



Chondritic magnesium isotopic composition of the terrestrial mantle: A case study of peridotite xenoliths from the North China craton

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ABSTRACT

In order to further investigate inter-mineral Mg isotope fractionation at mantle temperatures and to better constrain the Mg isotopic composition of the terrestrial mantle, we have studied a set of well-characterized mantle peridotite xenoliths from Sanyitang and Beiyuan, North China craton. The Sanyitang and Beiyuan peridotites, which have diverse origins with different mineralogy, chemical composition and degree of partial melting and metasomatism, display a small variation in Mg isotopic composition, with $\delta^{26}\text{Mg}$ varying from -0.48 to -0.12 and an average value of -0.29 ± 0.19 (2SD, $n=21$) in olivines, from -0.27 to -0.10 and an average value of -0.21 ± 0.09 (2SD, $n=12$) in orthopyroxenes and from -0.35 to -0.08 and an average value of -0.22 ± 0.14 (2SD, $n=15$) in clinopyroxenes. The Mg isotopic compositions of the coexisting olivine, orthopyroxene and clinopyroxene in all peridotites are identical within our external precision ($\sim \pm 0.1\%$, 2SD), suggesting that Mg isotope fractionation between olivine and pyroxenes at the temperatures of >900 °C is insignificant. These results are thus consistent with the absence of Mg isotope fractionation during basalt differentiation. The $\sim 0.4\%$ Mg isotopic variations in these peridotite samples, which are larger than our external precision, might result from thermal diffusion-driven isotope fractionation or melt-rock interactions.

Overall, the $\delta^{26}\text{Mg}$ of the mantle, based on peridotite minerals analyzed here, is estimated to be -0.26 ± 0.16 (2SD). This value is in excellent agreement with recent studies based on peridotites and oceanic basalts (Handler et al., 2009; Teng et al., 2007). It is also similar to $\delta^{26}\text{Mg}$ values of two additional dunite standards (DTS-1 and DTS-2) and two carbonaceous chondrites (Allende and Murchison) analyzed in this study as well as $\delta^{26}\text{Mg}$ of all published chondrites (~ -0.3). The silicate Earth thus has a chondritic Mg isotopic composition.

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1. Introduction

Studies of isotopic variations in terrestrial and extraterrestrial rocks can be used to identify the processes that govern planetary accretion and differentiation. For example, Mg isotopes have been used to estimate the relative contributions of chondrules and calcium–aluminum inclusions to the formation of the terrestrial planets and asteroids because of their distinctive Mg isotopic compositions (Young and Galy, 2004; Norman et al., 2006; Wiechert and Halliday, 2007). However, Mg isotopic composition of the Earth is still not well-constrained. Some studies on mantle peridotites indicate that the Earth has heavier Mg isotopic compositions compared to chondrites (Wiechert and Halliday, 2007; Young et al., 2008) while other studies, also based on mantle peridotites as well as oceanic basalts, yield different conclusion that the

Earth and chondrites, on average, have identical Mg isotopic compositions (Norman et al., 2006; Teng et al., 2007; Chakrabarti and Jacobsen, 2009; Handler et al., 2009).

In addition, it is still debated if Mg isotope fractionation can happen among peridotite minerals or not. Studies on basalt differentiation reveal limited Mg isotope fractionation during basaltic differentiation (Teng et al., 2007), which indicates that Mg isotope fractionation should be even smaller at mantle temperatures considering that equilibrium isotope fractionation decreases as the temperature increases (Chacko et al., 2001). However, significant Mg isotope fractionation among mantle minerals has been reported in several recent studies (Young and Galy, 2004; Pearson et al., 2006; Young et al., 2008). If the conclusions of these studies are indeed right, then it is more complicated to constrain the Mg isotopic composition of the Earth since many previous studies only use olivines to represent the bulk Earth (Young and Galy, 2004; Norman et al., 2006; Wiechert and Halliday, 2007; Young et al., 2008; Handler et al., 2009). Recently, Handler et al. (2009) investigated Mg isotopic compositions of olivines and a few coexisting pyroxenes from a range of locations and found limited inter-mineral Mg isotope fractionation and the upper mantle, based on their data, is chondritic.

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In order to further investigate inter-mineral Mg isotope fractionation at mantle temperatures, study the effects of mantle metasomatism on Mg isotopic compositions of peridotites and better constrain the Mg isotopic composition of the mantle, we have studied a set of well-characterized mantle peridotite xenoliths from Sanyitang and Beiyang, North China craton. Our results, which are similar to Handler et al. (2009)'s but different from those reported in Wiechert and Halliday (2007) and Young et al. (2008), suggest that there is no measurable inter-mineral Mg isotope fractionation in mantle peridotites and the Mg isotopic composition of the silicate Earth, as represented by peridotites, is chondritic.

2. Geological background and samples

The North China craton is one of the oldest continental nuclei in the world (Jahn et al., 1987; Liu et al., 1992) and the largest cratonic block in China. It is bounded on the south by the Paleozoic to Triassic Qinling–Dabie–Sulu orogenic belt (Li et al., 1993; Meng and Zhang, 2000) and on the north by the Central Asian Orogenic Belt (Sengor et al., 1993; Davis et al., 2001) (Fig. 1a). To the west, the craton is cut by the Daxing'anling–Taihangshan Gravity Lineament (DTGL), which is likely caused by the diachronous lithospheric thinning of the craton; to the east, the craton is cut by the Tan-Lu Fault Zone (TLFZ).

Unlike other Archaean cratons worldwide, the North China craton has experienced widespread tectono-thermal reactivation since the Phanerozoic, as evidenced by the Paleozoic kimberlites, Mesozoic

calc-alkaline volcanic rocks and widespread Cenozoic basalts on the craton (Griffin et al., 1992; Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Zhang et al., 2002, 2003; Gao et al., 2004). Types and compositions of mantle xenoliths and xenocrysts reflect the changes in the lithospheric structure (Griffin et al., 1998; Fan et al., 2000; Zheng et al., 2001, 2003; Zhang, 2005). Peridotite xenoliths, xenocrysts and diamond inclusions entrained in Ordovician diamondiferous kimberlites are characterized by low CaO, Al₂O₃ and high Mg[#] ($= 100 \times \text{Mg}/(\text{Mg} + \text{Fe})$ cationic ratio, >92), indicating a thick (>200 km) and cold (~40 mW/m²) lithosphere existed in the NCC during the Paleozoic (Fan and Menzies, 1992; Griffin et al., 1998; Fan et al., 2000; Zheng et al., 2003). However, peridotite xenoliths captured in Tertiary basalts show relatively high CaO, Al₂O₃ and low Mg[#] (<92), suggesting a thinner (<80 km) and hotter (~60 mW/m²) lithosphere beneath the North China craton in the Cenozoic (Fan et al., 2000; Zheng et al., 2001).

The xenoliths investigated here are spinel-facies peridotites from Tertiary basalts at Sanyitang and Beiyang area in the craton (Fig. 1b, c). All the xenoliths are fresh, ranging in sizes from 5 to 15 cm and in composition from lherzolites to wehrlites. Detailed mineral major and trace element data, thermometry, whole rock major and trace element data, platinum group element concentrations and Sr, Nd, and Os isotope data are available from earlier (Zhao et al., 2007) and ongoing work (Xiao, 2009). Selected chemical compositions and mineralogical compositions of all peridotites are also reported in Table 1.

