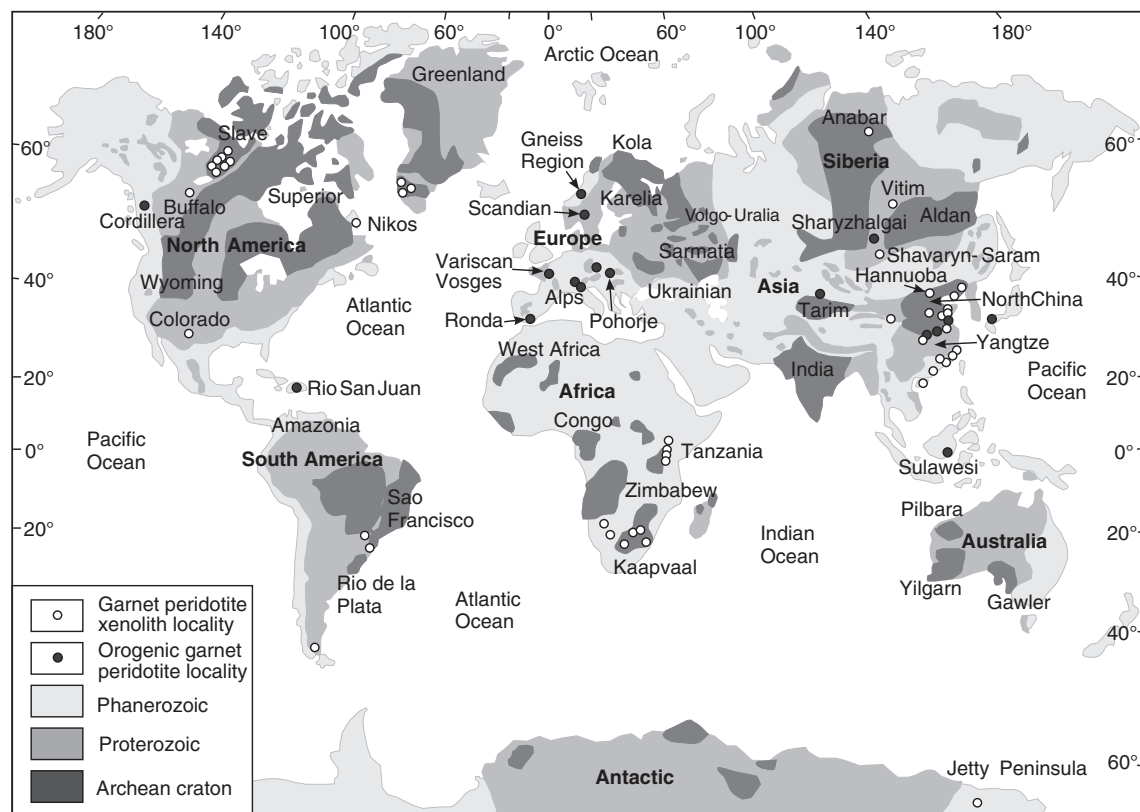
Fig. 1. Distributions of global Archean cratons, garnet peridotite xenoliths and orogenic garnet peridotites, modified from Zhao et al. (2004) and Su et al. (2011). The localities of spinel-facies peridotites are quite a lot and thus are not shown in this map.

Xu, 2001; Tang et al., in press and references therein). The ever-increasing investigations on the mechanisms responsible for the great lithospheric thinning and the dramatic change in chemical composition of the SCLM, such as the delamination model (Gao et al., 1998, 2004; Wu et al., 2003; Xu et al., 2006, 2008a; Chu et al., 2009), the thermo-mechanical erosion model (Menzies et al., 1993; Xu, 2001; Xu et al., 2004a,b, 2009; Huang et al., 2012), the replacement model (Zheng et al., 2001, 2005, 2006a, 2007; Zheng, 2009), and the progressive melt modification model (Zhang et al., 2002, 2003, 2007a, 2009a, 2010; Zhang, 2005; Tang et al., 2008, 2011, 2012; Xu et al., 2008b), now make "the destruction of the North China Craton" a very hot topic (Zhu et al., 2011). However, the primary issues such as the mechanism and processes of the transformation of the SCLM are yet to be well constrained.

The proposed models have distinct implications for the lithospheric thinning and compositional change of the North China Craton (Menzies et al., 2007; Wu et al., 2008; Zhang et al., 2009a). Lithospheric delamination is the foundering of dense lithosphere into less dense asthenosphere (Kay and Kay, 1993). As SCLM is intrinsically less dense than underlying asthenosphere due to compositional differences, a critical amount of shortening is required. Crustal shortening and thickening may result in a crustal root that becomes denser than the SCLM and should delaminate with it (Kay and Kay, 1993). The effects of delamination can explain the rapid stress change and intense tectonic reactivation, and profound changes in crustal and mantle-derived magmatism of the North China Craton (Gao et al., 1998, 2004; Wu et al., 2003; Xu et al., 2006, 2008a). As the dynamical model shows, the result of lithospheric delamination should be the removal of SCLM and a portion of lower crust. If the delamination is the right mechanism for the lithospheric thinning of the North China Craton, the present SCLM must be young, likely Mesozoic as the lithospheric thinning mainly occurred during the Mesozoic (Zhu et al., 2012 and references therein) and the present SCLM should form from upwelling of hot

asthenosphere at the base of the crust and cooling subsequent to the lithospheric thinning. However, the published Re–Os isotopic data for Cenozoic basalt-hosted xenoliths show a large variation of ages ranging from Archean to Cenozoic (Gao et al., 2002; Wu et al., 2003, 2006; Zheng et al., 2007; Xu et al., 2008b,c; Chu et al., 2009; Zhang et al., 2009a; Liu et al., 2011) and suggest the persistence of ancient SCLM (Rudnick et al., 2006), inconsistent with the expectation of the delamination model. Chen et al. (2013) argued against the delamination model based on the new evidence from Mesozoic high-Mg dioritic rocks in the North China Craton: the euhedral overgrowths of high-Ca plagioclase and high-Mg pyroxene over low-Ca plagioclase and low-Mg pyroxene, respectively, and highly radiogenic Os isotopic compositions, reflecting a process of magma mixing between siliceous crustal melts and basaltic magma from metasomatized mantle.

The model of coupled thermo-mechanical and chemical erosion (Xu, 2001) has been considered as an important mechanism to thin the lithosphere. The lithospheric thinning may proceed with gradual upward migration of the lithosphere–asthenosphere boundary. Alternatively, the thinning could proceed in the way that the old SCLM was penetrated and desegregated by hot mantle materials which rise along lithospheric shear zones and spread like mushroom clouds (Xu, 2001). In this case, the remains of SCLM should have Archean ages, as the SCLM prior to its thinning beneath the North China Craton has Archean ages (Gao et al., 2002; Wu et al., 2006; Zhang et al. 2008a; Chu et al., 2009). As a consequence, the SCLM is stratified with old lithosphere overlying newly-formed lithosphere mantle (Griffin et al. 1998b; Menzies and Xu, 1998; Xu et al., 2004a). Similarly, the replacement model (Zheng et al. 2001) is also based on the lithosphere–asthenosphere interaction that can modify the SCLM roots of ancient cratons and lead to their replacement by more fertile material (Griffin et al., 1992, 1998a,b; Pearson, 1999a,b; O'Reilly et al., 2001). The lithospheric replacement appears to be a consequence of mechanical rifting, providing conduits of upwelling asthenospheric material, and

the newly-accreted lithospheric mantle could be heterogeneously distributed (Zheng et al., 2001). Both the thermo-mechanical erosion and emplacement models can well explain the coexistence of old and young SCLM. If they are the main mechanisms responsible for the lithospheric thinning, the present SCLM should have two peaks of Archean and Mesozoic ages due to the large-scale thinning in the Mesozoic (Zhang et al., 2009a). However, the present-day SCLM, sampled as xenoliths by the Cenozoic basalts, has a continuity of ages from Archean to Cenozoic (Tang et al., 2013, in press and references therein), indicating that the two models are not the main mechanisms for the lithospheric thinning of the North China Craton. In addition, the two models cannot well explain the compositional changes of the relics of Archean SCLM (Zhang et al., 2009a).

The progressive melt modification model (Zhang et al., 2002, 2007a, 2008a, 2009a, 2010; Zhang, 2005; Xu et al., 2008b) suggested that old refractory SCLM was transformed to young fertile mantle through melt–rock reaction. This model predicts that the present-day SCLM should have a broad spectrum of ages and compositions. Thus, it can explain the continuity of ages and rapid compositional change of the SCLM (Zhang et al. 2002, 2003, 2007a,b, 2009a; Zhang, 2005). Refertilization of the SCLM by peridotite-melt reactions is believed to be a key point to destroy the North China Craton because it will change the chemical composition, thermal regime and physical property of the SCLM, based on the recent reviews (Gao et al., 2009; Xu et al., 2009; Zhang, 2009; Zheng, 2009; Zheng and Wu, 2009). Consequently, here we will focus our discussion primarily on the evidence for refertilization of the Archean SCLM, attempting to expand on the previous studies by integrating major and trace element, Sr, Nd and Os isotopic data of peridotite xenoliths from the craton according to our ever increasing understanding of the SCLM evolution of the North China Craton and other cratons worldwide.

2.1. Major and trace element evidence

As there are large amounts of whole-rock and sulfide Re–Os data of peridotite xenoliths from the Hannuoba locality, a Cenozoic basalt highland covering over 1700 km^2 (Chen et al., 2001) of the northern North China Craton (Fig. 1), the Hannuoba basalt-hosted xenoliths are set apart from the other North China Craton xenoliths to show the geochemical variations of peridotite xenoliths from the individual locality. It is commonly believed that kimberlite-hosted peridotite xenoliths are representative of ancient cratonic SCLM, while basalt-hosted xenoliths represent the samples of Phanerozoic mantle (Boyd, 1989; Griffin et al., 2009 and references therein). Thus, the xenoliths data in this paper are separated into kimberlite- versus basalt-hosted groups.
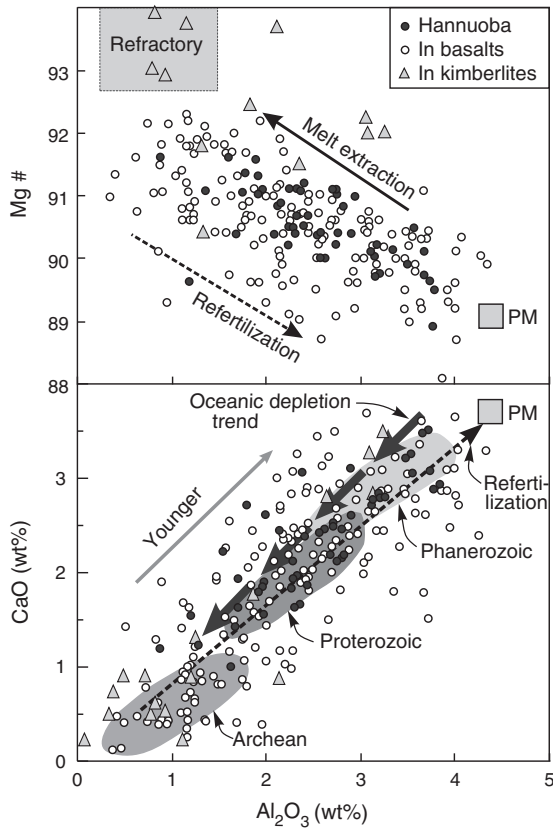
The peridotite xenoliths from the North China Craton show considerable variation in major element compositions from fertile (close to primitive mantle) to highly refractory (with MgO content higher than 48%; Fig. 2). Some refractory peridotites, in particular, Paleozoic kimberlite-borne xenoliths, have compositions approaching the average cratonic peridotite from the Kaapvaal craton and fall in the compositional fields for cratonic peridotites (Boyd, 1989; Griffin et al., 1999a; Lee and Rudnick, 1999) and melting residues of fertile peridotite (Herzberg, 2004). The peridotite xenoliths from the North China Craton define a strong trend of increasing Al$_2$O$_3$ content with increasing CaO content (Fig. 3). The variations in major oxides are observed not only in the peridotite samples from the individual Hannuoba locality, but also in those either hosted by other Cenozoic basalts or hosted by the Paleozoic diamondiferous kimberlites on this craton. Many of the peridotite xenoliths display SiO$_2$ enrichment relative to the residues of fertile peridotite (Fig. 4). There is a roughly negative correlation between Al$_2$O$_3$ and La/Yb ratios (Fig. 5).

