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Re–Os isotope systematics of mantle xenoliths from South Korea: Evidence for complex growth and loss of lithospheric mantle beneath East Asia

Seung Ryeol Lee [a,b,*], Richard J. Walker [a]

[a] Isotope Geochemistry Laboratory, Department of Geology, University of Maryland, College Park, MD 20742, USA
[b] Geology Division, Korea Institute of Geoscience and Mineral Resources, Daejeon 305-350, South Korea

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Abstract

We report Re–Os isotopic data for seventeen mantle xenoliths from the Jeju and Baekryeong Islands, Pyeongtaek, and Boeun, South Korea. All are spinel peridotites, hosted by late Tertiary to Quaternary (~5.0 Ma to historic) alkali basalt flows and range in composition from depleted harzburgites to variably depleted lherzolites. All of the measured $^{187}Os/^{188}Os$ and $^{187}Re/^{188}Os$ ratios are subchondritic to chondritic (0.1155 to 0.1285 and 0.022 to 0.391, respectively), with the exception of two samples with $^{187}Re/^{188}Os$ (>0.6). Model Os T_{RD} ages of ~1.9 to 1.8 Ga for three strongly depleted harzburgites (Mg#=90.6 to 91.2) indicate that Paleoproterozoic subcontinental lithospheric mantle (SCLM) is currently preserved beneath the Korean peninsula. The slopes of linear trends of $^{187}Os/^{188}Os$ vs. Al_2O_3 are also consistent with this interpretation, although a lack of correlation between $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ indicates likely recent perturbations in Re concentrations, especially in the lherzolites. Collectively, the new data indicate that the age of the current SCLM beneath South Korea is considerably younger than the overlying Archean crust, suggesting possible removal and replacement of the Archean SCLM during the Proterozoic. This replacement event may be temporally coincident with widespread intracrustal reworking events that occurred in South Korea during the Paleoproterozoic (~2.1 to 1.8 Ga). The results of this study and previous studies of other East Asian tectonic blocks provide strong evidence for the periodic construction and destruction of SCLM beneath East Asia during the Archean, Proterozoic, and Phanerozoic, and extend to the east the range of known complicated age structure of the current SCLM beneath East Asia.

Keywords: Re–Os; Mantle xenoliths; Subcontinental lithospheric mantle; South Korea; East China; East Asia

1. Introduction

Studies of xenoliths from subcontinental lithospheric mantle (SCLM) have revealed that the melt depletion ages of deep cratonic keels are often in broad agreement with the major crust building ages of their overlying craton (Walker et al., 1989; Shirey and Walker, 1998; Pearson, 1999). Such coherency of ages is also observed in some post-Archean circumcratonic regions (Pearson, 1999). These observations imply long-term crust–mantle coupling both on- and off-cratons, and indicate a genetic relationship between crust stabilization and the

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[*] Corresponding author. Isotope Geochemistry Laboratory, Department of Geology, University of Maryland, College Park, MD 20742, USA. Tel.: +1 301 405 4054; fax: +1 301 405 3597.
E-mail address: leesr@geol.umd.edu (S.R. Lee).

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formation of thick lithospheric keels at the time of craton building.

There are also some examples where the deep lithospheric roots beneath certain cratons were evidently affected by post-cratonization tectonic disturbance, and were either partly removed or even completely replaced by much younger lithospheric mantle (e.g., O'Reilly et al., 2001). For example, the creation of East Asia was dominated by the Mesozoic continental collision between two major Precambrian continental blocks: the Sino-Korean craton and the South China craton (Fig. 1). The Sino-Korean craton, also known as the North China craton, is one of the world's oldest Archean terranes, preserving crustal remnants as old as ~3.8 Ga (Liu et al., 1992). The Nd T_{DM} model ages of felsic rocks present in the craton suggest the major crustal growth event occurred between ~2.9 and 2.6 Ga (Chen and Jahn, 1998; Wu et al., 2003). The final cratonization of the Sino-Korean craton was accomplished via Paleoproterozoic continent–continent collision between the eastern and western blocks. This collision is now manifested by the Trans-North China Orogen (Zhao et al., 2001). In contrast, the South China craton is a typical Proterozoic terrane with rare Archean continental nuclei (Chen and Jahn, 1998; Ma et al., 2000; Qiu et al., 2000; Bryant et al., 2004). It achieved final amalgamation by the accretion of the Yangtze craton and the Cathaysian block during the Neoproterozoic (Chen and Jahn, 1998).

Studies of mantle xenoliths from Paleozoic kimberlites present in both cratons suggest that thick, cool, melt-depleted SCLM keels with formation ages roughly consistent with the ages of the overlying crust, underlay the Sino-Korean and South China cratons at the time of the kimberlite volcanism (Menzies et al., 1993; Griffin et al., 1998; Wang et al., 1998; Zhang et al., 2001). Geophysical data and isotopic studies of mantle xenoliths from Cenozoic basalts, however, suggest that

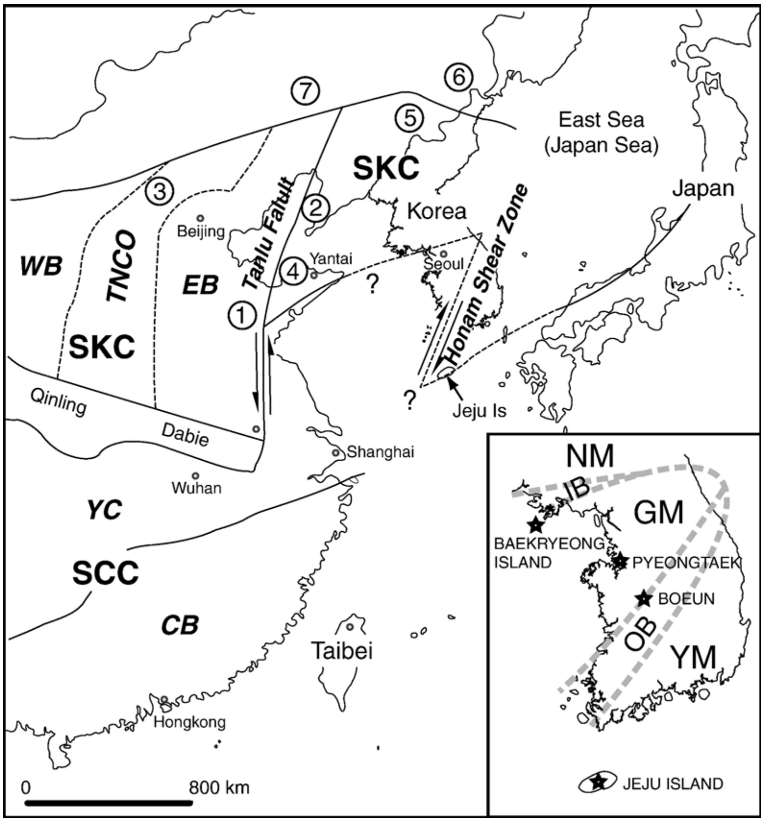

Fig. 1. Regional tectonic map of East Asia. Sample locations are shown as stars in the inset figure. SKC, Sino-Korean craton; TNCO, Trans-North China Orogen; EB, Eastern block; WB, Western block; SCC, South China craton; YC, Yangtze craton; CB, Cathaysian block; NM, Nangrim massif; GM, Gyeonggi massif; YM, Yeongnam massif; Imjingang belt (IB); Ogcheon belt (OB). The Nangrim, Gyeonggi, and Yeongnam massifs are bounded by two intervening Neoproterozoic–Phanerozoic fold-and-thrust belts, the Imjingang belt and the Ogcheon belt, respectively. Numbers in circles represent the locations of the Paleozoic (1 and 2) and Cenozoic (others) volcanic eruptions that contain mantle xenoliths: 1. Mengyin; 2. Fuxian; 3. Hannuoba; 4. Qixia; 5. Longgang; 6. Wangqing; 7. Shuangliao.

the present lithospheric mantle beneath eastern China is now much thinner (<120 km) compared with typical cratonic regions worldwide (Griffin et al., 1998). These observations indicate that at least some portions of the thick Archean/Proterozoic keels present during the Paleozoic were replaced by thin, hot, fertile lithospheric mantle during the late Mesozoic and Cenozoic (Griffin et al., 1998; Xu et al., 2000; Zhang et al., 2001; Zheng et al., 2004). Some evidence indicates that a modicum of Archean and Proterozoic SCLM beneath the South China craton has survived, despite apparent extensive Mesozoic–Cenozoic lithospheric thinning (Wang et al., 2003).