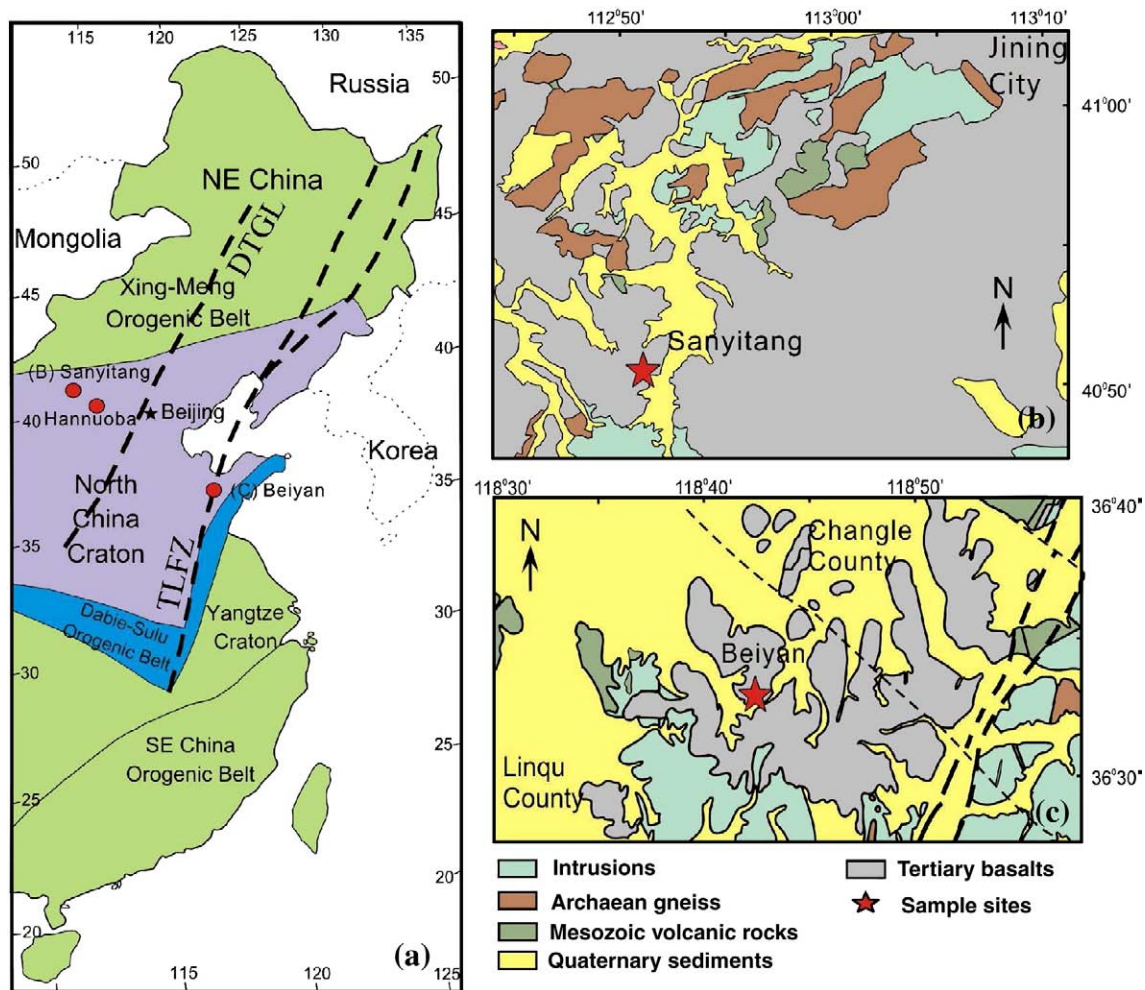


Fig. 1. (a) Simplified geological map of the North China craton and its surrounding areas (modified after Fan et al. (2000)). DTGL and TLFZ represent the Daxing'anling–Taihangshan Gravity Lineament and the Tan-Lu Fault zone, respectively. Sanyitang is located on the west of the DTGL, at the northern margin of the North China craton, while Beiyang lies within the TLFZ, at the central part of eastern North China craton. (b) Geological map of the Sanyitang area. (c) Geological map of the Beiyang area.

Table 1

Whole-rock and mineralogical characteristics of mantle peridotites from Sanyitang and Beiyang area, North China craton.

Sample no.	Mg [#] ^a Ol ^b	CaO WR	Modal abundances, wt.%					T(°C) ^c _{Ca-Opx}
			Ol	Opx	Cpx	Spl	Phl	
<i>Sanyitang lherzolites</i>								
SYT06-05	89.9		70	19	10	1	924	
SYT06-06	90.0		69	20	9	2	903	
SYT06-07	90.1		70	19	10	1	933	
SYT06-08	90.6		71	21	7	1	939	
SYT06-39	90.4		70	20	8	2	932	
SYT06-41	90.8		60	15	13	2	10	941
SYT06-42	90.5		58	17	10	2	13	945
<i>Beiyang lherzolites</i>								
CLB05-07	87.7	4.54	70	9	20	1	951	
CLB05-22	85.6	2.38	70	11	17	2	964	
CLB05-25	86.4	3.58	63	14	22	1	942	
CLB05-30	86.4	3.88	60	22	17	1	953	
CLB05-31	90.7	2.90	70	16	12	2	945	
<i>Beiyang wehrlites</i>								
CLB05-01	87.0	2.57			27	1		
CLB05-35	81.7	7.64			25	2		
CLB05-46	86.5	3.32			28	1		
CLB05-80	83.3	4.51			25			

^a Mg[#] = Mg²⁺/(Mg²⁺ + Fe²⁺) atomic ratio.^b Ol = olivine; Opx = orthopyroxene; Cpx = clinopyroxene; Spl = spinel; Phl = phlogopite; WR = whole rock.^c T estimates are after Brey and Kohler (1990).

Sanyitang is located west of the DTGL, at the northern margin of the North China craton (Fig. 1a). The Sanyitang basalts mainly consist of tholeiitic and alkali basalts dated to 9–33 Ma by the K–Ar methods (Zhang and Han, 2006). Samples in this study include 2 phlogopite-bearing and 5 phlogopite-free spinel lherzolites. Modal abundances are estimated to be 58–71 (vol.%) olivine, 15–21 (vol.%) orthopyroxene, 7–13 (vol.%) clinopyroxene and 1–2 (vol.%) spinel, while the phlogopite in the phlogopite-bearing lherzolites is 10–13 (vol.%). The phlogopite-bearing lherzolites have relatively low olivine, orthopyroxene and high clinopyroxene abundances (Table 1). All these xenoliths are metasomatized to various degrees, as revealed by rare earth elements in the clinopyroxenes, which have depleted heavy rare earth elements and variably enriched light rare earth elements (Fig. 2).

Beiyang lies in the TLFZ, at the central part of eastern North China craton (Fig. 1a). The lavas in this area are dominantly composed of alkali olivine basalt, olivine nephelinite, nephelinite and basanite. Samples in this study include 5 spinel lherzolites and 4 wehrlites. The mineral mode of these xenoliths is 60–75 (vol.%) olivine, 0–22 (vol.%) orthopyroxene, 12–28 (vol.%) clinopyroxene and 0–2 (vol.%) spinel. These rocks might be produced by interactions of the refractory protoliths with silicate melts, which partially or completely replaced orthopyroxene with clinopyroxene and increased CaO (2.3–7.7%) abundances of whole rocks (Table 1). The rock–melt reactions may be related to the extension of the TLFZ. The TLFZ was a strike-slip fault from the Jurassic to early Cretaceous and had been transferred into an extensional graben in the later Cretaceous and Tertiary (Zhu et al., 2001, 2005), which was likely to be a magma conduit because the mantle samples closer to the TLFZ were modified by interactions with silicate melts more significantly, as evidenced by their major, trace elements and Sr, Nd, Os isotopic data (Xiao, 2009).