It is known that the extraction of mafic to ultramafic melts from a fertile peridotite with a primitive mantle composition will result in a residue with depletion in basaltic components such as Al$_2$O$_3$, CaO, TiO$_2$ and Na$_2$O (e.g., Herzberg, 2004). Abyssal peridotites, most
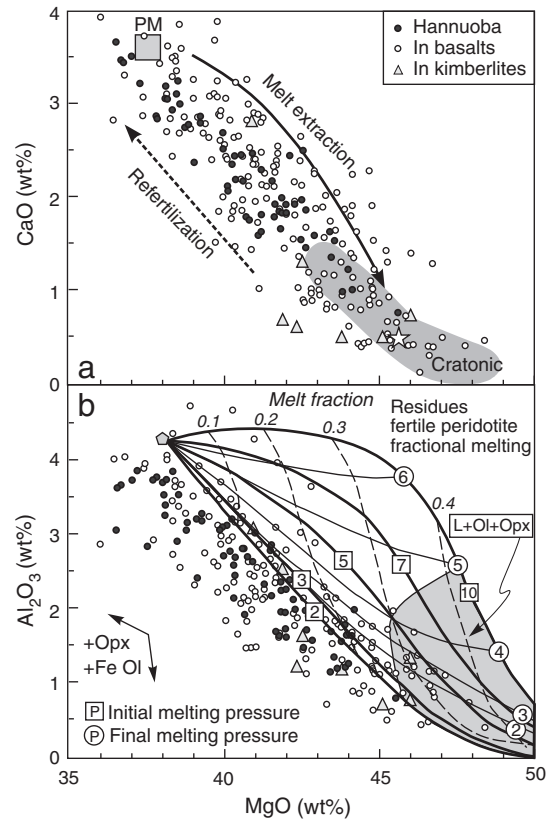

Fig. 2. Plots of Al$_2$O$_3$ (wt.%) and CaO (wt.%) versus MgO (wt.%) for the peridotite xenoliths from the North China Craton. Data sources: Hannuoba peridotites (Fan and Hooper, 1989; Song and Frey, 1989; Tatsumoto et al., 1992; Xie and Wang, 1992; Chen et al., 2001; Rudnick et al., 2004; Tang et al., 2007; Zhang et al., 2009a; Liu et al., 2011); Cenozoic basalt-borne xenoliths (Fan and Hooper, 1989; Zheng et al., 1998, 2001, 2005; Fan et al., 2000; Wu et al., 2003, 2006; Ma and Xu, 2006; Tang et al., 2008, 2011, 2012, 2013; Xu et al., 2008c; Chu et al., 2009; Liu et al., 2011); Paleozoic kimberlite-borne xenoliths (Zhang et al., 2008a; Chu et al., 2009) on the North China Craton. Grey shaded field, star symbol and PM in (a) represent Tanzanian cratonic peridotites (Lee and Rudnick, 1999), the average composition of peridotite xenoliths from the Archon (Griffin et al., 1999a) and primitive mantle (McDonough and Sun, 1995), respectively. Melt extraction trend (solid line) and refertilization trend (broken line) in (a) are from the results of quantitative petrological modeling (Niu, 1997). Fractional melting grid of fertile peridotite (Herzberg, 2004) is given in (b). Bold lines labeled with squares, initial melting pressures; light lines labeled with circles, final melting pressures; light dashed lines, melt fractions; grey shaded fields, compositions of residual harzburgite designated as [L + Ol + Opx]. Addition of Opx and olivine to residues with Mg#<~90 is indicated by vectors (Herzberg, 2004).

alpine and ophiolite peridotites, as well as many peridotite xenoliths from cratonic margins fall along an oceanic depletion trend (Fig. 3), reflecting melt extraction from fertile pyrolitic mantle at relatively low pressures (Boyd, 1989). Thus, negative correlations between whole-rock MgO (Fig. 2) or Mg# (Fig. 3) and indices of fertility (such as Al$_2$O$_3$ and CaO) are traditionally interpreted as the results of melt extraction (Frey and Green, 1974; Boyd and Nixon, 1978; Kurat et al., 1980; Stosch and Seck, 1980; Boyd and Mertzman, 1987; Boyd et al., 1997). However, the approximately linear correlation between the major oxide contents is more a result of refertilization of originally refractory residues than a trend expected of melt extraction of mantle peridotites because model residue compositions formed by fractional melting of fertile peridotite (Niu, 1997; Herzberg, 2004) define hyperbolic trends on the plots of major oxides (Fig. 2), whereas newly-formed peridotites will display a linear correlation between MgO and Al$_2$O$_3$ or CaO (Niu, 1997). Thus, the linear correlations between MgO and indices of fertility observed in these peridotites indicate refertilization process (Griffin et al., 2009; Zhang, 2009), as is initially proposed to explain the texture and chemical trends observed in some oceanic peridotites, which cannot be sufficiently explained by

Fig. 3. Plots of CaO (wt.%) and Mg# versus Al₂O₃ (wt.%) for the peridotite xenoliths from the North China Craton. Mg# = 100 × molar Mg/(Mg + Fe). Oceanic depletion trend shows expected compositions (refractory) of residues after progressive melt extraction from fertile Primitive Mantle compositions (Boyd, 1989). Refertilization trend mimics the oceanic trend, but runs in the opposite direction. The correlations between the compositions of the peridotite xenoliths also reflect a similar refertilization process (Le Roux et al., 2007; Griffin et al., 2009). Age fields for Archean, Proterozoic and Phanerozoic are from O'Reilly et al. (2001). Other data sources are the same as those identified in Fig. 2.
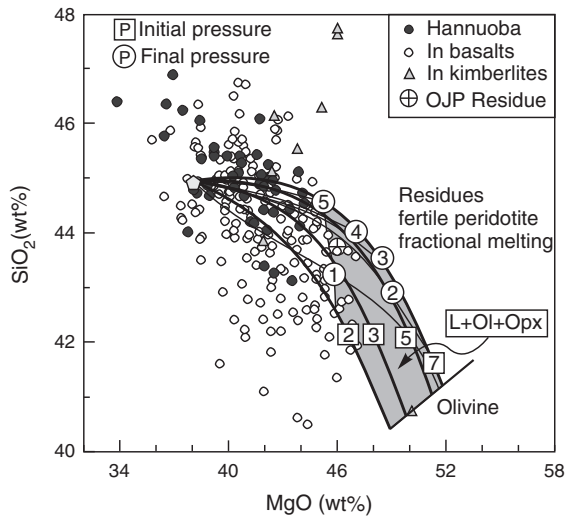

Fig. 4. Diagram of MgO versus SiO₂ (wt.%) for the peridotites from the North China Craton. Fractional melting grid of fertile peridotite is from Herzberg (2004). Bold lines labeled with squares, initial melting pressures; light lines labeled with circles, final melting pressures; grey shaded fields, compositions of residual harzburgite designated as [L + Ol + Opx]. OJP is a model residue computed by mass balance from the model primary magma from the Ontong Java Plateau (Herzberg, 2004). Most samples are too rich in SiO₂ to be residues of fertile peridotite. Other data sources are the same as in Fig. 2.
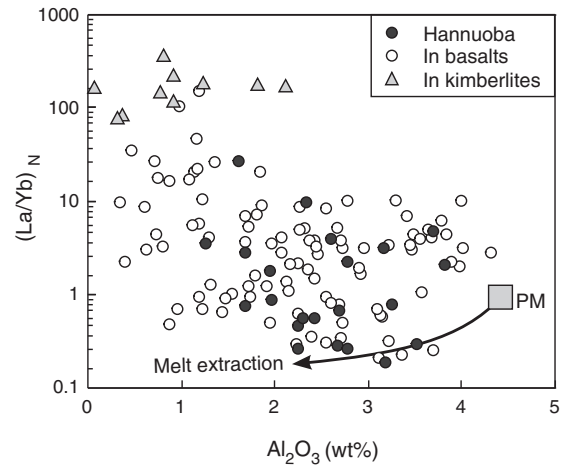
Fig. 5. Variation diagram of (La/Yb)ₙ versus Al₂O₃ (wt.%) for the peridotite xenoliths from the North China Craton. Data sources: Hannuoba peridotites (Song and Frey, 1989; Chen et al., 2001; Rudnick et al., 2004; Tang et al., 2007; Zhang et al., 2009a); Cenozoic basalt-borne xenoliths (Zheng et al., 2001, 2005; Wu et al., 2003; Ma and Xu, 2006; Tang et al., 2008, 2011; Xu et al., 2008c; Chu et al., 2009). Normalization factors after Anders and Grevesse (1989). Other data sources are the same as in Fig. 2.

simple batch and fractional melting models (Elthon, 1992; Niu and Hekinian, 1997; Niu, 1997, 2004; Hellebrand et al., 2002; Barth et al., 2003; Brunelli et al., 2006; Seyler et al., 2007).
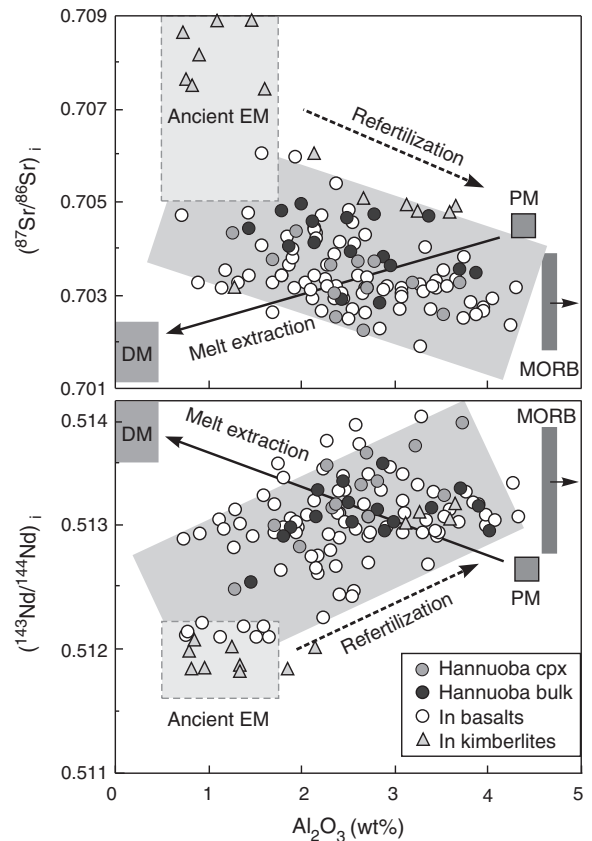
Fig. 6. Relationship between initial Sr–Nd isotopic ratios and Al₂O₃ (wt.%) for the peridotite xenoliths from the North China Craton. The fields for Sr–Nd isotopic compositions of depleted mantle (DM), mid-oceanic ridge basalt (MORB), primitive mantle (PM), and ancient enriched mantle (EM) are from Zindler and Hart (1986). Al₂O₃ contents for MORB, PM, DM and EM are estimates from Presnall et al. (2002), McDonough and Sun (1995) and Griffin et al. (2009). Data sources: Hannuoba peridotites (Song and Frey, 1989; Tatsumoto et al., 1992; Rudnick et al., 2004; Tang et al., 2007; Zhang et al., 2009a); Cenozoic basalt-borne xenoliths (Ma and Xu, 2006; Tang et al., 2008, 2011; Xu et al., 2008c; Chu et al., 2009). Other data sources are the same as in Fig. 2.

Since the elements Ca and Al are removed from the mantle residue during melt extraction, "typical" Archean SCLM estimated from garnet xenocrysts and xenolith suites is highly depleted and refractory (Griffin et al., 2009), with CaO and Al_2O_3 contents less than 1 wt.% and 1.5 wt.%, respectively (Fig. 3). In contrast, most Proterozoic and Phanerozoic SCLM are only moderately depleted compared with primitive mantle (O'Reilly et al., 2001; Beyer et al., 2006; Griffin et al., 2009). However, refertilization of an originally depleted source by melts rich in basaltic components can produce essentially the same trend by addition of Al, Ca and Fe to the peridotites, crystallizing clinopyroxene (cpx) at the expense of olivine and orthopyroxene (opx) (Griffin et al., 2009 and references therein). Therefore, the linear correlation between whole-rock Al_2O_3 and CaO contents in the peridotites, a common phenomenon in mantle peridotite xenoliths worldwide (Boyd, 1989; Boyd et al., 1997; Griffin et al., 1999a, 2003a, 2009), reflects refertilization trend that parallels the "depletion trend", but runs in the opposite direction (Fig. 3).

According to the comprehensive mass-balance petrological model of Herzberg (2004), many of the peridotites from the North China Craton fall out of the fields for melting residues of fertile peridotite due to their high contents of Al_2O_3 (Fig. 2) and SiO_2 (Fig. 4), exhibiting too enrichment in opx to be residues (Fig. 2). Therefore, the observed trends between major oxide contents of these peridotites reflect refertilization rather than simple depletion, which is also evidenced by a number of petrologic and geochemical observations that many peridotite xenoliths appear to have had opx added during melt-rock reaction or some other processes (Kelemen et al., 1992, 1998; Herzberg, 1993; Griffin et al., 1999b).

The $(La/Yb)_N$ ratios in the peridotite xenoliths from the North China Craton (Fig. 5) are apparently higher than that of primitive mantle and deviate from the expected trend if these xenoliths are the melting residues of primitive mantle. Therefore, the variations in major and trace element contents in these peridotites were the results of refertilization. This inference is also supported by the data of Sr, Nd and Os isotopes in these peridotites (see below).