The Korean peninsula, the easternmost extension of the Precambrian Sino-Korean craton and South China craton, consists of three Precambrian blocks: from north to south, Nangrim, Gyeonggi, and Yeongnam massifs, separated by two intervening fold-and-thrust belts, the Imjingang and Ogcheon belts, respectively (Fig. 1). The Nangrim massif is apparently a direct continuation of the Sino-Korean craton, whereas the crustal affinities of the Gyeonggi and Yeongnam massifs with the Chinese cratons are still ambiguous (e.g., Lee et al., 2003a). The Nd T_{DM} model ages for the crustal rocks of the peninsula suggest that crustal growth events occurred mainly during the Archean. Most Archean crustal materials, however, were severely reworked during the Paleoproterozoic (Lan et al., 1995; Cheong et al., 2000; Lee et al., 2003a; Sagong et al., 2003). The early crustal growth history of the South Korean massifs was evidently similar to that of the Sino-Korean craton, but the prevalent extensional or rifting events during the Neoproterozoic are more similar to events that occurred in the South China craton (Lee et al., 2003b). These contradictions have prevented simple correlation between the two southern Korean massifs and Chinese cratons, and there remains much uncertainty regarding the Mesozoic accretional history of East Asia. Whether or not the complex age structure of the SCLM underlying the East China continues to the east is, thus, an important aspect of assessing accretional causes and timing.

Here we report Re–Os isotopic data for seventeen mantle xenoliths from South Korea and use these data to evaluate the ages of the lithospheric mantle beneath the Korean peninsula. The Re–Os system has proven useful for constraining the timing of melt depletion that often accompanies the formation of SCLM. This is because the parent element Re is incompatible while Os is compatible during most mantle melting scenarios.

Partial or complete removal of the parent and retention of the daughter leads to retardation or cessation of growth of ^{187}Os from the time of melt removal. Further, Os is relatively immune to post-crystallization disturbance compared with highly incompatible element isotope systems (e.g., Rb–Sr, Sm–Nd, U–Pb) (Shirey and Walker, 1998; Pearson, 1999). Our Re–Os data are then also compared with data for Chinese peridotite xenoliths in order to more fully explore the age structure of the SCLM beneath East Asia.

2. Mantle xenoliths

The mantle xenoliths examined here come from four localities in South Korea: Jeju Island in the southern extension of the Yeongnam massif, Boeun in the Ogcheon belt, and Pyeongtaek and Baekryeong Island in the Gyeonggi massif (Fig. 1). All are spinel peridotites, hosted by late Tertiary to Quaternary (~5.0 Ma to historic) alkali basalt flows (Choi et al., 2001; Kim et al., 2002), although rare clinopyroxenite and websterite are also reported from Jeju Island (Choi et al., 2001). All are anhydrous peridotites consisting of olivine, orthopyroxene, clinopyroxene and spinel, and overall exhibit a protogranular or protogranular/porphyroclastic texture. No penetrative fabrics, such as foliation or lineation, have been observed, although kink bands in olivine and orthopyroxene are common. In thin section, silicate minerals show only limited evidence of alteration, with the exception of peridotites from Boeun, in which olivine and pyroxene are slightly altered. Most of the peridotites from Jeju Island and Boeun contain traceable amounts of sulfides, which occur as either interstitial phases or crack-fillings, often accompanied by tracks of fluid inclusions within adjoining silicates. No visible sulfides were identified via reflective light microscopy in peridotites from Baekryeong Island and Pyeongtaek.

The P–T conditions of the xenoliths have been reported to be in the range of 945 to 1020 °C and 12 to 19 kbar (42 to 63 km depth) from Boeun and Baekryeong Island, and 880 to 1042 °C and 13 to 26 kbar (46 to 91 km depth) from Jeju Island, based on two-pyroxene geothermometry and Ca-in-olivine and Al-solubility-in-pyroxene geobarometry (Lee, 1996; Choi et al., 2001). These results suggest that the xenoliths were derived from relatively shallow lithospheric mantle with a much hotter geothermal gradient than typical for cratonic mantle.

The spinel peridotites display a wide range of compositions from strongly depleted harzburgites to fertile lherzolites (Table 1). The majority (14 out of 17 samples) are variably depleted to fertile spinel lherzolites, consisting roughly in mode of olivine (50% to

75%), orthopyroxene (15% to 30%), clinopyroxene (8% to 17%), and spinel (1% to 3%). The lherzolites have Al_2O_3 and CaO contents of 2.2 to 4.1 and 1.9 to 4.3 wt.%, respectively, with Mg# ranging from 89.1 to 90.4. Two samples (JJ2-5 and JJ2-6) from Jeju Island and one sample (BR5) from Baekryeong Island, located in the southernmost and northernmost locales, respectively, are strongly depleted harzburgites, consisting of olivine (70% to 80%), orthopyroxene (15% to 25%), clinopyroxene (3% to 5%), and spinel (1% to 2%). They have Al_2O_3 and CaO contents of 1.0 to 1.5 and 0.6 to 1.1 wt.%, respectively, and Mg# of 90.6 to 91.2 (Table 1). The high proportion of the lherzolites to harzburgites may indicate that the former dominate the SCLM currently underlying the continental crust of South Korea, although our sampling is still statistically limited. The Al_2O_3 and CaO concentrations and Mg# of all peridotites are negatively correlated, implying that the major element trends resulted from varying degrees of partial melting. However, there exists a modest compositional gap between the harzburgites and lherzolites, suggesting either insufficient sampling, or a bimodal sampling of at least two melting events.

3. Analytical methods

Rhenium–Os isotopic data were obtained at the Isotope Geochemistry Laboratory (IGL), University of Maryland. Whole-rock powders (2 to 2.5 g) were finely ground using agate, then dissolved and equilibrated with a mixed ^{185}Re–^{190}Os spike using a modified Carius tube technique with reverse aqua regia, and heated to 240 °C for >12 h (Shirey and Walker, 1995). Osmium was extracted and purified by solvent extraction (Cohen and Waters, 1996) and microdistillation, and Re by two successive anion exchange columns. Total procedural blanks during the course of the study were 3 ± 2 and 15 ± 10 pg for Os and Re, respectively.

Osmium isotopic compositions were analyzed by negative thermal ionization mass spectrometers using either a VG Sector 54 mass spectrometer with Faraday cups in static mode, or a 12 in. radius NBS mass spectrometer with an electron multiplier in dynamic peak hoping mode. Additional details regarding chemical separations and mass spectrometry can be found in Walker et al. (2002). In-run precision on the $^{187}Os/^{188}Os$ isotopic ratios of the analyzed samples is better than ±0.3% (2σ). External reproducibility of the $^{187}Os/$

Table 1
Some major element concentrations and Re–Os isotope data of peridotite xenoliths from South Korea