3. Analytical methods

Magnesium isotopic analyses were performed at the Isotope Laboratory of the University of Arkansas, Fayetteville. All chemical procedures were carried out in a clean laboratory environment. About

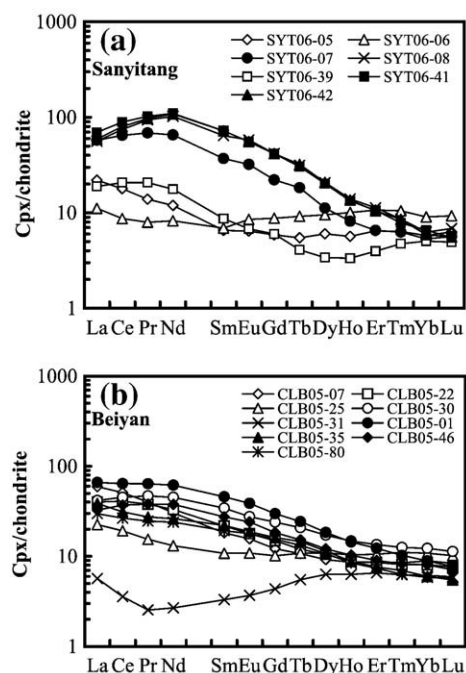


Fig. 2. Chondrite-normalized REE patterns of cpx from the Sanyitang and Beiyang xenoliths. Normalization values are from Anders and Grevesse (1989). Data are from Xiao (2009) and Zhao et al. (in press). The analytical uncertainty is better than 5%.

99% pure minerals were picked up under a binocular microscope. Approximately 5 mg of minerals were dissolved in Saville screw-top beakers in a mixture of concentrated HF–HNO₃ (~3:1). The capped beakers were heated at a temperature of 160 °C on a hot plate in a laminar flow exhaust hood for 1–3 days. In order to achieve 100% dissolution, the solutions were evaporated to dryness, dissolved in a mixture of concentrated HNO₃–HCl and heated overnight at a temperature of 70–80 °C. Then the solutions were evaporated to dryness the following day, refluxed with concentrated HNO₃ and then again evaporated to dryness. This dried residue was finally dissolved in 1 N HNO₃, in preparation for chromatographic separation.

Separation of Mg was achieved by cation exchange chromatography with Bio-Rad 200–400 mesh AG50W-X8 pre-cleaned resin (rinsed with >20 times column volume of 4 N HCl and 18.2 MΩ cm Milli-Q® water) in 1 N HNO₃ media by the established procedure of Teng et al. (2007). Samples containing ~100 µg of Mg were loaded on the resin and eluted by 1 N HNO₃. Same procedure was processed 1 time for olivine samples and 2 times for the other samples to obtain a pure Mg solution (i.e., ratio of the concentration of any other cations to that of Mg was <0.05) for mass spectrometry.

Magnesium isotopic compositions were analyzed by the standard bracketing method using a Nu Plasma MC-ICPMS, combined with DSN-100 desolvation nebulizer system at the University of Arkansas. No molecular interferences or double charge interferences were observed during the isotopic analyses. The in-run precision on the ²⁶Mg/²⁴Mg ratio for a single measurement run of one block of 40 ratios is $\pm 0.02\%$ (2SD). The internal precision on the measured ²⁶Mg/²⁴Mg ratio based on ≥ 3 repeat runs of same sample solution during a single analytical session is $\pm 0.1\%$ (2SD) for most of samples. Long-term precision, based on repeat analyses of synthetic solution and natural materials, is $\pm 0.1\%$ (2SD) (Teng et al., in press).

Accuracy of our analysis has been assessed in two ways. One way was to analyze well-known solution, mineral and rock samples including pure Mg standard Cambridge-1, two dunite standards (DTS-1 and DTS-2), one Kilbourne Hole olivine (KH Ol), two carbonaceous chondrites (Allende and Murchison) and sea water (Table 2). Our results agree well with reported data. DTS-1 and KH olivine yielded

Table 2
Magnesium isotopic compositions of minerals in mantle peridotites from Sanyitang and Beiyang area, North China craton and reference materials.

Sample	Mineral ^a	n ^b	$\delta^{26}\text{Mg}$ ^c	2SD ^d	$\delta^{25}\text{Mg}$ ^c	2SD ^d	
<i>Sanyitang lherzolites</i>							
SYT06-05	Ol	4	-0.29	0.10	-0.18	0.07	
	Opx	3	-0.24	0.06	-0.10	0.06	
	WR ^h		-0.28		-0.16		
SYT06-06	Ol(S) ^e	4	-0.24	0.05	-0.13	0.07	
	Ol(S) ^f	4	-0.29	0.10	-0.18	0.03	
	Ol(S) ^f	3	-0.27	0.06	-0.15	0.06	
	Opx(S)	4	-0.24	0.08	-0.11	0.09	
	Cpx	4	-0.23	0.09	-0.13	0.10	
SYT06-07	WR ^h		-0.26		-0.14		
	Ol	3	-0.21	0.08	-0.11	0.03	
	Opx	4	-0.21	0.03	-0.09	0.05	
	Cpx	3	-0.24	0.10	-0.15	0.08	
SYT06-08	WR ^h		-0.21		-0.10		
	Ol	3	-0.29	0.07	-0.12	0.03	
	Opx(S)	4	-0.17	0.14	-0.10	0.12	
	Cpx	4	-0.25	0.06	-0.14	0.05	
SYT06-39	WR ^h		-0.27		-0.11		
	Ol	3	-0.18	0.03	-0.08	0.07	
	Opx(S)	4	-0.25	0.06	-0.11	0.13	
	Cpx	4	-0.24	0.06	-0.14	0.07	
SYT06-41	WR ^h		-0.19		-0.09		
	Ol	4	-0.26	0.12	-0.15	0.08	
	Opx	4	-0.21	0.07	-0.07	0.03	
	Cpx	4	-0.28	0.04	-0.13	0.05	
SYT06-42	WR ^h		-0.26		-0.13		
	Ol(S)	4	-0.30	0.13	-0.16	0.10	
	Opx	4	-0.25	0.07	-0.14	0.09	
	Cpx	5	-0.22	0.07	-0.11	0.08	
WR ^h			-0.29		-0.25		
	<i>Beiyang lherzolites and wehrlites</i>						
	CLB05-07	Ol	4	-0.24	0.10	-0.12	0.07
		Opx	4	-0.18	0.02	-0.09	0.05
Cpx		4	-0.14	0.06	-0.06	0.09	
WR ^h			-0.23		-0.12		
CLB05-22	Ol	4	-0.12	0.06	-0.04	0.05	
	Opx	5	-0.10	0.07	-0.05	0.02	
	Cpx	4	-0.08	0.10	-0.04	0.02	
	WR ^h		-0.11		-0.04		
CLB05-25	Ol	4	-0.16	0.04	-0.09	0.09	
	Opx	3	-0.17	0.01	-0.04	0.05	
	Cpx	4	-0.13	0.09	-0.04	0.07	
	WR ^h		-0.16		-0.08		
CLB05-30	Ol	3	-0.31	0.07	-0.16	0.09	
	Opx	4	-0.27	0.04	-0.14	0.04	
	Cpx	4	-0.23	0.09	-0.11	0.05	
	WR ^h		-0.30		-0.15		
CLB05-31	Ol	4	-0.33	0.09	-0.19	0.04	
	Ol ^f	4	-0.30	0.07	-0.13	0.07	
	Opx	4	-0.22	0.09	-0.11	0.11	
	Cpx	4	-0.19	0.08	-0.07	0.11	
	WR ^h		-0.30		-0.14		
CLB05-01	Ol	4	-0.25	0.09	-0.13	0.03	
	Cpx	4	-0.27	0.08	-0.15	0.06	
	WR ^h		-0.25		-0.13		
CLB05-35	Ol	4	-0.43	0.08	-0.16	0.02	
	Ol ^f	3	-0.48	0.07	-0.24	0.11	
	Ol ^f	4	-0.45	0.02	-0.23	0.07	
	Cpx	3	-0.35	0.09	-0.22	0.06	
	WR ^h		-0.44		-0.23		
CLB05-46	Ol	4	-0.27	0.09	-0.11	0.05	
	Cpx	4	-0.19	0.06	-0.07	0.05	
	WR ^h		-0.26		-0.11		
CLB05-80	Ol(S)	4	-0.43	0.09	-0.20	0.05	
	Cpx	4	-0.33	0.07	-0.17	0.06	
	WR ^h		-0.42		-0.20		
<i>Seawater, rock and synthetic standards</i>							
IL-Mg-1 ^g	Synthetic ^f	4	+0.01	0.07	0.00	0.06	
IL-Mg-1		4	+0.03	0.07	+0.01	0.06	
IL-Mg-1		4	+0.05	0.08	+0.04	0.06	
Seawater		4	-0.83	0.07	-0.42	0.05	
Cambridge-1	Pure Mg	4	-2.63	0.09	-1.32	0.06	