2.2. Sr–Nd isotopic evidence

The Sr and Nd isotope compositions of the peridotite xenoliths (whole-rock and cpx data) from the North China Craton show a large variation, ranging from the character of depleted mantle to enriched mantle (Fig. 6). The isotopic ratios, in general, correlate with whole-rock Al_2O_3 contents; fertile peridotites (with high Al_2O_3 contents) are higher in $^{143}Nd/^{144}Nd$ ratios and lower in $^{87}Sr/^{86}Sr$ ratios than refractory samples (low in Al_2O_3). This correlation was previously observed in the Hannuoba peridotite xenoliths (Song and Frey, 1989; Rudnick et al., 2004; Zhang et al., 2009a) and was ascribed to ancient melt depletion followed by recent metasomatism by a fluid or melt having an evolved isotopic signature (Rudnick et al., 2004). However, this explanation cannot well account for the absence of correlation 1/Sr and $^{87}Sr/^{86}Sr$ and the scatter on the plots of Sr–Nd isotopes versus Al_2O_3, and thus requires additional process (Rudnick et al., 2004).

Partial melting will result in the decrease of Rb/Sr ratio but increase Sm/Nd ratio of a peridotite, refractory peridotites (low Al_2O_3) thus are lower in Rb/Sr and higher Sm/Nd than primitive mantle. As a result, refractory peridotites should be lower in $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ ratios than fertile peridotites and primitive mantle, which is completely opposite to the observation from these peridotites (Fig. 6). Therefore, the correlations between Sr–Nd isotopic compositions and whole-rock chemical compositions are hardly consistent with residues evolved only from partial melting of peridotites with primitive mantle composition, possibly reflecting different degrees of refertilization of originally refractory peridotite precursors through reaction with asthenosphere-derived melts (Griffin et al., 1999b, 2003a, 2004a,b; 2009; Xu et al., 2003, 2008b; Rudnick et al., 2004; Zheng et al., 2007; Zhang, 2009).

Based on previous studies of the peridotite samples from the North China Craton (Tang et al., 2008, 2011, 2013; Xu et al., 2008b,c, 2010; Zhang et al., 2009a, 2012; Liu et al., 2011), we suggest that most of these peridotite xenoliths have been recently refertilized by asthenosphere-derived melts after early partial melting. The percolating melts derived from asthenosphere should be similar to depleted mantle in their low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ ratios, while refractory peridotites have evolved Sr and Nd isotopic compositions (EM1-like) due to ancient enrichment events likely related to the Paleoproterozoic subduction/collision between the eastern and western blocks of the North China Craton (Zhang et al., 2004; Wang et al., 2006; Xu et al., 2008c; Tang et al., 2008, 2011, 2013). Therefore, recent refertilization of the refractory peridotites by reaction with asthenospheric melts led to the decrease of $^{87}Sr/^{86}Sr$ ratios and the increase of $^{143}Nd/^{144}Nd$ ratios associated with the increase of Al_2O_3 in the
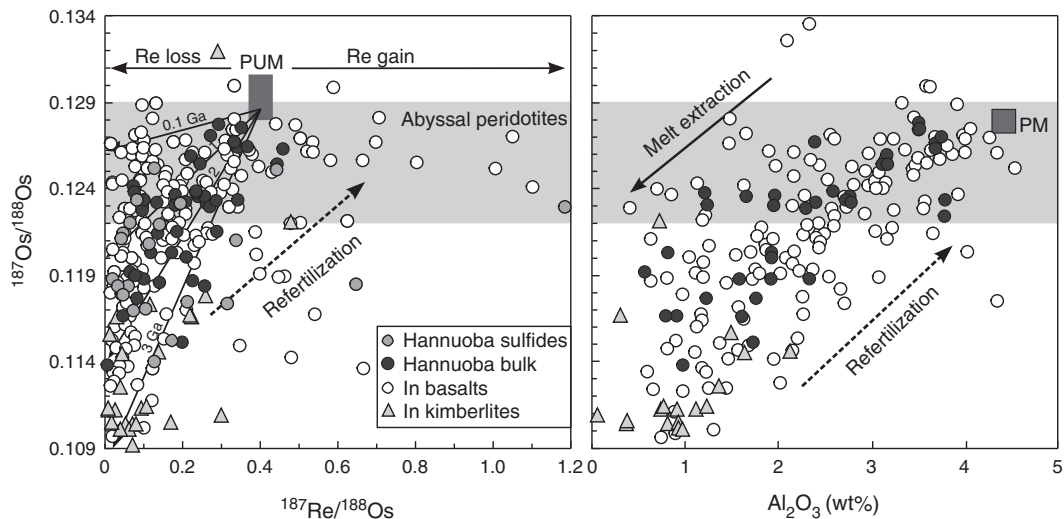
Fig. 7. Diagrams of $^{187}Re/^{188}Os$ and Al_2O_3 (wt.%) versus $^{187}Os/^{188}Os$ for the peridotites from the North China Craton. Data sources: abyssal peridotites (Snow and Reisberg, 1995); Hannuoba peridotites (Gao et al., 2002; Xia et al., 2004; Zheng et al., 2007; Xu et al., 2008b; Zhang et al., 2008a, 2009a; Liu et al., 2011); Cenozoic basalt-borne xenoliths (Zhi et al., 2001; Gao et al., 2002; Wu et al., 2003, 2006; Zhi and Qin, 2004; Zheng et al., 2007; Xu et al., 2008c; Chu et al., 2009; Liu et al., 2011); Paleozoic kimberlite-borne xenoliths (Gao et al., 2002; Wu et al., 2006; Zhang et al., 2008a; Chu et al., 2009). Area labeled PUM (the primitive upper mantle) and isochrons at various times (0.1, 1, 2 and 3 Ga) are from Meisel et al. (2001) and Pearson (1999b), respectively.

relatively fertile peridotites. The large variations in Sr–Nd isotopic compositions and Al_2O_3 contents (Fig. 6) thus likely reflect the varying degrees of refertilization. Many cases of transformation of highly refractory lithospheric mantle (subcalcic harzburgites) via refertilization, producing relatively fertile peridotites (lherzolites) and pyroxenites have been well documented (Stiefenhofer et al., 1997; Mukasa and Shervais, 1999; Pearson, 1999a; Lenoir et al., 2001; Griffin et al., 2003b, 2005; Carlson et al., 2004; Müntener et al., 2004; Beyer et al., 2006; Raffone et al., 2009). It should be noted that some peridotite xenoliths, with fertile chemical compositions (e.g., close to primitive mantle in Al_2O_3 content; Fig. 6) and MORB-like Sr–Nd isotopic compositions, could represent the newly-accreted lithospheric mantle, as is recognized beneath the eastern North China Craton (Griffin et al., 1998b; Menzies and Xu, 1998; Xu et al., 1998; Zheng et al., 1998, 2005; Fan et al., 2000; Xu and Bodinier, 2004; Zhang et al., 2010). However, it is still poorly established whether these fertile lherzolites actually represent fragments of the refertilized mantle peridotites, or simply parts of the new accretion of lithospheric mantle, due to their indistinguishable characteristics of petrology and geochemistry, similar to those of "oceanic" mantle peridotites.

2.3. Re–Os isotopic evidence

The Re–Os isotopic system is considered to be a reliable means to determine the age of melt extraction of mantle peridotites (e.g., Walker et al. 1989). Osmium is a highly compatible element and is preferentially retained in the mantle during partial melt generation. Rhenium is moderately incompatible and enters the melt (it is worth noting that Re is highly compatible in sulfides; Griffin et al., 2004a; Aulbach et al., 2009). Thus, melt depletion generates a low Re/Os ratio in the residue which, with time, through the decay of ^{187}Re (parent) to ^{187}Os (daughter), evolves to unradiogenic $^{187}Os/^{188}Os$ ratios compared to those of the contemporaneous undepleted mantle (e.g., Walker et al., 1989; Shirey and Walker, 1998; Pearson, 1999a; Meisel et al., 2001). Thus, Os isotope systematics for cratonic peridotites appear to be dominantly influenced by the ancient depletion events that caused them to separate from the convecting mantle. In contrast, both parent and daughter elements in other radiogenic systems (e.g. Rb–Sr and Sm–Nd) are strongly concentrated in the melt during mantle melting and these systems are susceptible to later enrichment events (Pearson, 1999a and references therein). Therefore, the Re–Os system has proven to be particularly useful in tracing the geochemical evolution of mantle rocks and in defining the chronology of mantle evolution (Walker et al., 1989; Shirey and Walker, 1998; Pearson, 1999a; Peslier et al., 2000b; Saal et al., 2001; Pearson et al., 2003; Carlson, 2005; Reisberg et al., 2005).

At first, the Re–Os system was considered to be immune from disturbance caused by metasomatism due to low Os contents in common metasomatic agents (Walker et al., 1989; Handler et al., 1997; Shirey and Walker, 1998; Pearson, 1999a; Reisberg et al., 2005). Many recent studies, however, have provided evidence that the Re–Os system in mantle peridotites can be disturbed and even totally resetted by late-stage melt percolation and peridotite-melt reaction, especially when reaction preceded eruption (when a portion of the mantle was carried to the surface as a xenolith) by large time intervals (Brandon et al., 1996; Pearson et al., 1998; Chesley et al., 1999; Burton et al., 2000; Becker et al., 2001; Alard et al., 2002; Widom et al., 2003; Zhang et al., 2008a, 2009a, 2012; Ackerman et al., 2009; Xiao and Zhang, 2011).

Re–Os mantle model age (T_{MA}) is used to constrain the time of melt depletion and metasomatic processes involving sulfide (such as Cu, Fe and Ni sulfides) melts. T_{Ma} ages are based on the extrapolation of the Os isotope composition of a peridotite to the chondritic evolution curve, using the measured Re/Os ratio of the sample (Walker et al., 1989; Shirey and Walker, 1998). Nevertheless, T_{MA} may be future ages or ages older than the true age of a melt extraction
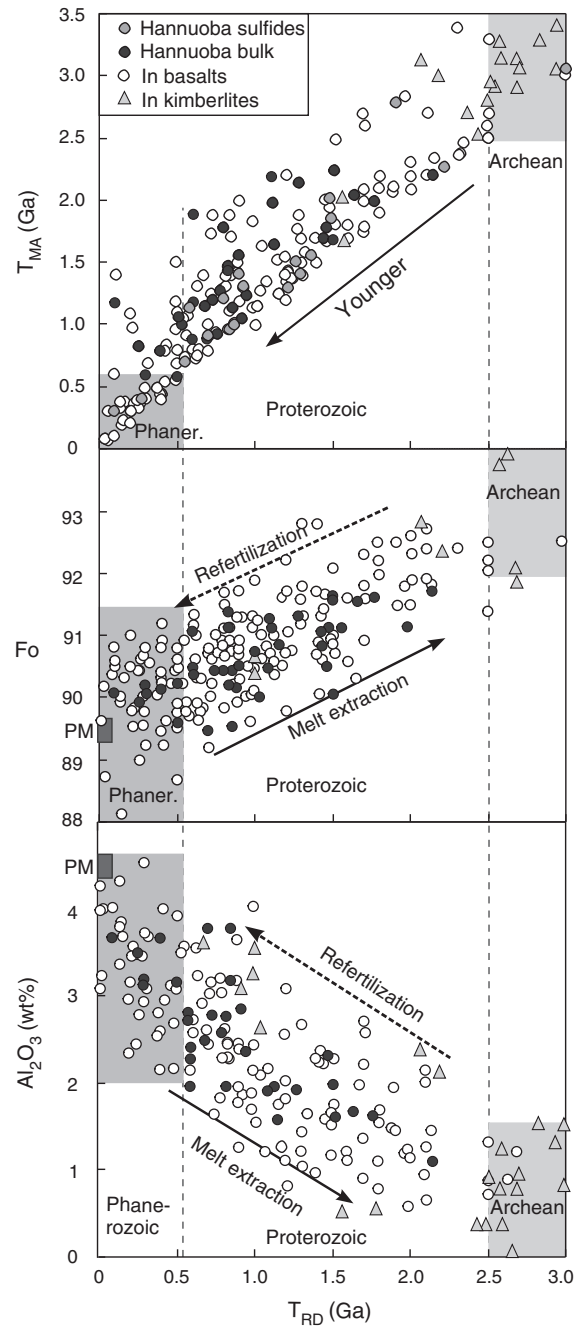
Fig. 8. Diagrams of T_{MA}, Fo and Al_2O_3 (wt.%) versus T_{RD} model ages of peridotite xenoliths and sulfides from the North China Craton. Data sources are the same as in Fig. 7.

because Re may be added to or removed from a peridotite by the processes of mantle metasomatism and interactions between peridotite xenolith and host rocks (Shirey and Walker, 1998; Pearson, 1999b; Gao et al., 2002; Wu et al., 2003; Griffin et al., 2004a; Carlson, 2005; Wu et al., 2006; Xu et al., 2008b; Zhang et al., 2008a). The time of Re depletion (T_{RD}) age is by definition the minimum age of Re depletion assuming zero Re/Os in the sample (i.e. complete Re depletion). T_{RD} represents the time of separation of a peridotite from a chondritic reservoir (Walker et al., 1989; Shirey and Walker, 1998). T_{RD} ages approach the true age of melting for highly depleted peridotites because Re is almost completely removed from the residue at high degrees of melting. Whereas, the T_{RD} age will underestimate the true age of a melt extraction event for relative fertile peridotites and those affected by substantial Re or Os addition well prior to xenolith eruption (Shirey

and Walker, 1998; Brandon et al., 1999; Burton et al., 1999; Chesley et al., 1999; Pearson, 1999a; Burton et al., 2000; Becker et al., 2001, 2004; Saal et al., 2001; Büchl et al., 2002; Schmidt and Snow, 2002; van Acken et al., 2008; Zhang et al., 2008a, 2009a).