Sample	CaO (wt.%)	Al_2O_3 (wt.%)	Mg#	Re (ppb)	Os (ppb)	$^{187}Re/^{188}Os$	$^{187}Os/^{188}Os$	2σ	T_{RD}
Baekryeong Island (~5 Ma)									
BR1	1.90	2.24	90.4	0.035	1.90	0.0879	0.12483	0.00017	0.66
BR2	3.21	3.49	89.6	0.017	0.45	0.1778	0.12853	0.00024	0.15
BR3	2.44	2.59	89.6	0.088	1.12	0.3760	0.12666	0.00020	0.41
BR4	1.99	2.44	89.9	0.025	0.70	0.1726	0.12130	0.00019	1.14
BR5	1.08	1.46	91.2	0.053	1.43	0.1778	0.11659	0.00036	1.78
Pyeongtaek (~5 Ma)									
PT1	4.25	3.85	89.6	b.d.[1]	1.10	n.d.[2]	0.12572	0.00026	0.54[3]
Boeun (~5 Ma)									
BE1	3.13	4.05	89.6	0.105	1.96	0.2599	0.12548	0.00021	0.57
BE2	2.90	3.48	89.6	0.076	0.92	0.3992	0.12555	0.00020	0.56
BE3	2.43	2.76	90.0	0.088	1.11	0.3828	0.12413	0.00021	0.76
Jeju Island (~0.6 Ma)									
JJ1-2	3.79	3.65	89.1	0.131	0.95	0.6683	0.12851	0.00015	0.15
JJ2-1	2.88	3.23	89.5	*4.36*	1.44	*14.58*	0.12648	0.00008	0.60
JJ2-1(rep)				0.104	1.28	0.3910	0.12677	0.00012	0.39
JJ2-2	2.52	2.91	89.7	0.093	0.69	0.6409	0.12695	0.00033	0.37
JJ2-5	0.59	1.02	91.1	0.016	2.05	0.0371	0.11551	0.00018	1.92
JJ2-6	0.64	0.95	90.6	0.016	2.18	0.0354	0.11654	0.00032	1.78
JJ2-7	3.02	2.27	89.7	0.079	0.99	0.3841	0.12396	0.00034	0.78
JJ2-8	2.28	2.85	89.6	0.045	1.37	0.1579	0.12291	0.00036	0.92
JJ2-9	3.47	2.86	89.7	0.067	1.09	0.2930	0.12469	0.00028	0.68

[1] b.d. — below detection limit. [2] n.d. — not determined. [3] Calculated with no age correction. PUM values of $^{187}Os/^{188}Os = 0.1296$ and $^{187}Re/^{188}Os = 0.433$ (Meisel et al., 2001) were used for the calculation of T_{RD} ages.

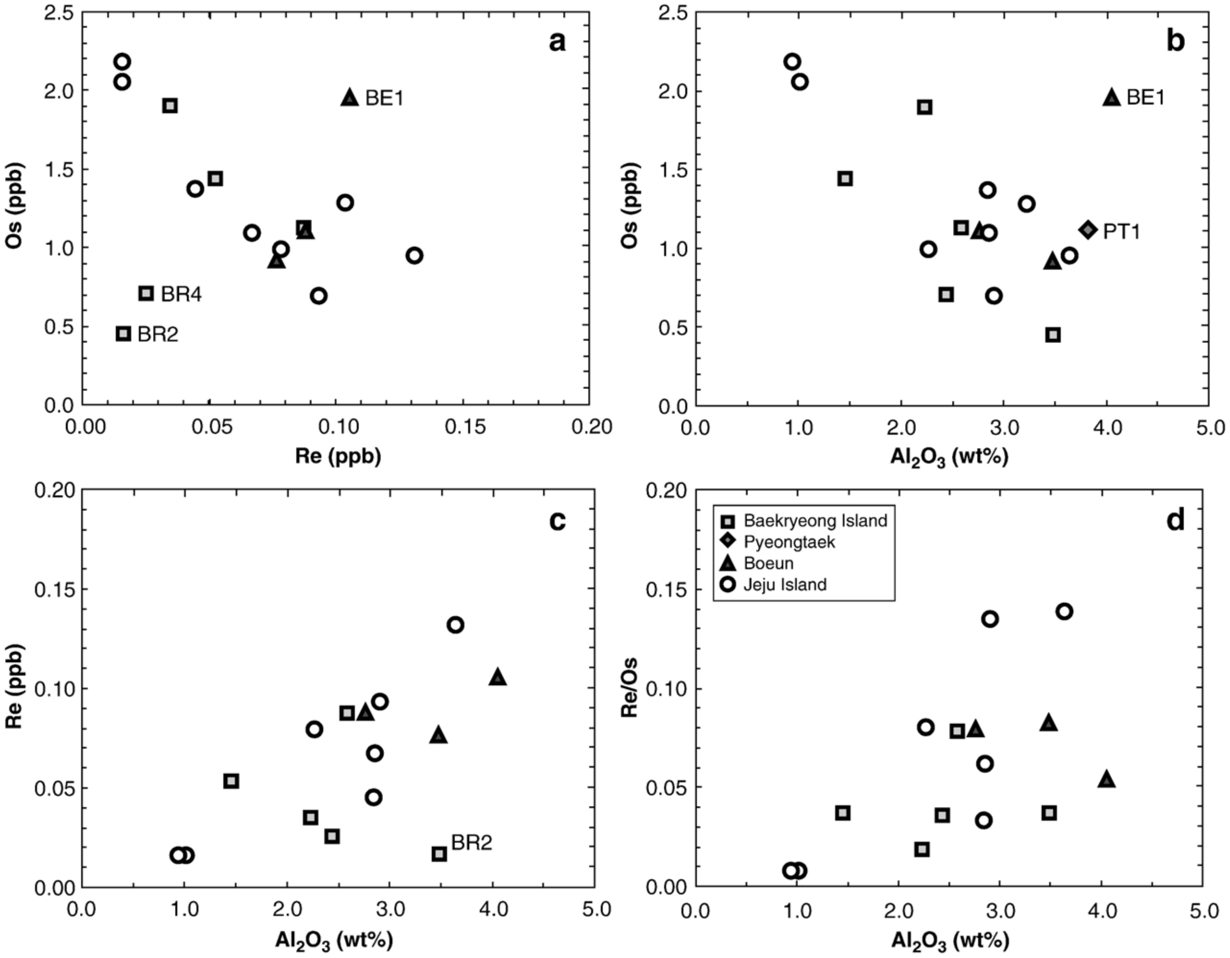

Fig. 2. (a) Rhenium and Os abundances of South Korean mantle xenoliths (in ppb). (b) Osmium abundance (in ppb) versus whole-rock Al_2O_3 (wt.%). (c) Rhenium abundance (in ppb) versus whole-rock Al_2O_3 (wt.%). (d) Re/Os versus whole-rock Al_2O_3 (wt.%).

^{188}Os ratio from sample JJ2-1 using different mass spectrometers is nearly the same (~0.2%) (Table 1), indicative of no detectable instrumental bias on the measured ^{187}Os/^{188}Os ratio. The external precisions of ^{187}Os/^{188}Os determined through analyses of comparable quantities of Os in standard solutions (UMCP Johnson Mattey standards) are 0.11386 (±0.00008; $n=4$) and 0.1137 (±0.0005; $n=5$) for Faraday cup and electron multiplier, respectively.

The concentrations of Re were determined using a Nu Plasma multi-collector inductively coupled plasma mass spectrometer and two electron multipliers in a static mode. The sample solution (in 2% HNO_3) was introduced to the Ar plasma using an Aridus desolvating nebulizer. The instrumental fractionation of ^{185}Re/^{187}Re for the samples was monitored and corrected via interspersed analyses of natural Re solutions (^{185}Re/^{187}Re=0.597) of comparable Re concentrations. Analysis of interspersed laboratory standards with ^{185}Re enriched composition indicates external reproducibility of ~±0.3% for Re quantities of the magnitude analyzed here. The blank correction for Os was minimal (<0.5%), but Re blank corrections varied from 0.3 to 26%. One sample (PT1) of which the least amount of sample was available, contained the lowest Re concentration (<0.01 ppb) and required a 98% correction, and so Re was effectively below the detection limit.