Table 2 (continued)

Sample	Mineral ^a	n ^b	$\delta^{26}\text{Mg}$ ^c	2SD ^d	$\delta^{25}\text{Mg}$ ^c	2SD ^d
<i>Seawater, rock and synthetic standards</i>						
Allende	WR	4	-0.28	0.10	-0.17	0.07
Murchison	WR	4	-0.31	0.06	-0.17	0.06
KH	Ol	4	-0.32	0.10	-0.19	0.05
DTS-1	WR	4	-0.30	0.05	-0.13	0.09
DTS-2	WR	4	-0.38	0.14	-0.19	0.03
DTS-2	WR ^f	4	-0.32	0.07	-0.18	0.05

^aOl = olivine; Opx = orthopyroxene; Cpx = clinopyroxene; Spl = spinel; Phl = phlogopite; WR = whole rock.

^bn = number of repeat measurements by multi-collector inductively coupled plasma mass spectrometry.

$${}^c \delta^x \text{Mg} = \left(\frac{\left(\frac{x\text{Mg}}{24\text{Mg}} \right)_{\text{sample}}}{\left(\frac{x\text{Mg}}{24\text{Mg}} \right)_{\text{DSM-3}}} - 1 \right) \times 1000$$

where x = 25 or 26 and DSM3 is Mg solution made from pure Mg metal (Galy et al., 2003).

^d2SD = 2 times the standard deviation of the population of n repeat measurements of a sample solution.

^e(S), single grain.

^fReplicate analyses of separates from one sample.

^gIL-Mg-1 is a synthetic solution with concentration ratios of Mg:Fe:Al:Ca:Na:K:Ti = 1:1:1:1:1:0.1.

^hThe whole rock $\delta^{26}\text{Mg}$ is calculated based on our mineral $\delta^{26}\text{Mg}$ values and modal abundances of minerals in these peridotite samples from Xiao (2009) and Zhao et al. (in press). The whole rock Mg isotopic compositions are dominated by the olivines because the olivines contain 75–90% total Mg of the whole rocks.

$\delta^{26}\text{Mg}$ ($\delta^{26}\text{Mg} = [({}^{26}\text{Mg}/{}^{24}\text{Mg})_{\text{sample}}/({}^{26}\text{Mg}/{}^{24}\text{Mg})_{\text{DSM3}} - 1] \times 1000$, where DSM3 is Mg solution made from pure Mg metal (Galy et al., 2003)) of -0.30 ± 0.05 and -0.32 ± 0.10 , respectively, which are consistent with those of -0.30 ± 0.16 and -0.37 ± 0.06 for DTS-1 (Huang et al., 2009a) and -0.31 ± 0.09 ($n = 24$) for KH olivine (Teng et al., 2007). Our results for Cambridge-1 and Seawater are also consistent with published data (-2.63 ± 0.09 vs. -2.58 ± 0.14 for Cambridge-1 and -0.83 ± 0.07 vs. -0.80 to -0.86 for seawater) (Galy et al., 2003; Chang et al., 2003; Young and Galy, 2004). The Allende and Murchison carbonaceous chondrites have Mg isotopic compositions identical to previous values when the equivalent 2SD errors are considered (Young and Galy, 2004; Baker et al., 2005; Teng et al., 2007; Wiechert and Halliday, 2007). In addition to analyses of natural samples, we also prepare a synthetic multi-element standard solution IL-Mg-1 with concentration ratios of Mg:Fe:Al:Ca:Na:K:Ti = 1:1:1:1:1:0.1. This synthetic solution has matrix element concentrations similar to or higher than olivine and pyroxene samples analyzed in this study. Multiple analyses of IL-Mg-1 yield $\delta^{26}\text{Mg}$ values ranging from -0.07 to $+0.05$, with an average value of -0.01 ± 0.07 (2SD). This is in excellent agreement with the expected value of 0, further confirming that our data are both precise and accurate.

4. Results and discussion

Magnesium isotopic compositions of olivines, orthopyroxenes and clinopyroxenes from these peridotites display a small variation and, on average, are comparable to those of chondrites (Fig. 3). Olivines and pyroxenes from the Sanyitang lherzolites have similar Mg isotopic compositions, with $\delta^{26}\text{Mg}$ varying from -0.30 to -0.18 in olivines with an average value of -0.26 ± 0.08 (2SD), from -0.25 to -0.17 in orthopyroxenes with an average value of -0.22 ± 0.06 (2SD) and from -0.28 to -0.22 in clinopyroxenes with an average value of -0.24 ± 0.04 (2SD) (Table 2). Relative to minerals from Sanyitang lherzolites, olivines and pyroxenes from Beiyang peridotites display a slightly larger variation in Mg isotopic compositions ($\delta^{26}\text{Mg}_{\text{Ol}} = -0.48$ to -0.12 with an average value of -0.31 ± 0.23 (2SD); $\delta^{26}\text{Mg}_{\text{Opx}} = -0.27$ to -0.10 with an average value of -0.19 ± 0.13 (2SD); $\delta^{26}\text{Mg}_{\text{Cpx}} = -0.35$ to -0.08 with an average value of -0.21 ± 0.18 (2SD)) (Table 2). Overall, the $\delta^{26}\text{Mg}$ values of our mantle minerals vary from -0.48 to -0.08 , similar to those ($\delta^{26}\text{Mg} = -0.41$ to -0.14) reported in Handler et al.