In a lithospheric volume that has undergone melt depletion, followed by episodic refertilization events, sulfides in mantle perido- tites may record highly variable Re–Os model ages, reflecting the reaction between "old" sulfides (residual after melt depletion) and "young" sulfides (interstitial sulfides newly produced by melt/ fluid-peridotite reaction), which has been demonstrated in previous studies (Pearson et al., 1999, 2002; Alard et al., 2002; Griffin et al., 2002, 2004a; Aulbach et al., 2004; Xu et al., 2008b; Zhang et al., 2008b, 2009a, 2012; Harvey et al., 2010). Interstitial sulfides, preserved along silicate grain boundaries, are lower in Os and higher in Re concen- tration than "old" sulfides enclosed in silicate grains (Harvey et al., 2011). Thus, the bulk-rock Re and Os budget will be controlled by the Re–Os budget and proportions of the different generations of sulfides. The latter are dependent on melt/rock ratios and the degree of S-saturation of percolating melt because S-undersaturated melt can dissolve some sulfides (Lorand et al., 2003; Reisberg et al., 2004; Reisberg et al., 2005; Ackerman et al., 2009; Zhang et al., 2009a, 2012; Xiao and Zhang, 2011). As a result, melt infiltration could significantly change the Os isotopic compositions of peridotites due to the removal of primary sulfides (unradiogenic $^{187}Os/^{188}Os$) and subsequent precip- itation of sulfides bearing radiogenic Os (e.g., Alard et al., 2005; Powell and O'Reilly, 2007; Ackerman et al., 2009). Consequently, whole-rock Os isotope compositions reflect the proportions of different generations of enclosed and interstitial sulfides, which calls into question the signif- icance of many published whole-rock "depletion ages" (Pearson et al., 2002).

The Re–Os isotopic compositions of the peridotite xenoliths from the North China Craton vary greatly, with $^{187}Re/^{188}Os$ ranging from 0 to 1.2 and $^{187}Os/^{188}Os$ from 0.109 to 0.132 (Fig. 7). Most of the Paleozoic kimberlite-borne peridotites except a few with varying Os isotopic ratios have strongly unradiogenic isotopic compositions, consistent with ancient Re-depletion (Archean T_{RD} ages; Fig. 8). In contrast, the xenoliths hosted by Cenozoic basalts show a large range of Os isotopic compositions, from close to depleted mantle to primitive upper mantle (PUM) as estimated from abyssal peridotites (Brandon et al., 2000) and worldwide mantle xenoliths (Meisel et al., 2001). The $^{187}Os/^{188}Os$ ratios roughly correlate with the $^{187}Re/^{188}Os$ and Al_2O_3 (Fig. 7). The scatter in the data clearly requires more complex explanation than simple one-stage Re-depletion model. For example, numerous samples have bulk Re contents and $^{187}Re/^{188}Os$ ratios much higher than the PUM, yet fairly unradiogenic Os, indicating recent Re addition (Chesley et al., 1999; Meisel et al., 2001) at low melt/rock ratios or Os addition at high melt/rock ratios (Becker et al., 2001; Reisberg et al., 2004). The positive correlation between $^{187}Os/^{188}Os$ and Al_2O_3 is traditionally interpreted as the result of radiogenic ingrowth since an ancient episode of melt extraction (Reisberg and Lorand, 1995; Reisberg et al., 2004). However, this hypothesis does not account for the negative correlation of $^{87}Sr/^{86}Sr$ and the positive correlation of

$^{143}Nd/^{144}Nd$ with Al_2O_3. These covariations likely reflect incomplete mixing (refertilization) of refractory harzburgites with asthenospheric material during erosion of SCLM by upwelling asthenospheric mantle (Saal et al., 2001; Bodinier and Godard, 2003; Zhang, 2009). It is possible that some peridotites lying to the left hand side of the isochron of 3 Ga (Fig. 7) have lost Re due to sulphides breakdown during eruption of the xenoliths (Lorand, 1990) but this is hard to verify (Pearson, 1999a).

The Hannuoba peridotites have predominantly Proterozoic whole- rock Re–Os model ages, resembling the Cenozoic basalt-borne perido- tite xenoliths from other localities on the North China Craton (Fig. 8). In contrast, the in situ T_{RD} and T_{MA} ages of sulfides in the Hannuoba samples show a larger range, from Archean to Phanerozoic model ages, than the whole-rock ages (from Proterozoic to Phanerozoic) of the peridotites, strongly indicating that the whole-rock ages are the mixing ages of different generations of sulfides (Pearson et al., 2002; Xu et al., 2008b; Zhang et al., 2009a). The T_{RD} ages of these peridotites apparently correlate with whole-rock Al_2O_3 and olivine Fo contents (Fig. 8). This correlation is traditionally explained as melting trend because the high-degree partial melting of primitive mantle (Boyd, 1975; Jordan, 1975; Pollack, 1986; King, 2005) resulted in low Al_2O_3 and high olivine Fo. However, the above correlation also reflects the possibility of reaction trend of a depleted residue with asthenosphere-derived melts. The refertilization of peridotites could lower the mean Fo of olivine (Griffin et al., 2005, 2009; Zhang, 2005) and result in the positive correlations between Re and Al_2O_3, Yb and TiO_2 contents in the peridotites from the North China Craton (Zhang et al., 2009a), as is observed in the peridotites from the south- ern Bohemian massif (Becker et al., 2001). Therefore, the covariations of T_{RD} ages with Al_2O_3 and olivine Fo contents suggest that the mantle process that decreased the olivine Fo and increased the Al_2O_3 in the xenoliths through refertilization meanwhile rejuvenated the peridotites.

The xenoliths in the Paleozoic kimberlites have Archean Re–Os isotopic ages, suggesting the existence of Archean SCLM beneath the North China Craton during the Paleozoic (Gao et al., 2002; Wu et al., 2006; Zhang et al., 2008a; Chu et al., 2009). In contrast, the peridotite xenoliths in the Cenozoic basalts have dominantly Proterozoic T_{RD} ages, and only a few xenoliths from the eastern part of the craton have Phanerozoic T_{RD} ages (Fig. 8). The latter could be the fragments of the newly-accreted SCLM, as noted previously (Fan and Menzies, 1992; Xu et al., 1998; Zheng et al., 1998; Ying et al., 2006). Thus, the observation that Archean model ages are rare in Cenozoic basalts re- flect that nearly all the Archean SCLM has been replaced (Gao et al., 2002; Wu et al., 2006; Chu et al., 2009) and/or modified (Xu et al., 2008b; Zhang et al., 2008a, 2009a) by episodic additions of young mantle materials beneath the North China Craton (Xiao et al., 2010; Tang et al., 2011, 2012; Xiao and Zhang, 2011). Some basalt-hosted xenoliths have whole-rock (Xu et al., 2008c) or in situ sulphide (Zheng et al., 2007; Xu et al., 2008b) Archean T_{RD} ages (Fig. 8), implying the presence of Archean SCLM. However, the wide range of Os isotopic ratios and T_{RD} ages (Figs. 7 and 8) within sulfides from an individual peridotite xenolith supports the model of SCLM refertilization (Xu et

**Fig. 9.** Plots of Al_2O_3 (wt.%) and CaO (wt.%) versus MgO (wt.%) for the mantle peridotites from global ancient cratons and orogenic regions. Data sources: Siberian peridotites (Press et al., 1986; Ionov and Wood, 1992; Ionov et al., 1992a,b, 1993a,b, 1994, 1995a,b, 1996, 2005a,b, 2006a,b; Ionov and Hofmann, 1995, 2007; Pearson et al., 1995b, 2004; Boyd et al., 1997; Ionov, 2007, 2010); Australian peridotites (Frey and Green, 1974; Burwell, 1975; Wilkinson, 1975; O'Reilly and Griffin, 1987, 1988; Stolz and Davies, 1988; Chen et al., 1989; Frey et al., 1989; Yaxley et al., 1991; Canil et al., 1994; Becker, 1996; McBride et al., 1996; Handler et al., 1997, 2005; Eggins et al., 1998; Norman, 1998; Meisel et al., 2001; Alard et al., 2002); European peridotites (Paul, 1971; Kurat et al., 1980; Frey et al., 1985; Downes and Dupuy, 1987; Bodinier et al., 1988, 2004; Downes et al., 1992, 2002, 2003; Reisberg and Lorand, 1995; Vaselli et al., 1995, 1996; Becker, 1996; Meisel et al., 1997, 2001; Zangana et al., 1999; Beccaluva et al., 2001; Becker et al., 2001; Alard et al., 2002; Ionov et al., 2002; Femenias et al., 2003; Beyer et al., 2004, 2006; Medaris et al., 2005; Ackerman et al., 2007, 2009; Bianchini et al., 2007; Cvetkovic et al., 2007; Le Roux et al., 2007; Piccardo et al., 2007; Tessalina et al., 2007; van Acken et al., 2008; Mazzucchelli et al., 2009; Soustelle et al., 2009; Harvey et al., 2010); American peridotites (Frey and Prinz, 1978; Stosch and Seck, 1980; Ehrenberg, 1982; Feigenson, 1986; Roden et al., 1988; Liang and Elthon, 1990; Carlson and Irving, 1994; Nimz et al., 1995; Bernstein et al., 1998; Schmidberger and Francis, 1999; Stern et al., 1999; Lee et al., 2000; Peslier et al., 2000a, 2002; Meisel et al., 2001; Irvine et al., 2003; Carlson et al., 2004, 2007; Downes et al., 2004; Kopylova and Caro, 2004; Lucassen et al., 2005; Schilling et al., 2005; Ntaflos et al., 2007; Rivalenti et al., 2007; Bjerg et al., 2009); African peridotites (Carswell and Dawson, 1970; Nixon and Boyd, 1973; Nixon et al., 1981; Boyd and Mertzman, 1987; Erlank et al., 1987; Harte et al., 1987; Menzies et al., 1987; Winterburn et al., 1990; Boyd et al., 1993, 2004; Rudnick et al., 1993; Canil et al., 1994; Pearson et al., 1995a; Stiefenhofer et al., 1997; Meisel et al., 2001; Gregoire et al., 2003, 2005; Simon et al., 2003, 2007; Griffin et al., 2004a; Reisberg et al., 2004; Kuskov et al., 2006; Gibson et al., 2008; Raffone et al., 2009; Wittig et al., 2010a,b). Other data sources and fractional melting grids are the same as in Fig. 2.

al., 2008b). The effects of refertilization on mantle Re–Os isotopes have been well documented for the peridotites from other regions of the world (Pearson et al., 1999, 2002; Alard et al., 2002; Griffin et al., 2002, 2004a; Aulbach et al., 2004; Harvey et al., 2010). Therefore, the T_{RD} ages of Proterozoic and Phanerozoic for most of the samples from the North China Craton (Fig. 8) cannot represent the melt-extraction ages of the peridotites, but are the mixtures of different-generation sulfides produced by refertilization of the SCLM.