4. Results

Osmium and Re concentrations and Re–Os isotopic ratios are provided in Table 1. Osmium concentrations range from 0.45 to 2.18 ppb, with the three strongly depleted harzburgites having among the highest Os concentrations. These concentrations are generally comparable to spinel peridotite xenoliths from other regions worldwide, although their average (~1.3±0.5 ppb) is ~60% lower than the estimate for primitive upper mantle (PUM) of about 3 ppb (e.g., Handler et al., 1997; Peslier et al., 2000; Meisel et al., 2001; Handler et al., 2003). Rhenium concentrations, except for one sample (JJ2-1) with a very high Re content of 4.37 ppb, range from 0.05 to 0.13 ppb. Because a replicate analysis of the sample JJ2-1 yielded a Re concentration of 0.104 ppb, more consistent with its peridotite composition, we conclude the sample was either variably contaminated with Re from the host lava, or was contaminated during the chemical processing. Hence, the lower Re concentration is used for subsequent discussion. All but three samples (BR2, BR4 and BE1) show a good negative correlation between Os and Re concentrations (Fig. 2a). Osmium concentrations of all but one sample (BE1) are also negatively correlated with major element indices of melt depletion, such as Al_2O_3 and CaO, while Re concentrations of all but one sample (BR2) are positively correlated with these major elements (Fig. 2b and c). There is a weak positive correlation between Re/Os and Al_2O_3 (Fig. 2d).

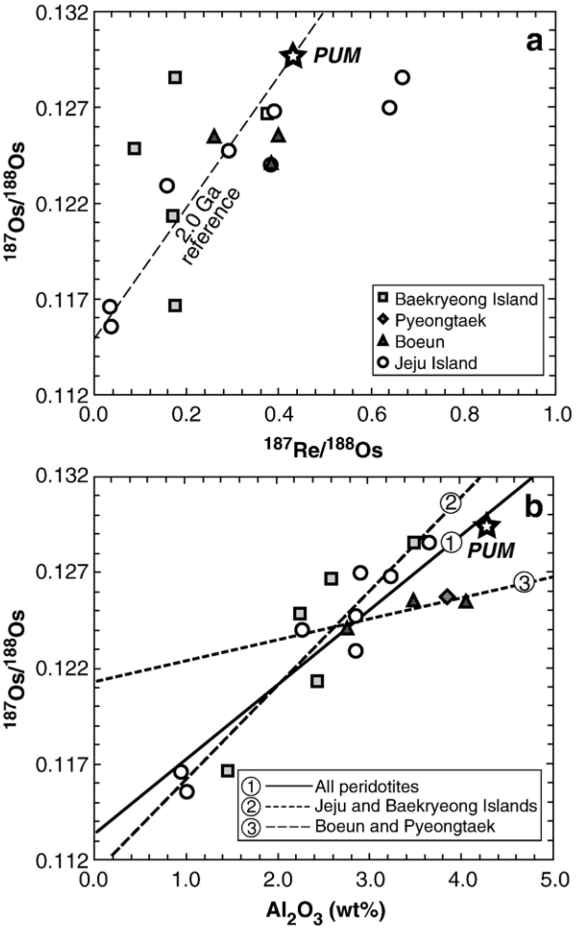

Fig. 3. (a) Re–Os isochron diagram for South Korean peridotite xenoliths. Symbols are the same as in Fig. 2d. The $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ ratios of most mantle xenoliths scatter along a 2.0 Ga reference isochron, projected from the PUM, indicative of a recent perturbation of Re/Os. (b) $^{187}Os/^{188}Os$ versus Al_2O_3 (wt.%). The equation of each regression line is: $Y_1=0.0038X+0.1135$ ($R^2=0.75$); $Y_2=0.0049X+0.1113$ ($R^2=0.87$); $Y_3=0.0011X+0.1213$ ($R^2=0.77$).

The $^{187}Os/^{188}Os$ of all samples are subchondritic to chondritic (0.1155 to 0.1285) (Table 1). The three harzburgites (JJ2-5, JJ2-6 and BR5) have the lowest $^{187}Os/^{188}Os$ ratios of 0.1155 to 0.1166. The lherzolites have ratios ranging from 0.1213 to 0.1285. Most of these are within the range of $^{187}Os/^{188}Os$ ratios presumed for the modern convecting upper mantle based on studies of abyssal peridotites and ophiolites (Snow and Reisberg, 1995; Brandon et al., 2000; Walker et al., 2002). The $^{187}Os/^{188}Os$ ratios are weakly inversely correlated with Os concentrations, and are positively correlated with major element indices of melt depletion (e.g., Al_2O_3 and CaO) (Fig. 3b). The $^{187}Re/^{188}Os$ ratios of most of the xenoliths are also subchondritic to chondritic (0.09 to 0.40, where chondritic is ~0.4). Two samples have slightly suprachondritic ratios (0.64 and 0.67 for JJ1-2 and JJ2-2, respectively) (Table 1).

5. Discussion

5.1. Closed Re–Os isotopic systematics?

The systematic variations between $^{187}Os/^{188}Os$ and melt extraction indices (e.g., Al_2O_3) observed in the Korean peridotites are consistent with ancient melt depletion events. Compared to the strong correlation between $^{187}Os/^{188}Os$ and Al_2O_3, however, the lack of correlation between $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$, together with several samples (e.g., BE1, BR2 and BR4) showing apparent deviation from the melting-induced trends between Re and Os concentrations and Al_2O_3, indicate a recent perturbation of the Re–Os system especially in the lherzolites. The open-system behavior is most likely dominated by Re loss/addition, probably at the time of incorporation in volcanic hosts. For example, the suprachondritic $^{187}Re/^{188}Os$, coupled with subchondritic $^{187}Os/^{188}Os$ in two samples (e.g., JJ1-2 and JJ2-2) requires recent addition of Re. Interaction with host magma is also indicated by Sr–Nd–Pb isotopic compositions of clinopyroxene separates from the Jeju peridotites that are consistent with metasomatic interactions with the Quaternary host basaltic liquids (Choi et al., 2005). In contrast, two samples (e.g., BR2 and BR4) of Baekryeong Island show apparent depletion of Re (and to a lesser extent Os) relative to the melting-induced trends between Re and Os concentrations and Al_2O_3, suggesting a relatively recent loss of Re (and possibly some Os). Such losses may have been caused by percolation of S-undersaturated melt through the rocks (Reisberg et al., 2005). The open-system effects appear to be relatively recent features, so they should not affect interpretations based on $^{187}Os/^{188}Os$ variations relative to immobile element indicators of melt depletion.

5.2. Age of the SCLM beneath the South Korea

In order to constrain the nature of the lithospheric mantle underlying South Korea and determine how it may relate to the SCLM underlying other parts of East Asia, it is necessary to assess whether or not the age of the SCLM is similar to or younger than that of the overlying crust. The Re–Os system has been applied in three types of age determinations of bulk samples for constraining the timing of melt depletion of SCLM: model age calculations for individual samples assuming derivation from chondritic mantles (Walker et al., 1989; Pearson et al., 1995); the conventional isochron technique (e.g., Gao et al., 2002); and model age projection for xenolith suites using major (e.g., Al_2O_3 and CaO) or trace elements (e.g., Lu) as proxies for Re/Os (Reisberg and Lorand, 1995; Peslier et al., 2000).

Model age estimations for individual peridotite xenoliths, based on the assumption of a chondritic upper mantle (Walker et al., 1989; Pearson et al., 1995), are probably the least robust in most instances, but can in some circumstances be used to constrain minimum melt depletion ages. Model T_{RD} ages provide a minimum estimate of the timing of melt depletion via comparison of the $^{187}Os/^{188}Os$ of the sample, corrected using the measured Re/Os to the eruption time of xenolith-bearing host lava, to a mantle evolution model (Shirey and Walker, 1998). Model T_{RD} ages may approach the true ages of melt depletion for highly depleted xenoliths, such as those of Archean cratons, as Re is almost completely extracted from the residue at high degrees of melting (Walker et al., 1989). Model T_{RD} ages estimated from relatively fertile xenoliths, however, tend to greatly underestimate the true melting age due to the fact that significant Re remains in the residue after melting. It is also necessary to note that, when interpreting Os model ages, the Os isotopic composition of the modern upper mantle is not well constrained. Estimates of $^{187}Os/^{188}Os$ vary from ~0.13 (Meisel et al., 2001), based on an estimate of the PUM, to an average abyssal peridotite value of ~0.125 (Snow and Reisberg, 1995). The choice of specific mantle evolution model, therefore, remains a major uncertainty in Re–Os model ages, resulting in model age differences of up to several hundred million years for Neoproterozoic and especially Phanerozoic materials (Pearson, 1999). In this study all model T_{RD} ages were calculated relative to the PUM (Meisel et al., 2001), which tends to give slightly older model ages than other mantle evolution models.