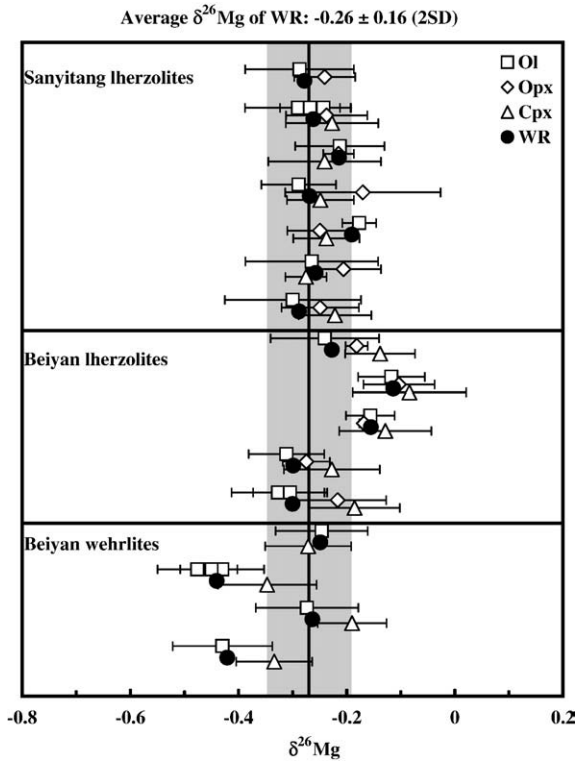


Fig. 3. Magnesium isotopic compositions of olivine (Ol), orthopyroxene (Opx) and clinopyroxene (Cpx) from the Sanyitang and Beiyang peridotite xenoliths, North China craton. The solid line and grey band represent the weighted average and two standard deviation ($\delta^{26}\text{Mg} = -0.27 \pm 0.08$) of all chondrites, which were calculated using IsoPlot 3.0 (Ludwig, 2003). Chondrite data are from Baker et al. (2005), Wiechert and Halliday (2007), Teng et al. (2007) and this study. Error bars for all data are 2SD. The solid circles show the calculated whole rock compositions for each sample. Data are from Table 2.

(2009) but significantly lighter than those ($\delta^{26}\text{Mg} = -0.12$ to 0.06) reported in Wiechert and Halliday (2007). The whole rock $\delta^{26}\text{Mg}$, calculated based on mineral $\delta^{26}\text{Mg}$ and MgO% values and their modal abundances in the peridotite, vary from -0.44 to -0.11 with an average of -0.26 ± 0.16 (2SD, $n = 16$).

4.1. The absence of inter-mineral and intra-mineral Mg isotope fractionation

Olivine grains separated from the same peridotite specimen have identical Mg isotopic compositions (Table 2), suggesting a lack of intra-mineral Mg isotope fractionation. This is in sharp contrast to Pearson et al. (2006) by using laser-ablation MC-ICPMS, which found significant intra-mineral Mg isotope fractionation ($>4\%$) in olivines from mantle peridotites. Furthermore, Mg isotopic compositions of coexisting olivine, orthopyroxene and clinopyroxene in peridotite samples are identical within our analytical uncertainty (Fig. 4). $\Delta^{26}\text{Mg}$, which represents the difference in Mg isotopic composition between coexisting minerals, is always less than 0.1, be it olivine, orthopyroxene or clinopyroxene (Fig. 4). This is similar to previous studies (Wiechert and Halliday, 2007; Handler et al., 2009), which reported very small fractionations between olivine and coexisting pyroxene within their analytical uncertainties. It is however, significantly different from other studies, which reported over 0.6‰ (and up to 4‰) Mg isotope fractionation in peridotite minerals (Young and Galy, 2004; Pearson et al., 2006; Young et al., 2008). The reason for the difference between our study and these studies is unknown. It may reflect different sets of samples (Young and Galy, 2004; Young et al., 2008) or analytical techniques related to laser-ablation MC-ICPMS (Pearson et al., 2006).

4.2. Magnesium isotopic variations in mantle peridotites

All peridotite samples in this study have similar Mg isotopic compositions except two wehrlites (CLB05-35 and CLB05-80). Compared to lherzolites and other wehrlites, olivines and pyroxenes from these two wehrlites have the lightest Mg isotopic compositions and the lowest Mg# (Fig. 5). Two processes could potentially produce lighter Mg isotopic compositions in peridotites xenoliths.

Recent studies have found significant Mg isotope fractionation can happen during chemical diffusion and thermal diffusion (Richter et al., 2008; Huang et al., 2009b). During the transport of peridotites xenoliths in basaltic lavas, Mg could potentially diffuse between xenoliths and lavas and produce kinetic isotope fractionation, in a way similar to Li isotopes (Rudnick and Ionov, 2007; Jeffcoate et al., 2007; Aulbach and Rudnick, 2009). The low Mg# suggests diffusion of Mg out of olivines from these two wehrlite samples. Since lighter isotopes diffuse faster than heavier ones (Richter et al., 2008), these wehrlites would have a

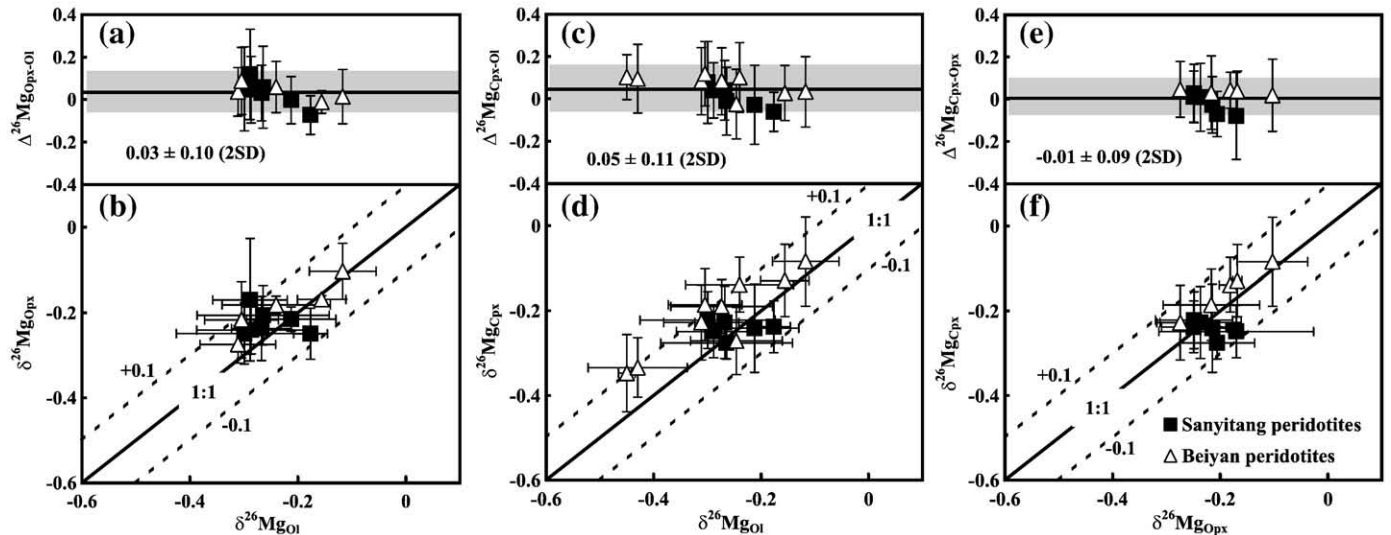


Fig. 4. Absence of inter-mineral Mg isotope fractionation in mantle peridotites from the North China craton. $\Delta^{26}\text{Mg}_{\text{X-Y}} = \delta^{26}\text{Mg}_{\text{X}} - \delta^{26}\text{Mg}_{\text{Y}}$, where X or Y = Ol, Opx or Cpx. The horizontal lines and grey bands in Fig 4.a, c and e represent the average values of $\Delta^{26}\text{Mg}_{\text{Opx-Ol}}$, $\Delta^{26}\text{Mg}_{\text{Cpx-Ol}}$ and $\Delta^{26}\text{Mg}_{\text{Cpx-Opx}}$, respectively. The solid lines and dashed lines in Fig 4. b, d and f represent functions of $Y = X$ and $Y = X \pm 0.1$, respectively. Data are from Table 2. Error bars for all data are 2SD.