2.4. Key role of refertilization in the destruction of the North China Craton

As discussed above, the characteristics of major and trace element, Sr–Nd and Re–Os isotopic compositions in the peridotite xenoliths suggest that the SCLM beneath the North China Craton formed during the Archean and experienced extensive refertilization. Episodic additions of melts resulted in the loss of Archean refractory signature of the SCLM and rejuvenate the ancient SCLM by lowering the Re–Os
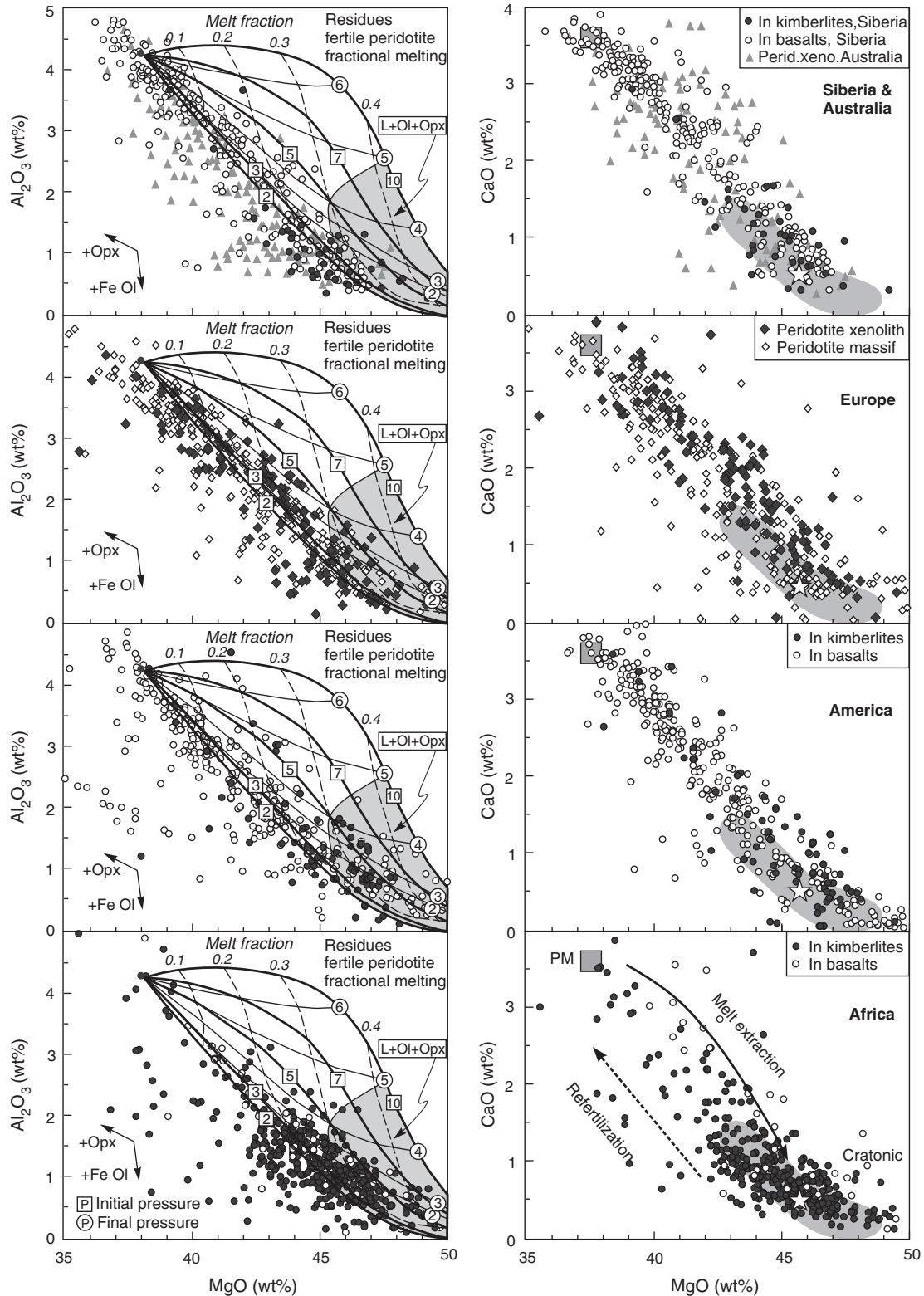
model ages to intermediate between the original formation age and the timing of the refertilization (Zhang et al., 2008a, 2009a).

Many case studies have reported textural or chemical evidence for refertilization of peridotites, such as, the tectonically-emplaced peridotites in Oman (Godard et al., 2000), Horoman (Saal et al., 2001), Lherz Maffis (Le Roux et al., 2007), western Alps (Müntener et al., 2004, 2010; Piccardo et al., 2007; Rampone et al., 2010) and the Western Gneiss Region of western Norway (Beyer et al., 2006). It appears that large-scale refertilization is specific of tectonically-emplaced, orogenic peridotites. However, refertilization has also been observed in the previously depleted, Archean SCLM (see below).

Since the Paleozoic, the North China Craton has experienced a series of circum-craton subduction/collision events, as evidenced by the Paleozoic to Triassic Qinling-Dabie-Sulu ultrahigh-pressure belt in south (Li et al., 1993; Ye et al., 2000), the Central Asian Orogenic Belt in north (Xiao et al., 2003; Zhang et al., 2003) and the Mesozoic–Cenozoic subduction of Pacific plate in east (Xu and Zhao, 2009; Zhu and Zheng, 2009). These events provided subducted-slab-derived fluids/melts that significantly modified the geochemical compositions and geophysical characteristics of the SCLM (Menzies et al., 2007; Windley et al., 2010; and references therein) and thus have been considered as the key driving force for the transformation of the ancient SCLM during the Mesozoic (Zhang et al., 2002, 2003, 2008a, 2009a, 2010; Chen and Zhou, 2005; Yang et al., 2012; Tang et al., 2013). Extensive refertilization and thinning of the SCLM by fertile material upwelling along breaks and weak zones in the Archean root could be further strengthened by the subduction of the Pacific plate since the Late Mesozoic (Zhu et al., 2011, 2012; Xu et al., 2012; Zheng et al., 2012; Tang et al., in press; and references therein). Accordingly, the SCLM has been refertilized by multistage peridotite-melt reactions (Zhang, 2005, 2009; Tang et al., 2007, 2011, 2012; Zhang et al., 2007a,b,2009a, 2010, 2011a). Early-stage melts might be mainly derived from recycled crustal materials because the Mesozoic modified SCLM have unradiogenic Nd isotopic compositions (Guo et al., 2001; Xu, 2002; Zhang et al., 2002, 2003, 2004; Yang et al., 2004; Wang et al., 2006). The infiltration of crustal melts in the SCLM and reaction with peridotites have been identified in xenocrysts, eclogite, pyroxenite and peridotite xenoliths from the Mesozoic basaltic rocks (Xu et al., 2006, 2008a; Zhang et al., 2002, 2003, 2004, 2007b, 2010, 2011b). In contrast, the melts during the recent refertilization could be mainly derived from the asthenosphere, which has been addressed based on the characteristics of elemental and isotopic compositions in the Cenozoic basalt-hosted peridotite xenoliths.

Petrologic and geochemical signatures of the SCLM modified by melt additions have been reflected by the basaltic rocks and deep-seated xenoliths from northern (Zhang et al., 2003; Gao et al., 2004; Xu et al., 2004a; Liu et al., 2005, 2010; Tang et al., 2007; Zheng et al., 2007; Xu et al., 2008b), eastern (Guo et al., 2001; Zhang et al., 2002, 2009b, 2010, 2011a,b; Zhang, 2005, 2007; Ying et al., 2006; Xu et al., 2008a; Xiao et al., 2010; Huang et al., 2012; Tang et al., 2012; Xu et al., 2012), southern (Zheng et al., 2006b; Liu et al., 2012) and western (Xu et al., 2005; Tang et al., 2006, 2008, 2011; Ying et al., 2007; Zhang et al., 2012) portions of the North China Craton. Therefore, the refertilization by episodic melt-peridotite reactions could be widespread in the SCLM beneath the whole craton and thus be an important mechanism for the rejuvenation and erosion of the Archean SCLM, leading to the great transformation of the SCLM and the destruction of the North China Craton.

3. Refertilization of SCLM worldwide

More than 2100 peridotite bulk rock analyses were compiled from 123 data sources in the literature. Among them, around 1800 analyses are for major element compositions, and yet relatively small numbers of analyses for Sr, Nd and Os isotopes because major and trace element, Sr, Nd and Os isotopic compositions are not always analyzed

in the same sample or all samples in a suite. These peridotite samples were firstly divided according to the geographic location (such as Siberia, Australia, Europe, America and Africa), and then subdivided according to tectonic environment (i.e. orogenic massif or volcanic xenoliths) (Fig. 9).

3.1. Element correlations in peridotites

According to the original recognition (Boyd, 1989; Boyd et al., 1997), Archean cratonic SCLM is represented by the peridotite xenoliths in African and Siberian kimberlites, and Phanerozoic circumcratonic mantle is represented by the xenoliths in intraplate basalts. It is interesting that some kimberlite-borne xenoliths from African, Siberian and American have relatively fertile compositions of major oxides, approaching to primitive mantle, and many xenoliths plot out of the grid for melting residues of fertile peridotite (Herzberg, 2004) due to their relatively low MgO and high Al_2O_3 contents (Fig. 9). These observations, combined with the linear correlations among whole-rock Al_2O_3, CaO and MgO contents (Fig. 9) and the strong trend of increasing CaO with increasing Al_2O_3 content (Fig. 10), suggest that some portions of the Archean SCLM worldwide have been refertilized to varying degrees as noted above for the peridotites from the North China Craton. In contrast, the variation in major oxide contents (Figs. 9–11) in the kimberlite-borne peridotite xenoliths from America and Africa is larger than that from Siberia, suggesting that the American and African SCLM could have been refertilized to a higher degree than the Siberian by the eruption of the kimberlites, as is also evidenced by their Sr, Nd and Os isotopic characteristics reviewed below.

The shallow SCLM beneath the western and central Europe experienced modification by interaction with melts/fluids according to the extensive review of the petrology, major and trace element and Sr–Nd isotopic geochemistry of peridotites from ultramafic xenolith suites and tectonically emplaced ultramafic massifs (Downes, 2001). The European peridotites show wide variation in chemical compositions, similar to the other continental peridotites worldwide (Fig. 9). The strongly linear correlations among Al_2O_3, CaO and MgO contents in the peridotites (Figs. 9 and 10) suggest that the SCLM beneath the Europe has been intensively refertilized, which is further proved by the large range of SiO_2 contents, showing excessive Si enrichment in many of the peridotites (Fig. 11). The same conclusion can be also fit for the Australian SCLM represented by the peridotite xenoliths from Australia (Figs. 9–11). The only difference between the two continents is that the European peridotites show larger variation in their compositions than the Australian, possible reflecting higher degrees of refertilization in the European SCLM than the Australian.

Low-Si ($SiO_2 < 45\%$) peridotite xenoliths entrained in the kimberlites from Siberia and southern Africa fall in the melting grid (Fig. 11) and can be residues of melt extraction from primitive mantle, while high-Si ($SiO_2 > 45\%$) peridotites obviously deviate from the melting grid and cannot be melting residues of primitive mantle because they are too enriched in SiO_2 (Kelemen et al., 1992, 1998; Herzberg, 2004). This observation suggests that some of the kimberlite-hosted samples are the refertilized, originally old and depleted mantle peridotites as is evidenced by the early studies of petrology, elemental and isotopic geochemistry of mantle peridotites (Smith and Boyd, 1987, 1992; Griffin et al., 1989, 2003b, 2005; Smith et al., 1993; Boyd et al., 1997; Beyer et al., 2006; Simon et al., 2007).

The Al_2O_3 contents in most global peridotite suites negatively correlate with $(La/Yb)_N$ ratios (Fig. 12), which reflects a similar refertilization trend as that observed in the North China Craton peridotite xenoliths. Broadly positive correlations between Re and Al_2O_3 or Na_2O in the global peridotites (Fig. 13), as well as their higher contents of Re and Na_2O than those of primitive mantle, suggest that they experienced refertilization rather than just depletion by partial melting. These observations, thus, reflect refertilization of peridotites with a long-term depletion history by Re-enriched melts,
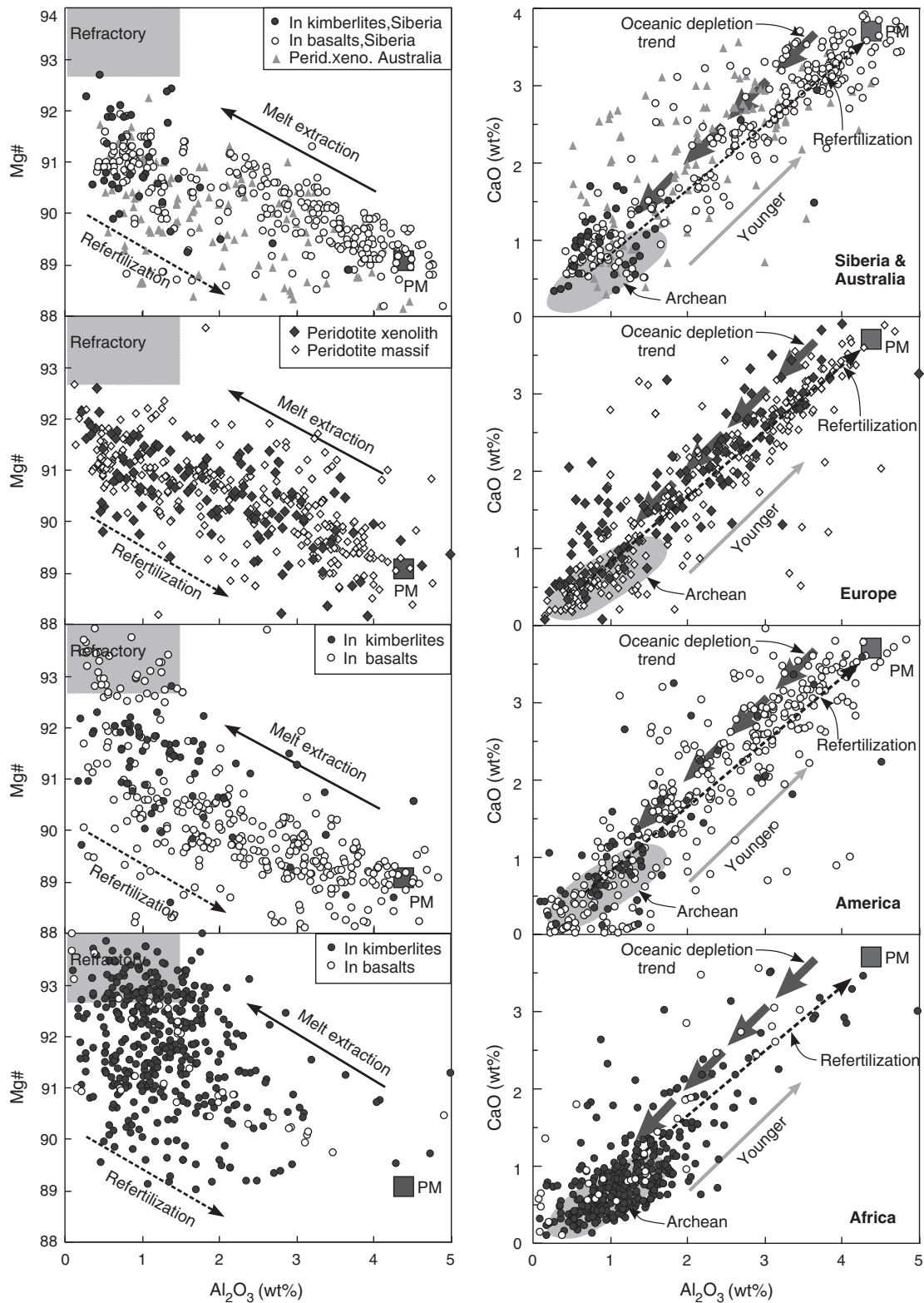
Fig. 10. Plots of Mg# and CaO (wt.%) versus Al$_2$O$_3$ (wt.%) for the mantle peridotites from ancient cratons and orogenic regions of the world. Data sources are the same as in Fig. 9.

similar to those observed from the Totalp ultramafic massif in the Eastern Swill Alps (van Acken et al., 2008).