Two harzburgites from Jeju Island (<0.64 wt.% CaO) and one from Baekryeong Island (1.08 wt.% CaO) are sufficiently refractory to yield useful model T_{RD} ages. All three give nearly identical T_{RD} ages of ~1.9 to 1.8 Ga (Table 1). These ages are considered to be conservative estimates of the oldest SCLM currently preserved beneath South Korea. The remaining lherzolite samples from all localities are significantly less depleted to fertile (>1.90 wt.% CaO) and give a wide range of T_{RD} ages from ~1.1 to ~0.2 Ga (Table 1). Because of incomplete Re removal due to relatively lower degrees of melt-depletion, these T_{RD} ages represent minimum ages of melt withdrawal.

The isochron method is the most robust for dating melt extraction from mantle peridotites if: 1) the original mantle was isotopically homogeneous, 2) the peridotites were variably melt and Re depleted at the same time, and 3) Re and Os were immobile since melt extraction. These conditions are rarely met in the case of peridotite xenolith suites. Nonetheless, there are a few xenoliths suites that have yielded reliable isochron ages (e.g., southwestern USA, Lee et al., 2001; Trans-North China Orogen, Gao et al., 2002). For the South Korean suite, there is no clear isochronous relationship among the entire suite of samples or among samples from a given volcanic center. In the $^{187}Re/^{188}Os$ versus $^{187}Os/^{188}Os$ isochron diagram (Fig. 3a), most samples deviate from a 2.0 Ga reference isochron projected from PUM composition, suggesting either a significant perturbation of Re/Os for some samples or melting at two or more times.

To overcome susceptibility of recent Re mobility in peridotite xenolith suites, linear trends defined by $^{187}Os/^{188}Os$ and immobile indicators of melt depletion (e.g., Al_2O_3, CaO and Lu) are often used as isochron analogues, with these elemental concentrations serving as proxies for Re/Os (Reisberg and Lorand, 1995). Compared to Re, these elements are much less susceptible to recent alteration and contamination. As with the isochron method, however, this method also assumes a single-stage of melt depletion, and requires an assumption to be made with regard to the Al_2O_3, CaO or Lu concentration of the residue at the point of complete Re removal. Such trends may also represent mixing lines reflecting refertilization of the lithosphere by either basalt or asthenospheric mantle (Reisberg and Lorand, 1995; Chesley et al., 1999), or lithosphere formation during two or more melting events, following a secular change in the degree of melt depletion with time (Reisberg and Lorand, 1995; Handler et al., 1997; Chesley et al., 1999).

Collectively, the Korean lherzolites and harzburgites show a positive correlation between $^{187}Os/^{188}Os$ and Al_2O_3 ($R^2=0.75$). Assuming that the correlation between $^{187}Os/^{188}Os$ and Al_2O_3 records a single melting event or series of melting events closely spaced in time, the trend from all peridotites gives a model age of ~1.8 Ga, with an initial $^{187}Os/^{188}Os$ estimate based on extrapolation to Al_2O_3 of 0.7 wt.%, a composition at which it has been suggested Re/Os approaches zero during partial melting of the upper mantle (Handler and Bennett, 1999). If each locale is considered separately, some differences in the individual trends appear. The trends from the Jeju ($R^2=0.93$) and Baekryeong ($R^2=0.78$) Islands give similar model ages of ~1.9 and ~2.1 Ga, respectively (not shown). Considering all data from both of these locales, the trend ($R^2=0.87$) yields a model age of ~1.98 Ga. The limited trend ($R^2=0.52$) defined by only lherzolite samples from both locales gives a younger model age of ~1.6 Ga. These model ages overlap with the corresponding T_{RD} ages (~1.9 to 1.8 Ga) for the harzburgites, suggesting that some of the SCLM beneath South Korea at present may have been created by a single melting event or series of melting events closely spaced in time during the Paleoproterozoic.

The $^{187}Os/^{188}Os$ versus Al_2O_3 trend for xenolith samples from the Jeju and Baekryeong Islands extrapolates to a $^{187}Os/^{188}Os$ of approximately 0.132 for an estimated Al_2O_3 value for PUM of 4.2 wt.%. This Os isotopic composition is about 2% more radiogenic than the current best estimate of PUM based on studies of numerous other SCLM xenolith suites (e.g., Meisel et al., 2001). The reason for the slightly apparent enrichment here is unknown. It may reflect some variability in the Os isotope of the PUM. More importantly here it could also indicate that the melt depletion event leading to the formation of the harzburgitic rocks occurred much earlier than melting that led to modest levels of depletion present in the more lherzolitic samples. That is, the melt depletion of the lherzolites may have occurred only recently, so there has been insufficient time for the Os isotopic composition of PUM to evolve away from these samples.

In contrast to the peridotites from the Jeju and Baekryeong Islands, the trend defined by three Boeun samples ($R^2=0.77$) is more shallow and gives a much younger model age of ~1.0 Ga (Fig. 3b). The one Pyeongtaek sample also plots along this trend. As noted above, uncertainties for such young model ages are large. One interpretation of the trend is that it reflects a relatively young, minor depletion event. However, further complicating this interpretation is the fact that these xenoliths are quite fertile, yet have ~4% lower $^{187}Os/^{188}Os$ than the PUM. This characteristic may reflect an ancient refertilization event caused by the injection of metasomatic melt/fluid with low Re/Os, as suggested by sample BE1 which has a relatively high Os concentration but usually low Re concentration (Fig. 2a and b). These possibilities, however, can only be tentatively proposed, given the numerous uncertainties.

On the basis of our new Re–Os data, it is concluded that Paleoproterozoic SCLM presently dominates beneath South Korea, although some portions of the SCLM may be younger, and some portions may have been affected by metasomatism/melt-percolation in some locales (e.g., Boeun and Pyeongtaek). Of greatest note, there is no evidence for the existence of Archean SCLM, as is present beneath the Chinese portion of the Sino-Korean craton (Gao et al., 2002).

5.3. Relation between crust and mantle

If melt removal leads to stabilization of SCLM, the production of mantle keels must coincide with or immediately postdate the formation of their respective portions of continental crust (Shirey and Walker, 1998; Pearson, 1999). This predicted coupling in the formation of crust-SCLM has been previously confirmed via studies of peridotite xenolith suites and orogenic peridotite massifs in many Archean and Proterozoic, on- and off-cratonic regions (Walker et al., 1989; Carson and Irving, 1994; Handler et al., 1997; Pearson, 1999; Chesley et al., 1999; Lee et al., 2001). As noted, there is also evidence that SCLM can be affected by post-cratonization tectonic disturbance, and in some instances is either partly removed or even completely replaced by much younger lithospheric mantle (e.g., O'Reilly et al., 2001; Gao et al., 2002; Wu et al., 2003). While Os isotopic model ages younger than overlying crust are usually interpreted to date post-cratonization removal or replacement events of pre-existing SCLM, there is growing evidence (Parkinson et al., 1998; Brandon et al., 2000; Schaefer et al., 2002) that Os isotopic heterogeneity caused by ancient melting can be preserved for >1 Ga in the convecting mantle. If such ancient depleted materials were added into the SCLM, the apparently old model ages may be unrelated to the true time of lithospheric formation (Reisberg et al., 2004, 2005). Despite this inherent uncertainty, in the following discussion, it is assumed that the model age represents the time of formation of the SCLM from a PUM. This is reasonable in this case because of the similarity of these ages with model ages determined for SCLM underlying East China.