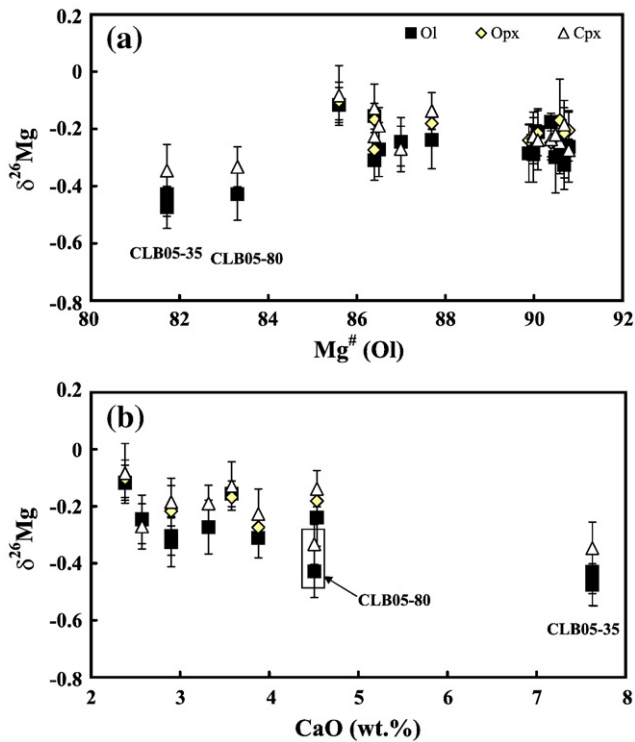


Fig. 5. Variations of $\delta^{26}\text{Mg}$ values as a function of $\text{Mg}^\#$ of olivines (a) and CaO (wt.%) of whole rocks (b) for the Sanyitang and Beiyang peridotites. Two wehrlites (CLB05-35 and CLB05-80) have slightly lighter Mg isotopes relative to other samples. Data are from Tables 1 and 2. Error bars are 2SD.

heavier isotopic compositions compared to high $\text{Mg}^\#$ samples. The opposite trend in samples studied here (Fig. 5), therefore, rules out kinetic Mg isotope fractionation by chemical diffusion.

The thermal diffusion, however, cannot be ruled out. During or before entrainment of these xenoliths in basaltic magma, local thermal gradient could present and produce the observed Mg isotope fractionation. The Beiyang wehrlites were metasomatised by interactions of refractory protoliths with silicate melts, which result in partial or complete replacement of orthopyroxenes with clinopyroxenes. The two wehrlites with light Mg isotopes, which have the highest CaO abundance and lowest $\text{Mg}^\#$, are likely to be most modified by interactions with the melts (Fig. 5). Therefore, these two wehrlites may be located closer to the magma conduit than other samples before they were entrained. A temperature gradient may exist between the cold lithospheric mantle wall rock and the hot melts. If so, these two wehrlites may have high temperatures and then have lighter Mg isotopic compositions (Richter et al., 2008; Huang et al., 2009b). According to the experimental results in molten basalt, the Mg isotope fractionation as a function of temperature corresponds to $3.6 \times 10^{-2}\text{‰}/\text{C}/\text{amu}$ (Richter et al., 2008). A temperature difference of about only 3 °C between these two wehrlites and other peridotites is required to produce such a Mg isotope fractionation. The reason why such a fractionation only observed in Beiyang peridotites may be the existence of the melt. According to Huang et al. (2009b)'s results, melt plays a critical role in causing thermal diffusion-driven kinetic isotope fractionation.

In addition to diffusion-induced isotope fractionation, rock–melt reactions (i.e., metasomatism) could also produce this isotopic variation. If the silicate melts have a slightly light Mg isotopic compositions (e.g., some light basalt melts, (Young and Galy, 2004; Teng et al., 2007; Huang et al., 2009a), then the light wehrlites may reflect the effects of metasomatism. Pearson et al. (2006) have suggested that metasomatism may enrich heavier Mg isotopes in peridotites significantly ($\sim 4\%$ in $\delta^{26}\text{Mg}$) due to chemical diffusion of Mg from olivine to melt. This large

enrichment of heavy Mg isotopes in olivines that was driven by chemical diffusion is not observed in our samples. Our data show a small enrichment of light Mg isotopes ($\sim 0.2\%$), barely beyond our analytical uncertainty, by mantle metasomatism. In any case, neither thermal diffusion nor rock–melt reactions has modified Mg isotopic compositions of these two wehrlites to any great extent ($\sim 0.2\%$ in $\delta^{26}\text{Mg}$).

4.3. Chondritic magnesium isotopic composition of the terrestrial mantle

Based on peridotite samples analyzed here, the average Mg isotopic composition of the mantle is estimated to be -0.26 ± 0.16 (2SD). This value is consistent with previous studies based on oceanic basalts (Teng et al., 2007) and peridotite xenoliths (Handler et al., 2009), but different from Wiechert and Halliday (2007)'s study that suggests significantly heavy Mg isotopic composition of the mantle.

Our estimated mantle $\delta^{26}\text{Mg}$ value is indistinguishable from the two carbonaceous chondrites (Allende and Murchison) analyzed here, as well as published chondrite data (Fig. 6). Therefore, similar to previous reports (Norman et al., 2006; Teng et al., 2007; Handler et al., 2009), our studies suggest that the silicate mantle (i.e. the Earth) has a chondritic Mg isotopic composition. Our studies further suggest that the need for a model such as that of Wiechert and Halliday (2007) that involves sorting of chondrules and calcium–aluminum-rich inclusions in the proto-planetary disk is not required to explain the Mg isotopic composition of the Earth.