Therefore, the characteristics of major and trace element compositions, as well as their correlations in the global peridotite samples, reflect widespread refertilization of the depleted SCLM worldwide. This is also evidenced by the variations of Sr–Nd isotopic ratios with Al$_2$O$_3$ (Fig. 14), notable scatter in Re–Os isotopic plots (Fig. 15), and covariations of Archean–Phanerozoic T$_{RD}$ ages with whole-rock Al$_2$O$_3$ and olivine Fo in these peridotites (Figs. 14–16), which will be discussed below.
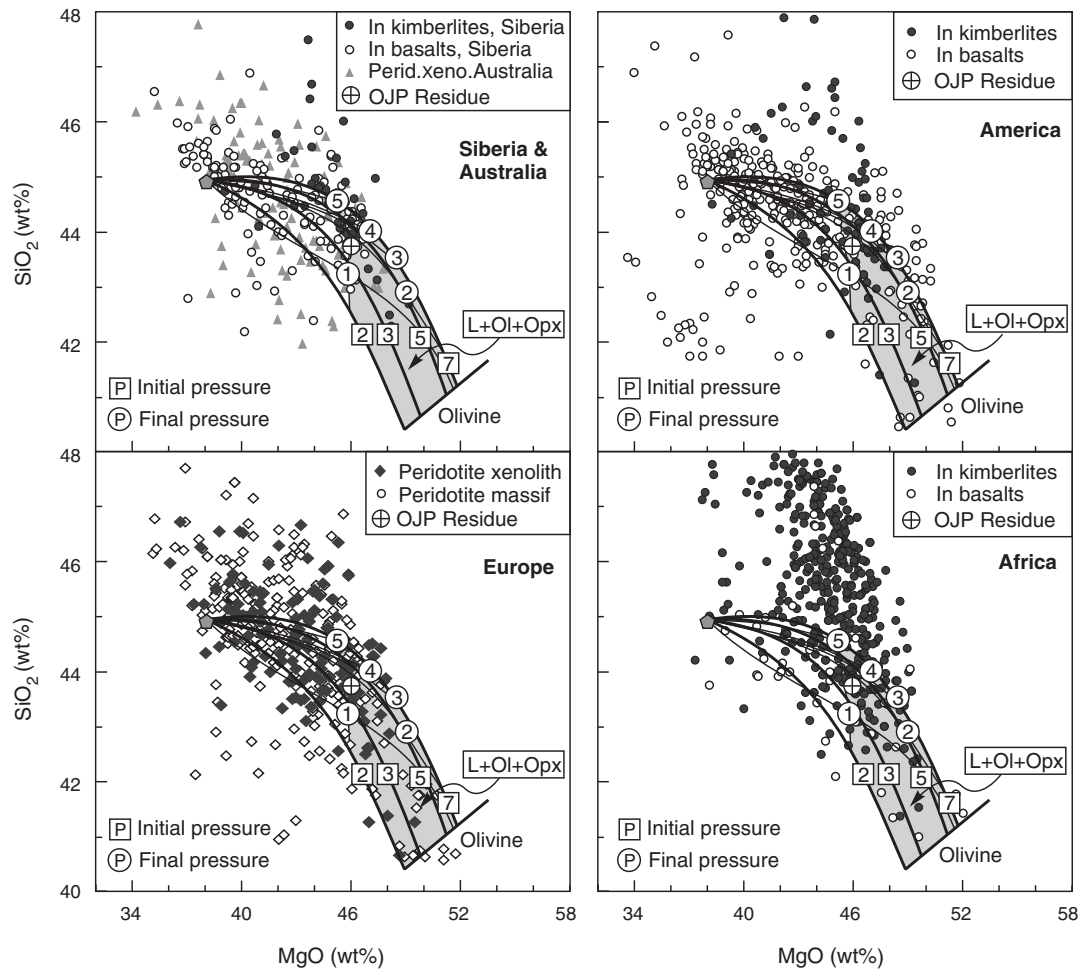
Fig. 11. Diagram of MgO versus SiO$_2$ (wt.%) for the peridotites from global ancient cratons and orogenic regions. Fractional melting grids are the same as in Fig. 4. Data sources are the same as in Fig. 9.

3.2. Variations of Sr and Nd isotopes with Al$_2$O$_3$ contents

The Sr–Nd isotopic compositions in the peridotites from Siberia, Australia, Europe, America and Africa vary greatly from extremely radiogenic isotopic compositions to highly unradiogenic isotopic ratios (Fig. 14). Both xenolithic and massif peridotite samples show positive correlation between Al$_2$O$_3$ contents and ^{143}Nd/^{144}Nd ratios and negative correlation between Al$_2$O$_3$ and ^{87}Sr/^{86}Sr ratios. These correlations can be observed in both kimberlite-borne and basalt-borne peridotite xenoliths. Since the number of data sets for African kimberlite-borne peridotites is very small, the correlations between Al$_2$O$_3$ and Sr–Nd isotopic compositions are not very apparent. However, the limited data show that the peridotite xenoliths in the African kimberlites have a large range of Sr–Nd isotopic compositions, varying from those of isotopically enriched mantle to depleted mantle (Pearson et al., 1995a; Simon et al., 2007), consistent with the radiogenic ^{87}Sr/^{86}Sr ratios (>0.710) and ^{143}Nd/^{144}Nd ratios (>0.513) for peridotites in the African kimberlites reported in early studies (Menzies and Murthy, 1980; Richardson et al., 1985; Walker et al., 1989; Stiefenhofer et al., 1997).

As noted above for the North China Craton peridotites, the correlations of ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd with Al$_2$O$_3$ (Fig. 14) are not consistent with the expected character of melting residues, but reflect refertilization processes after originally partial melting. Therefore, the ancient enriched SCLM beneath some typical cratons worldwide, represented by the peridotites with highly radiogenic ^{87}Sr/^{86}Sr and unradiogenic ^{143}Nd/^{144}Nd ratios (Fig. 14), have undergone localized

or relatively large-scale melt infiltration although many of them still keep the signature of typical ancient cratons. For example, many peridotite xenoliths from the Archean lithospheric mantle beneath the Kaapvaal craton of southern Africa display extreme Si enrichment (Fig. 11), which point to opx enrichment by either melt-rock reaction (refertilization) or cumulus addition (Kelemen et al., 1992, 1998; Rudnick et al., 1994; Herzberg, 2004; Simon et al., 2007).

3.3. Signature of Re–Os isotopic compositions

The Re–Os isotopic compositions in the global peridotites show extremely wide variations, with ^{187}Re/^{188}Os ratios from close to 0 to higher than 6 and ^{187}Os/^{188}Os from 0.109 to higher than 0.3 (Fig. 15). In general, the ^{187}Os/^{188}Os in the peridotites positively correlate with ^{187}Re/^{188}Os and Al$_2$O$_3$. The basalt-borne peridotites show relatively radiogenic, varying Os isotopic compositions and Proterozoic–Cenozoic T$_{RD}$ ages. Numerous peridotites have Re/Os ratios much higher than the PUM (Fig. 15). The very radiogenic Re–Os isotopic compositions and high Re abundances in some peridotites reflect Re and/or Os addition due to peridotite-melt reaction (Chesley et al., 1999; Becker et al., 2001; Meisel et al., 2001; Reisberg et al., 2004), causing the T$_{RD}$ ages of the peridotites to be younger than the true age of melt extraction (Pearson et al., 1995a). The positive correlation between ^{187}Os/^{188}Os and Al$_2$O$_3$ also reflect refertilization of refractory harzburgites by upwelling asthenospheric material as that aforementioned for the North China Craton.
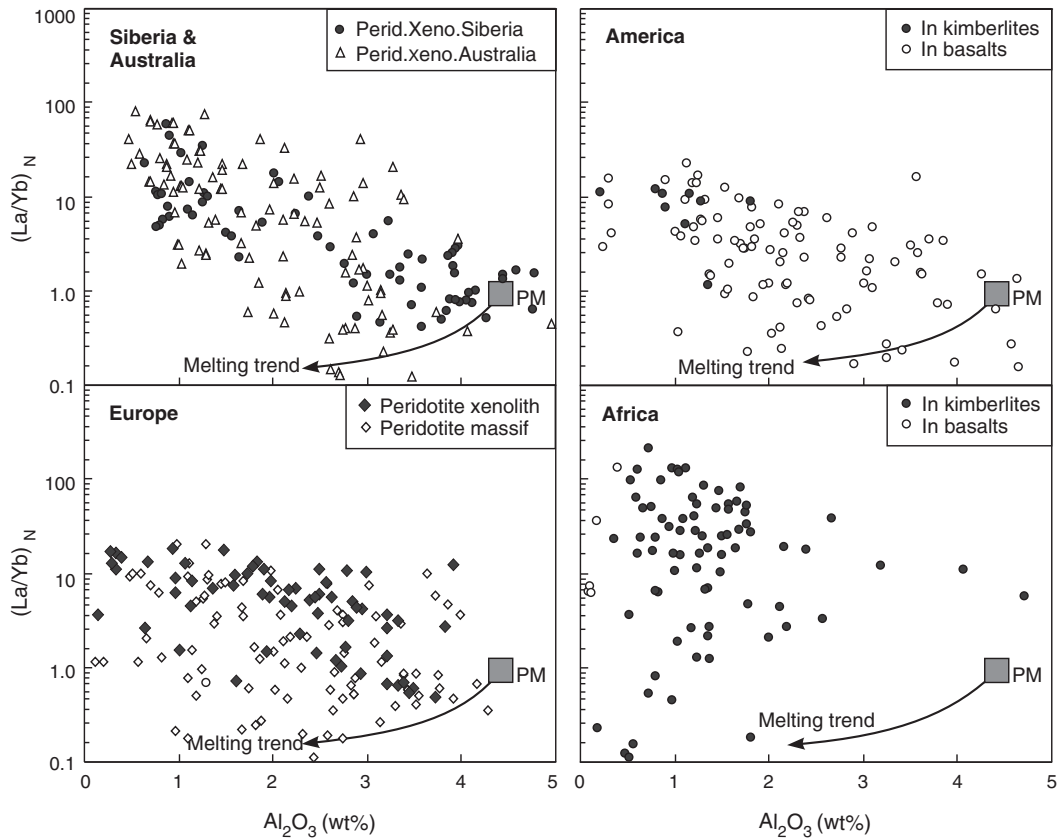
Fig. 12. Variation diagrams of (La/Yb)$_N$ versus Al$_2$O$_3$ (wt.%) for the peridotite from global ancient cratons and orogenic regions. Data sources are the same as in Fig. 9.

All studies of seven typical cratons so far (Fig. 1), the African Kaapvaal craton (Walker et al., 1989; Pearson et al., 1995a; Irvine et al., 2001; Carlson and Moore, 2004) and the Tanzanian craton (Chesley et al., 1999), the American Wyoming craton (Carlson and Irving, 1994; Carlson et al., 2004) and the Slave craton (Irvine et al., 2003), the Asian Siberian craton (Pearson et al., 1995b) and the North China Craton (Gao et al., 2002; Wu et al., 2006; Zhang et al., 2008a; Chu et al., 2009), and the North Atlantic craton (Hanghoj et al., 2001), indicate Archean formation of their SCLM roots, represented by the kimberlite-borne peridotites with Archean T$_{RD}$ ages (Fig. 16). Some peridotite bodies from the Western Gneiss Region, Europe also have Archean Re–Os model ages, implying an ancient melt-extraction event in the SCLM (Beyer et al., 2004). In contrast, most of the basalt-borne peridotites from the circum-cratonic lithospheric mantle have T$_{RD}$ ages of Proterozoic and Phanerozoic times (Fig. 16). Since the T$_{RD}$ ages provide only minimum estimates of the formation ages of peridotites, the Proterozoic ages for some xenoliths could reflect continued addition of fertile material to Archean SCLM. Moreover, the T$_{RD}$ ages of peridotites hosted by both kimberlites and basalts broadly correlate with olivine Fo and whole-rock Al$_2$O$_3$ contents. These observations are very similar to those of the peridotites from the North China Craton (Fig. 8), also reflecting refertilization of the peridotites.