In South Korea, Nd T_{DM} model ages of the constituent crustal massifs indicate major crustal extraction events during the Neoarchean (~2.9 to 2.5 Ga) (Lan et al., 1995; Cheong et al., 2000; Lee et al., 2003a). If there was a genetic linkage between crust and SCLM in this region, there should be Archean SCLM underlying South Korea. The Re–Os isotopic results, however, suggest that the modern SCLM, sampled by Cenozoic basalts, is mostly Paleoproterozoic (~1.9 to 1.8 Ga), but may also contain substantially younger SCLM. Although the limited sampling cannot exclude the possible existence of Archean SCLM, preserved locally at shallow levels, the inconsistency between formation ages of crust and SCLM suggests that large portions of Archean SCLM were replaced by SCLM created during Paleoproterozoic. It is well documented in both the Gyeonggi massif and Yeongnam massif, South Korea, that the widespread intracrustal reworking processes, mainly caused by crustal thickening and subsequent high-grade metamorphism and voluminous production of crust-derived granitoids, occurred during the Paleoproterozoic (~2.1 to 1.8 Ga) (Cheong et al., 2000; Lee et al., 2000; Lee and Cho, 2003; Kim and Cho, 2003; Kwon et al., 2003; Sagong et al., 2003). Because these events are clearly coeval with the ages of underlying Proterozoic SCLM, replacement of Archean SCLM during the Proterozoic may be attributed to these events. This could have occurred as a result of continental collision, similar to Trans-North China Orogen that resulted in final cratonization of the Sino-Korean craton between eastern and western blocks (Zhao et al., 2001; Gao et al., 2002; Sagong et al., 2003), and a similar age structure in the SCLM.

In addition to the prevalent Paleoproterozoic tectonothermal events, there is also significant evidence for extension- or rift-related magmatism in South Korea during the Neoproterozoic. Uranium–Pb zircon ages of 742 Ma and 756 Ma have been reported for meta-syenite and a meta-trachyte in the Gyeonggi massif and Ogcheon belt, respectively (Lee et al., 1998; Lee et al., 2003b), suggesting that the crustal thinning or rift-related felsic magmatism postdated the within-plate mafic magmatism in the Imjingang belt (U–Pb zircon age of 861 Ma; Cho, 2001) and in the central Gyeonggi massif (Sm–Nd whole-rock age of ca. 850 Ma; Lee and Cho, 1995). In addition to the Neoproterozoic magmatic activity, there is also considerable evidence for vigorous Mesozoic and Cenozoic tectonic activity, including high-*P* metamorphism and igneous activity, in the southern part of the Korean peninsula (e.g., Chough et al., 2000). Consequently, these tectonic processes may be linked to the apparent perturbation in Re–Os systematics of the lherzolite xenoliths from South Korea, possibly leading to the observed complexities.

5.4. Geodynamic implications for the SCLM evolution of East Asia

The new data from South Korean peridotite xenoliths provide further evidence for a complex age structure in the SCLM beneath East Asia. A compilation of $^{187}Os/^{188}Os$ versus Al_2O_3 data for peridotite xenoliths from major tectonic blocks of East Asia reveals several characteristics (Fig. 4). There is little evidence for the preservation of Archean SCLM at present beneath East Asia. The $^{187}Os/^{188}Os$ ratios of Cenozoic basalt-hosted xenoliths from all East Asian blocks are >0.115, suggesting ages of melt depletion during the Paleo- to Mesoproterozoic, and in some instance much later. The only evidence for Archean SCLM in post-Paleozoic volcanic systems comes from Archean Os T_{RD} ages for some sulfides from Miocene peridotite xenoliths of Penghu, South China craton (Wang et al., 2003). Even here, however, most model ages are Proterozoic or younger. Evidence for the prior existence of Archean SCLM underlying East Asia is limited to two Ordovician kimberlite-hosted peridotite xenoliths from Fuxian, Sino-Korean craton.

One very refractory xenolith from another Ordovician kimberlite locale (Mengyin) appears to have formed post-Archean SCLM, with a minimal age of melt depletion during the Mesoproterozoic (Gao et al., 2002). Collectively, these results may indicate that some portions of Archean SCLM preserved beneath the eastern block of the Sino-Korean craton during the early Paleozoic were already either strongly modified or eroded and removed by that time. Except for the two samples from Fuxian, refractory xenoliths with lowest $^{187}Os/^{188}Os$ from each of East Asian blocks have variable but similar T_{RD} ages of ~1.9 to 1.5 Ga, suggesting the preservation of dominantly Proterozoic SCLM beneath all East Asian blocks. This may indicate that a large proportion of the Proterozoic SCLM beneath East Asia survived severe Mesozoic continental collision and massive Cenozoic igneous activity, following widespread lithospheric thinning caused by paleo-circum Pacific subduction (Wilde et al., 2003; Wu et al., 2005).

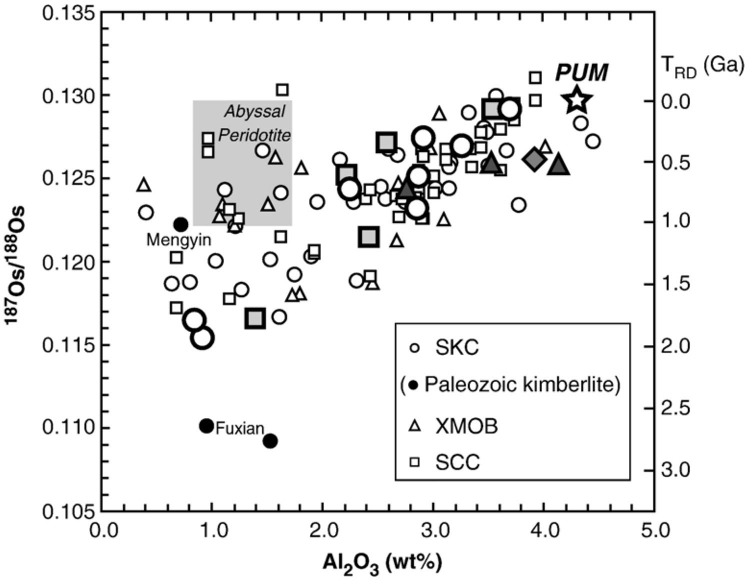

Fig. 4. $^{187}Os/^{188}Os$ versus whole-rock Al_2O_3 (wt.%) for peridotite xenoliths from the major tectonic units of East Asia. Symbols are the same as in Fig. 2d for South Korean xenoliths. Data sources: Sino-Korean craton (SKC) (Gao et al., 2002; Wu et al., 2003); Xing'an Mongolian Orogenic Belt (XMOB) (Wu et al., 2003); South China craton (SCC) (Zhi et al., 2001). Most of the relatively fertile xenoliths from all tectonic units, including South Korea, plot on the same broad $^{187}Os/^{188}Os$ vs. Al_2O_3 trend, indicating that the SCLM beneath East Asia at present is likely dominated by Proterozoic additions, and does not include much Archean SCLM. In all Chinese tectonic units, there are refractory xenoliths with minimally depleted $^{187}Os/^{188}Os$, suggesting apparent additions of much younger, Phanerozoic SCLM. Unlike for the Chinese tectonic units, however, there is no evidence for the addition of Phanerozoic SCLM in South Korea. The $^{187}Os/^{188}Os$ and whole-rock Al_2O_3 (wt.%) values of abyssal peridotites are from Snow and Reisberg (1995), Brandon et al. (2000), and Canil (2004), and the PUM values of $^{187}Os/^{188}Os = 0.1296$ and $^{187}Re/^{188}Os = 0.433$ are after Meisel et al. (2001).

Despite the fact that continental crust was evidently created and processed over more than 1 Ga within the East Asian blocks, the similarity in age from most xenolith samples throughout the region suggests that the Proterozoic and Phanerozoic tectonic processes played a major role in shaping the current age structure of the SCLM, either as a result of primary crustal building (e.g., South China craton and Xing'an Mongolian Orogenic Belt) or via secondary accretion resulting from assembly of Archean continental nuclei (e.g., Sino-Korean craton and South Korea).