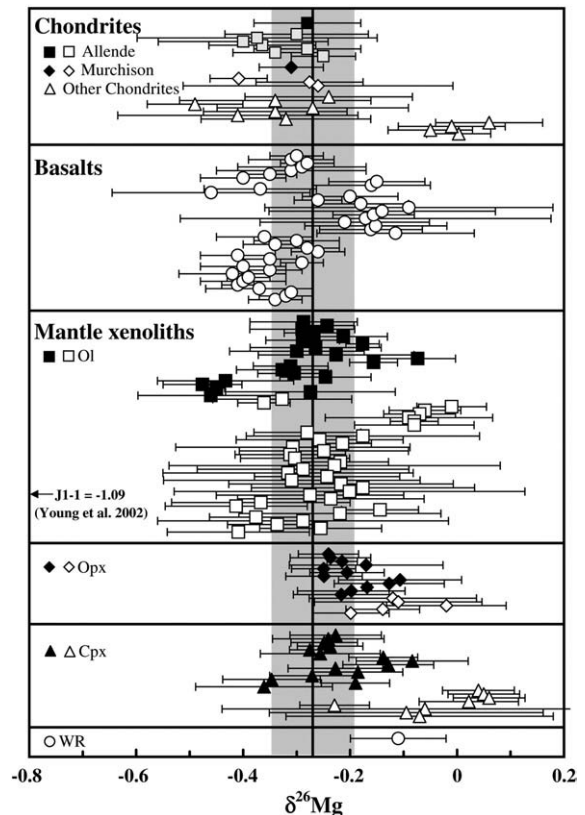


Fig. 6. Compilation of all available Mg isotopic data for chondrites, terrestrial basalts and mantle xenoliths. Solid symbols and open symbols represent data from this paper and from the literature, respectively. The solid line and grey band represent the weighted average and two standard deviation ($\delta^{26}\text{Mg} = -0.27 \pm 0.08$) of chondrites. Chondrite data are from Baker et al. (2005), Wiechert and Halliday (2007), Teng et al. (2007) and this study. Basalt data are from Young and Galy (2004), Bizzarro et al. (2005), Wiechert and Halliday (2007), Teng et al. (2007), Huang et al. (2009a) and Tipper et al. (2008). Mantle xenolith data are from Young and Galy (2004), Bizzarro et al. (2005), Thrane et al. (2006), Wiechert and Halliday (2007), Teng et al. (2007), Tipper et al. (2008), Handler et al. (2009) and Table 2. Error bars for all data are 2SD.

5. Conclusions

Olivines, clinopyroxenes and orthopyroxenes from Sanyitang and Beiyuan peridotites from the North China craton display a small variation in Mg isotopic composition, with $\delta^{26}\text{Mg}$ ranging from -0.48 to -0.08 , barely beyond our precision ($\sim \pm 0.1\%$, 2SD). Magnesium isotopic compositions of the coexisting olivine, orthopyroxene and clinopyroxene are indistinguishable within our external precision, suggesting that Mg isotope fractionation between olivines and pyroxenes at mantle temperatures is insignificant. This is consistent with previous studies on Kilauea Iki lavas that show an absence of Mg isotope fractionation during basalt differentiation. The overall $\sim 0.4\%$ Mg isotopic variation in peridotite samples might reflect thermal diffusion-driven kinetic isotope fractionation or mantle metasomatism.

Collectively, Mg isotopic composition of the mantle, based on samples analyzed here is estimated to be -0.26 ± 0.16 (2SD), similar to previous estimates (Teng et al., 2007; Handler et al., 2009). The fact that Mg isotopic composition of peridotites studied here, as well as most of published peridotites data, are identical to those of terrestrial basalts and chondrites, suggests that the silicate Earth has a chondritic Mg composition. The previous studies on a non-chondritic Mg isotopic composition of the Earth may either reflect limited samples or analytical artifacts.