As noted above, the refertilization of Archean depleted SCLM by melt additions resulted in the rejuvenation of the mantle peridotites. This inference is strongly supported by the *in situ* analyses of sulfides in peridotites that show multiple generations of sulfides with widely varying Os contents, Re/Os and ^{187}Os/^{188}Os, reflecting introduction of secondary sulfides during refertilization of the peridotites (Pearson et al., 1999, 2002; Alard et al., 2002, 2005; Griffin et al., 2002, 2004a; Powell and O'Reilly, 2007; Zhang et al., 2008b; Harvey et al., 2010). Compared with the peridotites from the Siberian kimberlites,

the samples from the American Wyoming craton (Carlson and Irving, 1994; Carlson et al., 2004) and the African Kaapvaal craton (Griffin et al., 2004a; Simon et al., 2007) show larger range of T$_{RD}$ ages, with minimum age of less than 1 Ga (Fig. 16), bearing a resemblance to those from the North China Craton (Fig. 8). This observation, combined with the large variations in major and trace element and Sr–Nd isotopic compositions of the cratonic peridotites (Figs. 2–6 and 9–14), indicate that the Archean SCLM beneath the North China Craton, the Wyoming craton and the Kaapvaal craton experienced higher degrees of refertilization than that beneath the Siberian craton. Among the cratons studied, the North China Craton could have undergone the most intensive refertilization, as is illustrated by the largest variations in major and trace element and Sr–Nd–Os isotopic compositions of peridotites. This is consistence with the recognition that the Archean keel of the North China Craton was more completely destroyed than those of other cratons around the world (Menzies et al., 1993, 2007; Griffin et al., 1998b; Fan et al., 2000; O'Reilly et al., 2001; Xu, 2001; Zhang et al., 2002, 2003; Carlson et al., 2005; Foley, 2008; Yang et al., 2008; Zhu and Zheng, 2009).

4. Summary and further implications

The ancient SCLM beneath the continents of the world experienced a multi-stage history of melt depletion and refertilization by episodic melt/fluid-peridotite reactions since segregation from the convecting mantle (McKenzie and Bickle, 1988; Zindler and Jagoutz, 1988; Pearson et al., 1995a; Pearson, 1999a; Harvey et al., 2010). Thus, the refertilization of cratonic and circum-cratonic lithospheric mantle is widespread. The first evidence for refertilization of Archean SCLM came from the Wyoming craton of American continent, which experienced the partial removal of cratonic mantle
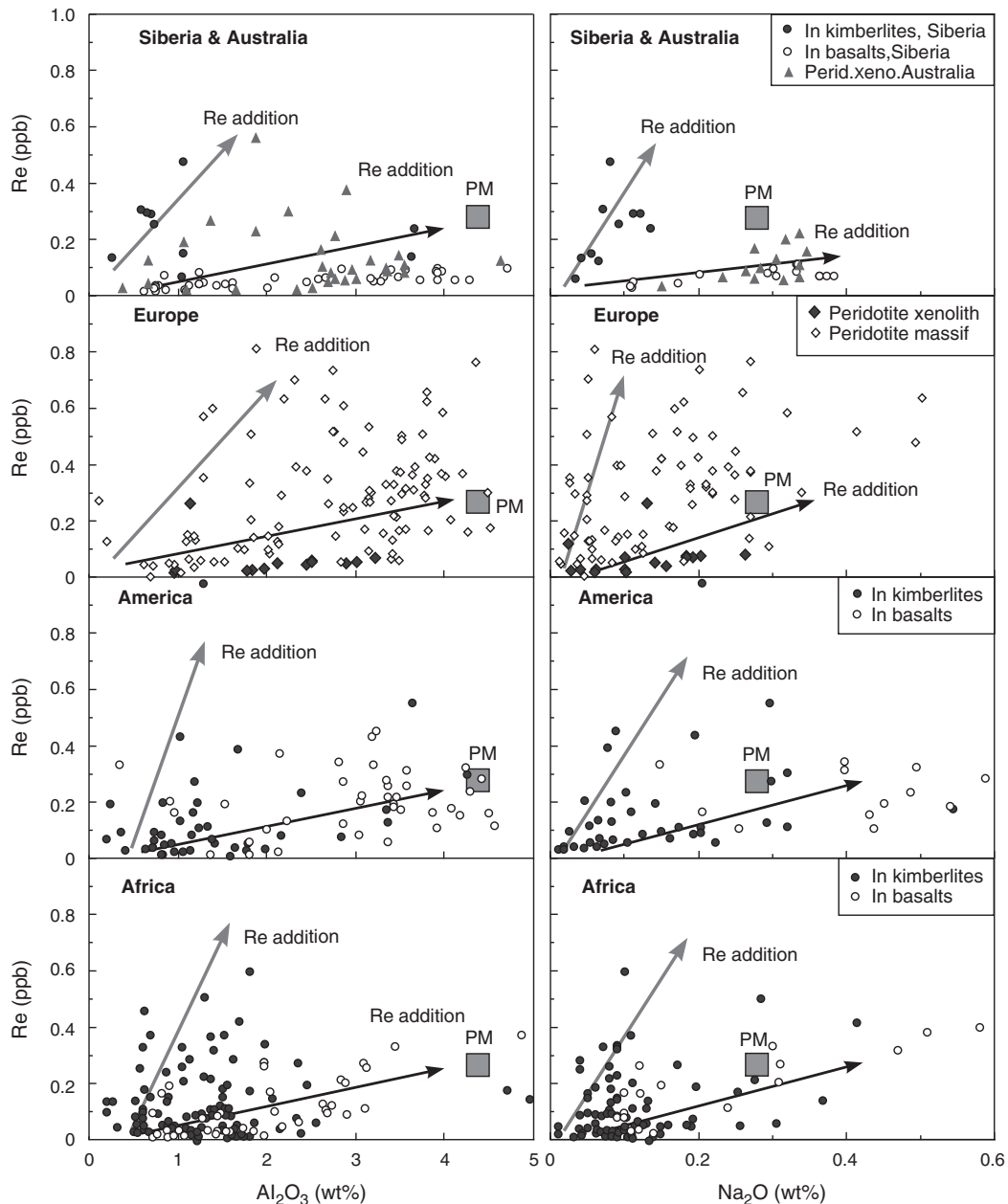
Fig. 13. Plots of Al_2O_3 (wt.%) and Na_2O (wt.%) versus Re (ppb) for the peridotites from global Archean cratons and orogenic regions. Data sources: Siberian peridotites (Press et al., 1986; Ionov et al., 1993a, 2005a, 2006a,b; Pearson et al., 1995b); Australian peridotites (Frey and Green, 1974; Canil et al., 1994; McBride et al., 1996; Handler et al., 1997, 2005; Alard et al., 2002); European peridotites (Reisberg and Lorand, 1995; Becker, 1996; Meisel et al., 1997, 2001; Becker et al., 2001; Alard et al., 2002; Beyer et al., 2004, 2006; Ackerman et al., 2007; Tessalina et al., 2007; van Acken et al., 2008; Harvey et al., 2010); American peridotites (Carlson and Irving, 1994; Lee et al., 2000; Peslier et al., 2000a, 2002; Meisel et al., 2001; Irvine et al., 2003; Carlson et al., 2004, 2007); African peridotites (Meisel et al., 2001; Simon et al., 2003, 2007; Griffin et al., 2004a; Pearson et al., 2004; Reisberg et al., 2004; Wittig et al., 2010a). Other data sources are the same as in Fig. 9.

beneath the southern part of the craton since the Devonian period, whereas the cratonic keel beneath the Montana is preserved (Eggler and Furlong, 1991; Carlson et al., 2004). The second evidence came from the North China Craton of Asia, where more complete destruction of Archean keel since Ordovician period was recognized (Fan and Menzies, 1992; Griffin et al., 1992, 1998b; Menzies et al., 1993; Fan et al., 2000; Xu, 2001; Zhu et al., 2012; Tang et al., in press). Other cratons have not yet suffered large-scale removal of their ancient keels but may find themselves in the early stages of disruption (Foley, 2008). These observations indicate that the SCLM beneath Archean cratons worldwide have been widely refertilized although the degrees of refertilization are very different.