The occurrences of refractory xenoliths with minimally depleted $^{187}Os/^{188}Os$ in some tectonic blocks (e.g., Xing'an Mongolian Orogenic Belt) provides clear evidence for additions of much younger, Phanerozoic SCLM throughout all of East China. Such young SCLM, however, is not yet positively identified in the SCLM underlying South Korea. The Phanerozoic replacement of the SCLM beneath East Asian blocks is consistent with geophysical data, indicative of relatively thin SCLM at present beneath East China (e.g., Griffin et al., 1998). The tectonic processes responsible for the Phanerozoic replacement of the SCLM beneath East Asia are a subject of considerable debate. Gao et al. (2002) attributed the removal event to the continental collision between the Sino-Korean craton and South China craton during the Triassic. Wu et al. (2003), on the basis of the NNE accretion trend of the Phanerozoic SCLM, concluded that the replacement was due to the evolution of the circum-Pacific continental margin during the late Mesozoic and the Cenozoic. Despite very intense tectonic activities in East Asia during the late Phanerozoic, the SCLM beneath South Korea apparently was not affected by these events, although considerable evidence for vigorous Mesozoic and Cenozoic tectonic activity, including the high-*P* metamorphism and igneous activity, is observed in overlying crust of South Korea (Chough et al., 2000). The Korean peninsula may, thus, delineate the easternmost boundary of the Phanerozoic SCLM delamination. Determining why it may have avoided removal of Proterozoic SCLM may provide new insights to the causes of SCLM delamination.

6. Conclusions

New results suggest that the complicated age structure in the SCLM beneath East China extends eastward to South Korea, and further highlights the periodic construction and destruction of SCLM during the Archean, Proterozoic and Phanerozoic in East Asia. The removal and replacement of pre-existing SCLM by younger SCLM are evidently related to a series of continental accretionary processes that resulted in not only the stabilization of a single craton, but also accretion of several stable cratons into a larger continental block. In contrast to most assumptions regarding the longevity of SCLM beneath cratons, East Asia provides an example of SCLM that has become highly modified, and variably replaced by younger SCLM during tectonic events including continental collision and extension.

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References

Brandon, A.D., Snow, J.E., Walker, R.J., Morgan, J.W., Mock, T.D., 2000. ^{190}Pt–^{186}Os and ^{187}Re–^{188}Os systematics of abyssal peridotites. Earth Planet. Sci. Lett. 177, 319–335.

Bryant, D.L., Ayers, J.C., Gao, S., Miller, C.F., Zhang, H., 2004. Geochemical, age, and isotopic constraints on the location of the Sino-Korean/Yangtze suture and evolution of the northern Dabie Complex, east central China. GSA Bull. 116, 698–717.

Canil, D., 2004. Mildly incompatible elements in peridotites and the origins of mantle lithosphere. Lithos 77, 375–393.

Carson, R.W., Irving, A.J., 1994. Depletion and enrichment history of subcontinental lithospheric mantle: an Os, Sr, Nd and Pb isotopic study of ultramafic xenoliths from the northwestern Wyoming Craton. Earth Planet. Sci. Lett. 126, 457–472.

Chen, J., Jahn, B.-M., 1998. Crustal evolution of southeastern China: Nd and Sr isotopic evidence. Tectonophysics 284, 101–133.

Cheong, C.-S., Kwon, S.-T., Park, K.-H., 2000. Pb and Nd isotopic constraints on Paleoproterozoic crustal evolution of the northeastern Yeongnam massif, South Korea. Precambrian Res. 102, 207–220.

Chesley, J.T., Rudnick, R.L., Lee, C.-T., 1999. Re–Os systematics of mantle xenoliths from the east African rift: age, structure, and history of the Tanzanian craton. Geochim. Cosmochim. Acta 63, 1203–1217.

Cho, M., 2001. A continuation of Chinese ultrahigh-pressure belt in Korea: evidence from ion microprobe U–Pb zircon ages. Gondwana Res. 4, 708.

Choi, S.H., Jwa, Y.-J., Lee, H.Y., 2001. Geothermal gradient of the upper mantle beneath Jeju Island, Korea: evidence from mantle xenoliths. Isl. Arc 10, 175–193.

Choi, S.H., Kwon, S.-T., Mukasa, S.B., Sagong, H., 2005. Sr–Nd–Pb isotope and trace element systematics of mantle xenoliths from Late Cenozoic alkaline lavas, South Korea. Chem. Geol. 221, 40–64.

Chough, S.K., Kwon, S.-T., Ree, J.-H., Choi, D.K., 2000. Tectonic and sedimentary evolution of the Korean Peninsula: a review and new view. Earth Sci. Rev. 52, 175–232.

Cohen, A.S., Waters, F.G., 1996. Separation of osmium from geological materials by solvent extraction for analysis by TIMS. Anal. Chem. 332, 269–275.

Gao, S., Rudnick, R.L., Carlson, R.W., McDonough, W.F., Liu, Y.-S., 2002. Re–Os evidence for replacement of ancient mantle lithosphere beneath the North China craton. Earth Planet. Sci. Lett. 198, 307–322.

Griffin, W.L., Zhang, A.-D., O'Reilly, S.Y., Ryan, C.G., 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton. In: Flower, M.F.J., Chung, S.-L., Lo, C.-H., Lee, T.Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. Geodynamic Series, vol. 27. American Geophysical Union, Washington, DC, pp. 107–126.

Handler, M.R., Bennett, V.C., 1999. Behaviour of platinum-group elements in the subcontinental mantle of eastern Australia during variable metasomatism and melt depletion. Geochim. Cosmochim. Acta 63, 3597–3618.

Handler, M.R., Bennett, V.C., East, T.M., 1997. The persistence of off-cratonic lithospheric mantle: Os isotopic systematics of variably metasomatised southeast Australian xenoliths. Earth Planet. Sci. Lett. 151, 61–75.

Handler, M.R., Wysoczanski, R.J., Gamble, J.A., 2003. Proterozoic lithosphere in Marie Byrd Land, West Antarctica: Re–Os systematics of spinel peridotite xenoliths. Chem. Geol. 196, 131–145.

Kim, J.M., Cho, M., 2003. Low-pressure metamorphism and leucogranite magmatism, northeastern Yeongnam Massif, Korea: implication for Paleoproterozoic crustal evolution. Precambrian Geol. 122, 235–251.

Kim, K.H., Nagao, K., Jang, H.S., Sumino, H., Chung, J.I., 2002. Nd, Sr and noble gas isotopic compositions of alkali basaltic rocks and mantle xenoliths in the Baegryongdo. Econ. Environ. Geol. 35, 523–532.

Kwon, Y.W., Oh, C.W., Kim, H.S., 2003. Granulite-facies metamorphism in the Punggi area, northeastern Yeongnam Massif, Korea and its tectonic implications for East Asia. Precambrian Geol. 122, 253–273.

Lan, C.-Y., Lee, T., Zhou, X.-H., Kwon, S.-T., 1995. Nd isotopic study of Precambrian basement of South Korea: evidence for Early Archean crust. Geology 23, 249–252.

Lee, H.Y., 1996. Petrochemical study of mantle xenoliths in alkali basalts from South Korea: P/T regime of the upper mantle. Int. Geol. Rev. 38, 320–335.

Lee, S.R., Cho, M., 1995. Tectonometamorphic evolution of the Chuncheon amphibolite, central Gyeonggi massif, South Korea. J. Metamorph. Geol. 13, 315–328.

Lee, S.R., Cho, M., 2003. Metamorphic and tectonic evolution of the Hwacheon granulite complex, central Korea: composite P–T path resulting from two distinct crustal-thickening events. J. Petrol. 44, 197–225.

Lee, K.-S., Chang, H.-W., Park, K.-H., 1998. Neoproterozoic bimodal volcanism in the central Ogcheon belt, Korea: age and tectonic implication. Precambrian Res. 89, 47–57.

Lee, S.R., Cho, M., Yi, K.-W., Stern, R., 2000. Early Proterozoic granulites in central Korea: tectonic correlation with Chinese cratons. J. Geol. 108, 729–738.

Lee, C.-T., Yin, Q.-Z., Rudnick, R.L., Chesley, J.T., Jacobsen, S.B., 2001. Osmium isotopic evidence for Mesozoic removal of lithospheric mantle beneath the Sierra Nevada. Science 289, 1912–1916.