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References

- Anders, E., Grevesse, N., 1989. Abundances of the elements – meteoritic and solar. *Geochim. Cosmochim. Acta* 53 (1), 197–214.
- Aulbach, S., Rudnick, R.L., 2009. Origins of non-equilibrium lithium isotopic fractionation in xenolithic peridotite minerals: examples from Tanzania. *Chem. Geol.* 258, 17–27.
- Baker, J.A., Bizzarro, M., Wittig, N., Connelly, J., Haack, H., 2005. Early planetesimal melting from an age of 4.5662 Gyr for differentiated meteorites. *Nature* 436, 1127–1131.
- Bizzarro, M., Baker, J.A., Haack, H., Lundgaard, K.L., 2005. Rapid timescales for accretion and melting of differentiated planetesimals inferred from ^{26}Al – ^{26}Mg chronometry. *Astrophys. J.* 632, L41–L44.
- Brey, G.P., Kohler, T., 1990. Geothermobarometry in 4-phase lherzolites. 2. New thermobarometers, and practical assessment of existing thermobarometers. *J. Petrol.* 31 (6), 1353–1378.
- Chacko, T., Cole, D.R., Horita, J., 2001. Equilibrium oxygen, hydrogen and carbon isotope fractionation factors applicable to geological systems. In: Valley, J.W., Cole, D.R. (Eds.), *Stable Isotope Geochemistry. Reviews in Mineralogy and Geochemistry*. Mineralogical Society of America, Washington, DC, pp. 1–82.
- Chakrabarti, R., Jacobsen, S.B., 2009. A combined silicon and magnesium isotopic study of bulk meteorites and the Earth. 40th Lunar and Planetary Science Conference: Abstract 2089.
- Chang, V.T.-C., Makishima, A., Belshaw, N.S., O'Nions, R.K., 2003. Purification of Mg from low-Mg biogenic carbonates for isotope ratio determination using multiple collector ICP-MS. *J. Anal. At. Spectrom.* 18, 296–301.
- Davis, G.A., Zheng, Y.D., Wang, C., Darby, B.J., Zhang, C.H., 2001. Mesozoic tectonic evolution of the Yanshan fold and thrust belt, with emphasis on Hebei and Liaoning provinces, northern China: Paleozoic and Mesozoic Tectonic Evolution of Central Asia: from Continental Assembly to Intracontinental Deformation, vol. 194, pp. 171–197.
- Fan, W.M., Menzies, M.A., 1992. Destruction of aged lower lithosphere and accretion of asthenosphere mantle beneath eastern China. *Geotecton. Metallog.* 16, 171–180.
- Fan, W.M., et al., 2000. On and off the North China Craton: where is the Archaean keel? *J. Petrol.* 41 (7), 933–950.
- Galy, A., et al., 2003. Magnesium isotope heterogeneity of the isotopic standard SRM980 and new reference materials for magnesium-isotope-ratio measurements. *J. Anal. At. Spectrom.* 18 (11), 1352–1356.
- Gao, S., et al., 2004. Recycling lower continental crust in the North China craton. *Nature* 432, 892–897.
- Griffin, W.L., O'Reilly, S.Y., Ryan, C.G., 1992. Composition and thermal structure of the lithosphere beneath south Africa, Siberia and China: proton microprobe studies. Abstract of International Symposium on Cenozoic volcanic rocks and deep-seated xenoliths of China and its environments. Beijing, pp. 65–66.
- Griffin, W.L., Andi, Z., 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: American Geophysical Union, Geodynamics Series*, pp. 107–126.
- Handler, M.R., Baker, J.A., Schiller, M., Bennett, V.C., Yaxley, G.M., 2009. Magnesium stable isotope composition of Earth's upper mantle. *Earth Planet. Sci. Lett.* 282, 306–313.
- Huang, F., Glessner, J., Ianno, A., Lundstrom, C.C., Zhang, Z.F., 2009a. Magnesium isotopic composition of igneous rock standards measured by MC-ICP-MS. *Chem. Geol.* 268 (1–2), 15–23.
- Huang, F., et al., 2009b. Chemical and isotopic fractionation of wet andesite in a temperature gradient: experiments and models suggesting a new mechanism of magma differentiation. *Geochim. Cosmochim. Acta* 73 (3), 729–749.
- Jahn, B.M., et al., 1987. 3.5 Ga old amphibolites from Eastern Hebei Province, China – field occurrence, petrography, Sm–Nd isochron age and ree geochemistry. *Precambrian Res.* 34 (3–4), 311–346.
- Jeffcoate, A.B., et al., 2007. Li isotope fractionation in peridotites and mafic melts. *Geochim. Cosmochim. Acta* 71, 202–218.
- Li, S.G., et al., 1993. Collision of the North China and Yangtze Blocks and formation of coesite-bearing eclogites – timing and processes. *Chem. Geol.* 109 (1–4), 89–111.
- Liu, D.Y., Nutman, A.P., Compston, W., Wu, J.S., Shen, Q.H., 1992. Remnants of greater-than-or-equal-to 3800 Ma crust in the Chinese part of the Sino–Korean Craton. *Geology* 20 (4), 339–342.
- Ludwig, K.R., 2003. *ISOPLLOT 3.0-A geochronological toolkit for Microsoft Excel: Berkeley Geochronology Center Special Publication*, vol. 4, p. 70.
- Meng, Q.R., Zhang, G.W., 2000. Geologic framework and tectonic evolution of the Qinling orogen, central China. *Tectonophysics* 323 (3–4), 183–196.
- Menzies, M.A., Fan, W.M., Zhang, M., 1993. Palaeozoic and Cenozoic lithoprobes and the loss of > 120 km of Archaean lithosphere, Sino–Korean craton, China. In: Prichard, H.M., Alabaster, T., Harris, N.B.W., Neary, C.R. (Eds.), *Magmatic Processes and Plate Tectonics: Geological Society special publication*, pp. 71–81.
- Norman, M.D., Yaxley, G.M., Bennett, V.C., Brandon, A.D., 2006. Magnesium isotopic composition of olivine from the Earth, Mars, Moon, and pallasite parent body. *Geophys. Res. Lett.* 33 (15), L15202. doi:10.1029/2006GL026446.
- Pearson, N.J., Griffin, W.L., Alard, O., O'Reilly, S.Y., 2006. The isotopic composition of magnesium in mantle olivine: records of depletion and metasomatism. *Chem. Geol.* 226 (3–4), 115–133.
- Richter, F.M., Watson, E.B., Mendybaev, R.A., Teng, F.-Z., Janney, P.E., 2008. Magnesium isotope fractionation in silicate melts by chemical and thermal diffusion. *Geochim. Cosmochim. Acta* 72, 206–220.
- Rudnick, R.L., Ionov, D.A., 2007. Lithium elemental and isotopic disequilibrium in minerals from peridotite xenoliths from far-east Russia: product of recent melt/fluid-rock reaction. *Earth Planet. Sci. Lett.* 256, 278–293.
- Sengor, A.M.C., Natalin, B.A., Burtman, V.S., 1993. Evolution of the Altai tectonic collage and Paleozoic crustal growth in Eurasia. *Nature* 364 (6435), 299–307.
- Teng, F.-Z., Wadhwa, M., Helz, R.T., 2007. Investigation of magnesium isotope fractionation during basalt differentiation: implications for a chondritic composition of the terrestrial mantle. *Earth Planet. Sci. Lett.* 261 (1–2), 84–92.
- Teng, F.Z., Yang, W. and Li, W.Y., in press. Precise and accurate analyses of Mg isotopes in natural samples by MC-ICPMS. *Analytical Chemistry*.
- Thrane, K., Bizzarro, M., Baker, J.A., 2006. Extremely brief formation interval for refractory inclusions and uniform distribution of ^{26}Al in the early solar system. *Astrophys. J.* 646 (2), L159–L162.
- Tipper, E.T., Louvat, P., Capmas, F., Galy, A., Gaillardet, J., 2008. Accuracy of stable Mg and Ca isotope data obtained by MC-ICP-MS using the standard addition method. *Chem. Geol.* 257 (1–2), 65–75.
- Wiechert, U., Halliday, A.N., 2007. Non-chondritic magnesium and the origins of the inner terrestrial planets. *Earth Planet. Sci. Lett.* 256, 360–371.
- Xiao, Y., 2009. Newly-accreted lithosphere – asthenosphere interaction: Evidence from mantle peridotitic xenoliths. Ph.D. Thesis, Institute of Geology and Geophysics, Chinese Academy of Science.
- Xu, Y.G., 2001. Thermo-tectonic destruction of the Archaean lithospheric keel beneath the Sino–Korean craton in China: evidence, timing and mechanism. *Phys. Chem. Earth* 26, 747–757.
- Young, E.D., Galy, A., 2004. The isotope geochemistry and cosmochemistry of magnesium. In: Johnson, C.M., Beard, B.L., Albarede, F. (Eds.), *Geochemistry of Non-Traditional Stable Isotopes. Reviews in Mineralogy & Geochemistry*. Mineralogical Society of America, Washington D.C., pp. 197–230.
- Young, E.D., Tonui, E., Manning, C.E., Schauble, E., MacCriss, C., 2008. Inter-mineral Magnesium isotope fractionation in the mantle and implications for the supra-chondritic $^{25}\text{Mg}/^{24}\text{Mg}$ of Earth. *Eos Trans. AGU* 89 (53) Fall Meet. Suppl., Abstract V13B-2125.
- Zhang, H.F., 2005. Transformation of lithospheric mantle through peridotite-melt reaction: a case of Sino–Korean craton. *Earth Planet. Sci. Lett.* 237 (3–4), 768–780.
- Zhang, W.H., Han, B.F., 2006. K–Ar chronology and geochemistry of Jining Cenozoic basalts, Inner Mongolia, and geodynamic implications. *Acta Petrol. Sin.* 22 (6), 1597–1607.
- Zhang, H.F., et al., 2002. Mesozoic lithosphere destruction beneath the North China Craton: evidence from major-, trace-element and Sr–Nd–Pb isotope studies of Fangcheng basalts. *Contrib. Mineral. Petrol.* 144 (2), 241–253.
- Zhang, H.F., et al., 2003. Secular evolution of the lithosphere beneath the eastern North China craton: evidence from Mesozoic basalts and high-Mg andesites. *Geochim. Cosmochim. Acta* 67 (22), 4373–4387.
- Zhao, X.M., et al., 2007. Metasomatism of Mesozoic and Cenozoic lithospheric mantle beneath the North China craton: evidence from phlogopite-bearing mantle xenoliths. *Acta Petrol. Sin.* 23 (6), 1281–1293.

- Zhao, X.M., Zhang, H.F., Yang, Y.H., in press. Metasomatism of Mesozoic and Cenozoic lithospheric mantle beneath eastern China: Evidence from Sanyitang mantle xenoliths. *Contributions to Mineralogy and Petrology*.
- Zheng, J.P., et al., 2001. Relict refractory mantle beneath the eastern North China block: significance for lithosphere evolution. *Lithos* 57 (1), 43–66.
- Zheng, J.P., Sun, M., Lu, F.X., Pearson, N., 2003. Mesozoic lower crustal xenoliths and their significance in lithospheric evolution beneath the Sino–Korean Craton. *Tectonophysics* 361 (1–2), 37–60.
- Zhu, G., Song, C.Z., Wang, D.X., Liu, G.S., Xu, J.W., 2001. Studies on Ar-40/Ar-39 thermochronology of strike-slip time of the Tan-Lu fault zone and their tectonic implications. *Sci. China, Ser. D Earth Sci.* 44 (11), 1002–1009.
- Zhu, G., Xie, C.L., Wang, Y.S., Niu, M.L., Liu, G.S., 2005. Characteristics of the Tan-Lu high-pressure strike-slip ductile shear zone and its Ar-40/Ar-39 dating. *Acta Petrol. Sin.* 21 (6), 1687–1702.