Much of the ancient depleted SCLM is recently refertilization by the upwelling of fertile asthenospheric material likely following previously existing suture zones between ancient blocks, breaks or weak zones in the Archean root (O'Reilly et al., 2001; Xu, 2001; Zheng et al., 2007; Foley, 2008; Xiao and Zhang, 2011). Actually, refertilization of ancient SCLM is an asthenospherization of lower parts of the SCLM, which may be controlled by the topography of the lithosphere base (Foley, 2008). This process resulted in a great change of geochemical composition and rejuvenation of the Archean SCLM (Chesley et al., 1999; Dawson, 2002; Carlson et al., 2004; Beyer et al., 2006; Griffin et al., 2009; Zhang et al., 2009a). Thus, the chronological significance of the whole-rock Re–Os isotopic composition in individual xenolith must be interpreted with great caution. However, an understanding
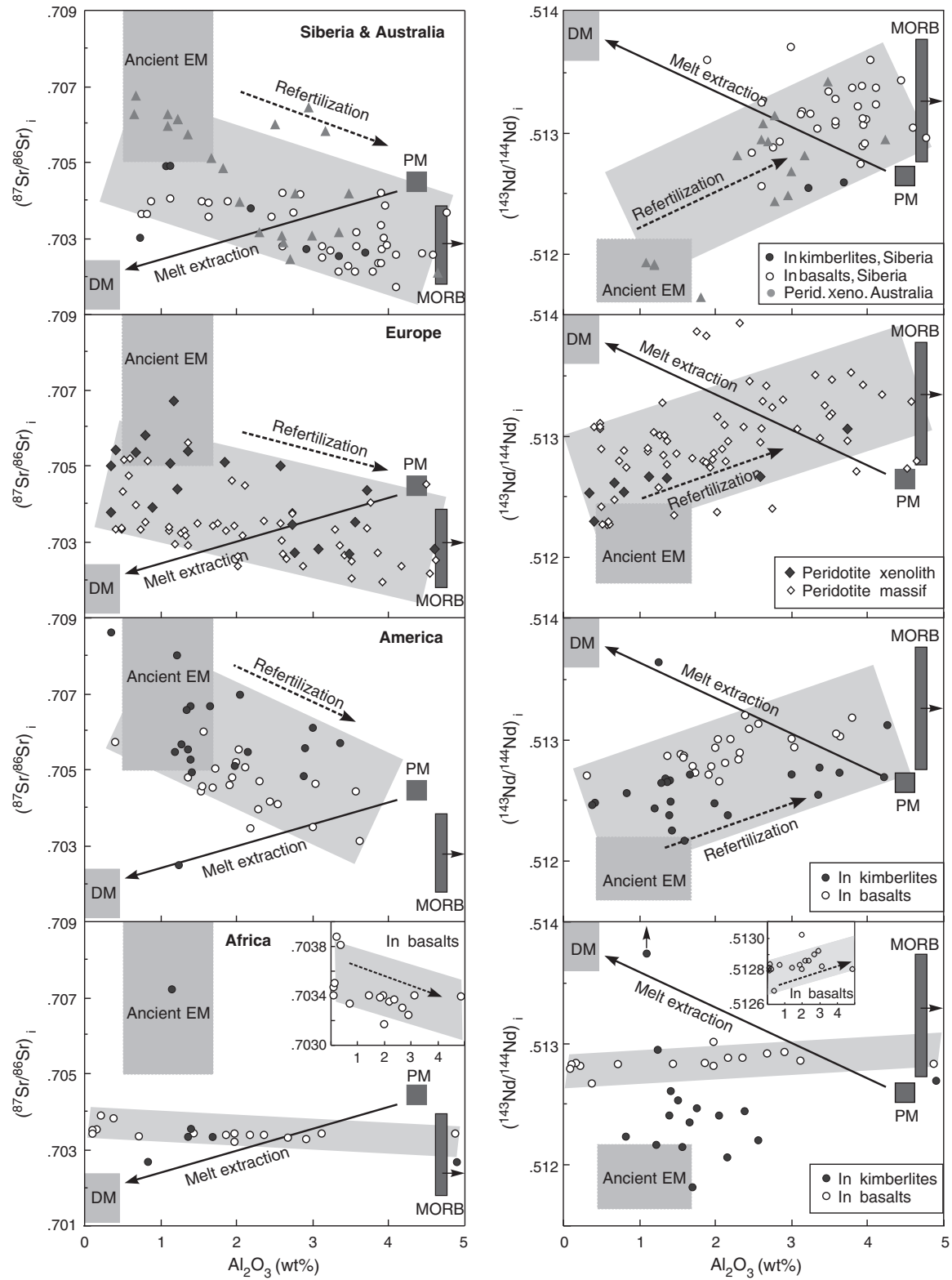
Fig. 14. Relationship between initial Sr–Nd isotopic ratios and Al_2O_3 (wt.%) for the peridotites from global Archean cratons and orogenic regions. Data sources: Siberian peridotites (Press et al., 1986; Ionov et al., 1992b, 1993a, 1994, 1995a, 2006a,b; Ionov and Hofmann, 1995, 2007; Pearson et al., 1995b); Australian peridotites (Yaxley et al., 1991; McBride et al., 1996; Handler et al., 1997, 2005); European peridotites (Paul, 1971; Becker, 1996; Meisel et al., 1997; Zangana et al., 1999; Becker et al., 2001; Downes et al., 2002; Bodinier et al., 2004; Bianchini et al., 2007; Tessalina et al., 2007; Ackerman et al., 2009; Mazzucchelli et al., 2009); American peridotites (Carlson and Irving, 1994; Schmidberger and Francis, 1999; Schmidberger et al., 2001; Carlson et al., 2004; Schilling et al., 2005; Ntaflos et al., 2007; Rivalenti et al., 2007; Bjerg et al., 2009); African peridotites (Rudnick et al., 1993; Pearson et al., 1995a; Simon et al., 2007; Wittig et al., 2010a). Other data sources are the same as in Fig. 6.
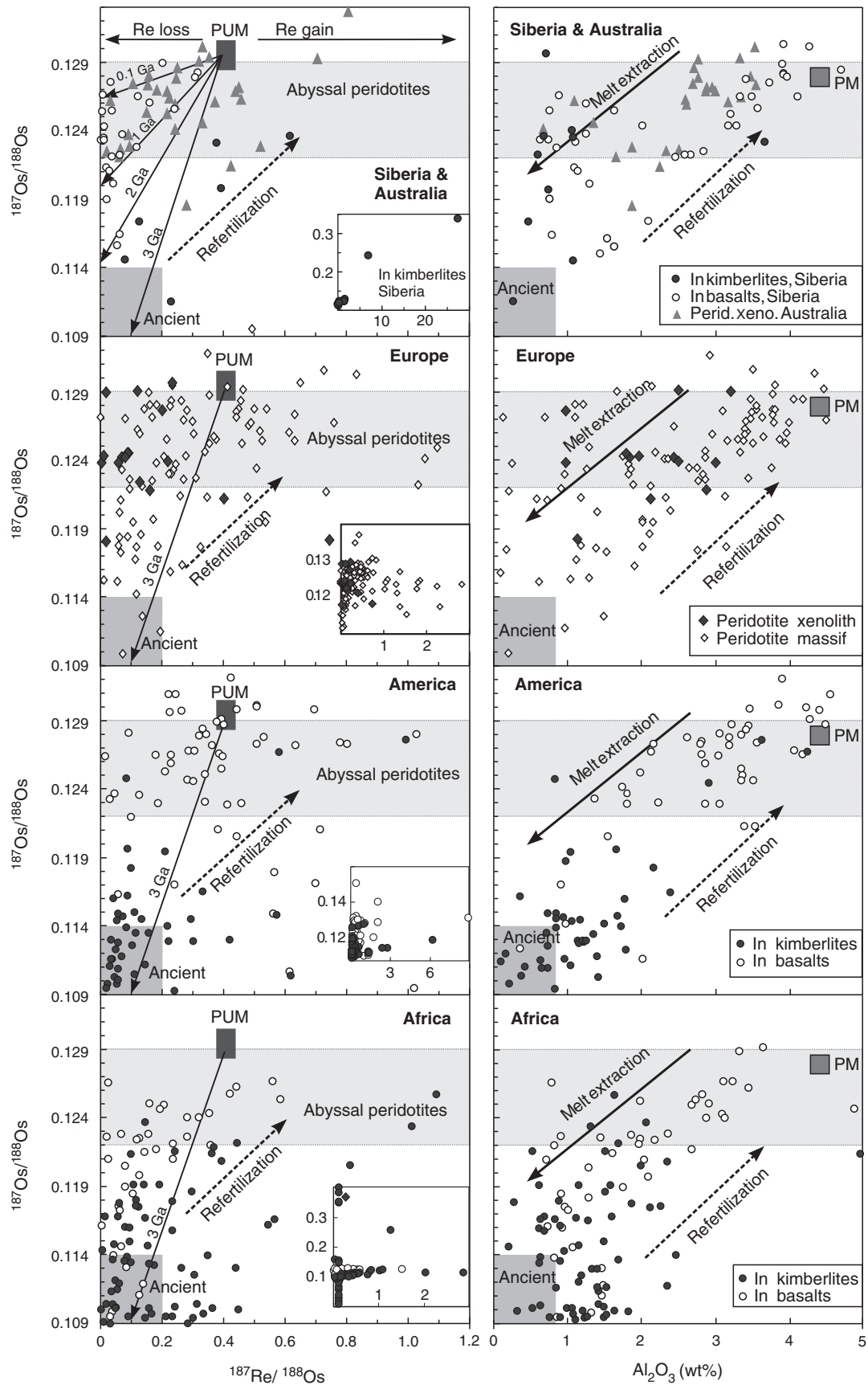
Fig. 15. Diagrams of $^{187}Re/^{188}Os$ and Al_2O_3 (wt.%) versus $^{187}Os/^{188}Os$ for the peridotites from global ancient cratons and orogenic regions. Data sources are the same as in Figs. 7 and 13.
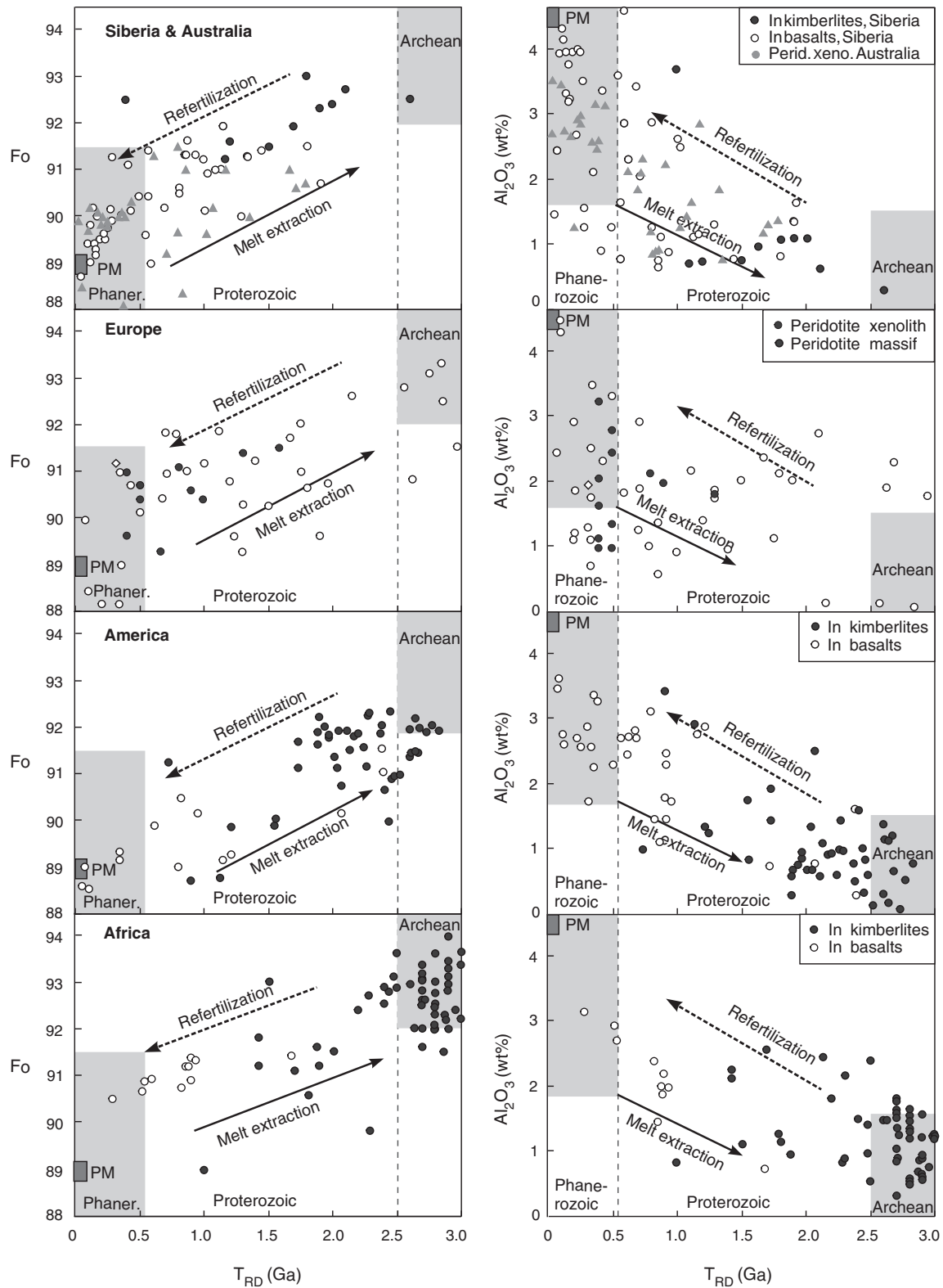
Fig. 16. Diagrams of T_{MA}, Fo and Al_2O_3 (wt.%) versus T_{RD} model ages of peridotites from global ancient cratons and orogenic regions. Data sources: Siberian peridotites (Press et al., 1986; Ionov et al., 1993a, 2005a, 2006a,b; Pearson et al., 1995b); Australian peridotites (Frey and Green, 1974; Canil et al., 1994; Handler et al., 1997, 2005; Alard et al., 2002); European peridotites (Becker, 1996; Meisel et al., 1997, 2001; Becker et al., 2001; Alard et al., 2002; Beyer et al., 2004, 2006; Ackerman et al., 2007; Tessalina et al., 2007); American peridotites (Lee et al., 2000; Peslier et al., 2000a, 2002; Meisel et al., 2001; Irvine et al., 2003; Carlson et al., 2004, 2007); African peridotites (Meisel et al., 2001; Simon et al., 2003, 2007; Griffin et al., 2004a; Wittig et al., 2010a). Other data sources are the same as in Fig. 8.

of petrography, coupled with integrated studies of whole-rock element, particularly including the platinum-group elements, isotope geochemistry and Re–Os dating of mantle sulphides, can be helpful to discover the significance of Re–Os isotope ages and secular, complex evolution of the mantle recorded in the xenoliths (Pearson et al., 2002, 2003; Beyer et al., 2006; Rudnick and Walker, 2009).

Harzburgites (cpx <5%) are widely regarded as refractory mantle residues after high-degree extraction of melt. In contrast, fertile lherzolites (cpx usually > 10%) are considered to represent relatively pristine mantle. Relatively refractory lherzolites can be melting residues of fertile peridotite when melt fractions are <0.23–0.35 and initial melting pressures are from about 2 to 7 GPa (Herzberg, 2004). However, increasing studies suggest that the lherzolites could be produced by refertilization processes involving interaction of ancient, refractory SCLM (harzburgites) with upwelling, fertile asthenospheric material. The refertilization process can exist in not only orogenic mantle peridotites (e.g., Godard et al., 2000; Saal et al., 2001; Müntener et al., 2004, 2010; Beyer et al., 2006; Le Roux et al., 2007; Piccardo et al., 2007; Rampone et al., 2010), but also peridotite xenoliths of cratonic SCLM worldwide (e.g., Eggler and Furlong, 1991; O'Reilly et al., 2001; Bell et al., 2003; Griffin et al., 2003a, 2009; Carlson et al., 2004; Foley, 2008; Zhang et al., 2009a). The refertilization of ancient, depleted SCLM therefore is a common phenomenon occurring within cratonic and circum-cratonic lithosphere. As a result, the lherzolite xenoliths with fertile compositions approaching primitive mantle, usually interpreted as fragments of asthenosphere or subducted oceanic lithosphere, can also be relics of the ancient lithospheric keel, strongly refertilized by recent infiltration of asthenosphere-derived melts (Smith et al., 1993; Zhang et al., 2009a, 2012).

Deformation experiments show that the presence of even a small fraction of basaltic melt or Si-rich fluid can result in a marked decrease of olivine-rich rocks strength (Hirth and Kohlstedt, 1995; Soustelle et al., 2010). Thus, the refertilization via melt/fluid infiltration will change the geophysical property of ancient SCLM by reducing the viscosity (Hirth and Kohlstedt, 1995; O'Reilly et al., 2001; Niu, 2005; Bürgmann and Dresen, 2008; Li et al., 2008; Peslier, 2010 and references therein) and increasing the density and heat flow (Hu et al., 2000), and lead to the destabilization and destruction of the SCLM (Windley et al., 2010; Zhu et al., 2012; Tang et al., in press; and references therein). Combined with previously published petrology of mantle peridotites, the wide variations in geochemical compositions of the peridotites worldwide indicate that cratonic SCLM is more susceptible to compositional change caused by refertilization than is generally assumed. Therefore, refertilization of depleted Archean keel through melt-peridotite reaction must play a key role in the compositional change and rejuvenation of the SCLM, leading to the final destruction of the Archean cratons.

Acknowledgments

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