Lee, S.R., Cho, M., Hwang, J.H., Lee, B.-J., Kim, Y.-B., Kim, J.C., 2003a. Crustal evolution of the Gyeonggi massif, South Korea: Nd isotopic evidence and implications for continental growths of East Asia. Precambrian Res. 121, 25–34.

Lee, S.R., Cho, M., Cheong, C.-S., Kim, H., Wingate, M.T.D., 2003b. Age, geochemistry, and tectonic significance of Neoproterozoic alkaline granitoids in the northwestern margin of the Gyeonggi massif, South Korea. Precambrian Res. 122, 297–310.

Liu, D.-Y., Nutman, A.P., Compston, W., Wu, J.-S., Shen, Q.-H., 1992. Remnants of ≥3800 Ma crust in the Chinese part of the Sino-Korean Craton. Geology 20, 339–342.

Ma, C., Ehlers, C., Xu, C., Li, Z., Yang, K., 2000. The roots of the Dabieshan ultrahigh-pressure metamorphic terrane: constraints from geochemistry and Nd–Sr isotopic systematics. Precambrian Res. 102, 279–301.

Meisel, T., Walker, R.J., Irving, A.J., Lorand, J.P., 2001. Osmium isotopic compositions of mantle xenoliths: a global perspective. Geochim. Cosmochim. Acta 65, 1311–1323.

Menzies, M.A., Fan, W.-M., Zhang, M., 1993. Palaeozoic and Cenozoic lithoprobe and the loss of >120 km of Archean lithosphere, Sino-Korean craton, China. In: Prichard, H.M., Alabaster, T., Harris, N.B.W., Nearly, C.R. (Eds.), Magmatic Processes and Plate Tectonics Geological Society Special Publication, vol. 76, pp. 71–81.

O'Reilly, S.Y., Griffin, W.L., Poudjom Djomani, Y.H., Morgan, O., 2001. Are lithospheres are forever? Tracking changes in subcontinental lithospheric mantle through time. GSA Today 11, 4–10.

Parkinson, I.J., Hawkesworth, C.J., Cohen, A.S., 1998. Ancient mantle in a modern arc: osmium isotopes in Izu–Bonin–Mariana forearc peridotites. Science 281, 2011–2013.

Pearson, D.G., 1999. The age of continental roots. Lithos 48, 171–194.

Pearson, D.G., Carlson, R.W., Shirey, S.B., Boyd, F.R., Nixon, P.H., 1995. The stabilization of Archean lithospheric mantle: a Re–Os isotope study of peridotite xenoliths from the Kaapvaal craton. Earth Planet. Sci. Lett. 134, 341–357.

Peslier, A.H., Reisberg, L., Ludden, J., Francis, D., 2000. Re–Os constraints on harzburgite and lherzolite formation in the lithospheric mantle: a study of northern Canadian Cordillera xenoliths. Geochim. Cosmochim. Acta 64, 3061–3071.

Qiu, Y.M., Gao, S., McNaughton, N.J., Groves, D.I., Ling, W., 2000. First evidence of >3.2 Ga continental crust in the Yangtze craton of South China and its implications for Archean crustal evolution and Phanerozoic tectonics. Geology 28, 11–14.

Reisberg, L.C., Lorand, J.-P., 1995. Longevity of sub-continental mantle lithosphere from osmium isotope systematics in orogenic peridotite massifs. Nature 376, 159–162.

Reisberg, L.C., Lorland, J.-P., Bedini, R.M., 2004. Reliability of Os model ages in pervasively metasomatised continental mantle lithosphere: a case study of Sidamo spinel peridotite xenoliths (East African Rift, Ethiopia). Chem. Geol. 208, 119–140.

Reisberg, L.C., Zhi, X., Lorland, J.-P., Wagner, C., Peng, Z., Zimmermann, C., 2005. Re–Os and S systematics of spinel peridotite xenoliths from east central China: evidence for contrasting effects of melt percolation. Earth Planet. Sci. Lett. 239, 286–308.

Sagong, H., Cheong, C.-S., Kwon, S.-T., 2003. Paleoproterozoic orogeny in South Korea: evidence from Sm–Nd and Pb step-leaching garnet ages of Precambrian basement rocks. Precambrian Res. 122, 275–295.

Schaefer, B.F., Turner, S., Parkinson, I., Rogers, N., Hawkesworth, C., 2002. Evidence for recycled Archean oceanic mantle lithosphere in the Azores plume. Nature 420, 304–307.

Shirey, S.B., Walker, R.J., 1995. Carius tube digestion for low-blank rhenium–osmium analysis. Anal. Chem. 67, 2136–2141.

Shirey, S.B., Walker, R.J., 1998. The Re–Os isotope system in cosmochemistry and high temperature geochemistry. Ann. Rev. Earth Planet. Sci. 26, 423–500.

Snow, J.E., Reisberg, L., 1995. Os isotopic systematics of the MORB mantle: results from altered abyssal peridotites. Earth Planet. Sci. Lett. 133, 411–421.

Walker, R..J., Carlson, R.W., Shirey, S.B., Boyd, F.R., 1989. Os, Sr, Nd and Pb isotope systematics of southern African peridotite xenoliths: implications for the chemical evolution of subcontinental mantle. Geochim. Cosmochim. Acta 53, 1583–1595.

Walker, R.J., Prichard, H.M., Ishiwatari, A., Pimentel, M., 2002. The osmium isotopic composition of convecting upper mantle deduced from ophiolite chromites. Geochim. Cosmochim. Acta 66, 329–345.

Wang, H.-Z., Takahashi, E., Sueno, S., 1998. Geochemical properties of lithospheric mantle beneath the Sino-Korean craton: evidence from garnet xenocrysts and diamond inclusions. Phys. Earth Planet. Int. 107, 249–260.

Wang, K.-L., O'Reilly, S.Y., Griffin, W.L., Chung, S.-L., Pearson, N.J., 2003. Proterozoic mantle lithosphere beneath the extended margin of the South China block: in situ Re–Os evidence. Geology 31, 709–712.

Wilde, S.A., Zhou, X., Nemchin, A.A., Sun, M., 2003. Mesozoic crust–mantle interaction beneath the North China craton: a consequence of the dispersal of Gondwanaland and accretion of Asia. Geology 31, 817–820.

Wu, F.-Y., Walker, R.W., Ren, X.-W., Sun, D.-Y., Zhou, X.-H., 2003. Osmium isotopic constraints on the age of lithospheric mantle beneath northeastern China. Chem. Geol. 196, 107–129.

Wu, F.-Y., Lin, J.-Q., Wilde, S.A., Zhang, X., Yang, J.-H., 2005. Nature and significance of the Early Cretaceous giant igneous event in eastern China. Earth Planet. Sci. Lett. 233, 103–119.

Xu, X., O'Reilly, S.Y., Griffin, W.L., Zhou, X., 2000. Genesis of young lithospheric mantle in southeastern China: an LAM-ICPMS trace element study. J. Petrol. 41, 111–148.

Zhang, H.-F., Sun, M., Lu, F.-X., Zhou, X.-H., Zhou, M.-F., Liu, Y.-S., Zhang, G.-H., 2001. Geochemical significance of a garnet lherzolite from the Dahongshan kimberlite, Yangtze craton, southern China. Geochem. J. 35, 315–331.

Zhao, G., Cawood, P.A., Simon, A.W., Sun, M., Lu, L., 2001. Metamorphism of basement rocks in the Central Zone of the North China craton: implications for Paleoproterozoic tectonic evolution. Precambrian Res. 103, 55–88.

Zheng, J., O'Reilly, S.Y., Griffin, W.L., Zhang, M., Lu, F., Liu, G., 2004. Nature and evolution of Mesozoic–Cenozoic lithospheric mantle beneath the Cathaysia block, SE China. Lithos 74, 41–65.

Zhi, X., Peng, Z., Chen, D., Yu, C., Sun, W., Reisberg, L., 2001. The longevity of subcontinental lithospheric mantle beneath Jiansu–Anhui region. Sci. China (Ser. D) 44, 1110–1118.