



Remnants of oceanic lower crust in the subcontinental lithospheric mantle: Trace element and Sr–Nd–O isotope evidence from aluminous garnet pyroxenite xenoliths from Jiaohe, Northeast China

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ABSTRACT

Pyroxenite xenoliths entrained in alkali basalts are usually interpreted to be high pressure cumulates from mantle-derived melts. However, those from Jiaohe, Northeast China may have originated from subducted oceanic crust. Their high bulk Al₂O₃ contents (12.2–17.4%) and Mg# (up to 0.88) resemble those of olivine-bearing cumulate gabbros. A crustal origin for the Jiaohe pyroxenites from plagioclase-bearing protoliths is further supported by positive Eu and Sr anomalies in both whole rock and in garnet and clinopyroxene analyses, low HREE abundances in garnet and low δ¹⁸O (4.9–5.1‰) relative to typical mantle values (5.5‰). Compared with average values for the corresponding mantle minerals, the δ¹⁸O values of the Jiaohe clinopyroxene (4.5–5.4‰) are lower, the δ¹⁸O values of garnet (5.1–5.6‰) are similar, whereas those of spinel are higher (5.2‰). In particular, there are disequilibrium O isotopic fractionations between garnet/spinel and clinopyroxene, resembling those of plagioclase/clinopyroxene pairs in seawater-altered oceanic crust. This is attributed to spinel and garnet inheriting their O isotope characteristics from plagioclase prior to transformation to these minerals during subduction metamorphism of altered oceanic gabbros, without isotopic re-equilibration at mantle conditions. Identification of remnants of subducted oceanic crust in the subcontinental lithospheric mantle is important to understanding mantle heterogeneity and genesis of intraplate magmatism.

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1. Introduction

Pyroxenites, the second most common ultramafic rock-type after spinel peridotites in the upper mantle, have received much attention in recent years. This is largely because pyroxenites and their derivatives may act as metasomatic agents responsible for mantle heterogeneity, and they can contribute to the genesis of MORB (Hirschmann and Stolper, 1996; Zhang et al., 2009) and intraplate magmas (Sobolev et al., 2005; Pilet et al., 2008). The nature and origin of pyroxenites are therefore a pre-requisite to understanding mantle geochemistry and magma diversity.

Most of pyroxenites entrained in alkali basalts are interpreted as derived by high pressure crystal-segregation from melts flowing through conduits in the mantle, as a result of temperature difference

between ascending melt and their peridotitic wall-rocks (e.g., Irving, 1980; Downes, 2007). Asthenosphere, enriched continental lithosphere mantle or hydrothermally altered oceanic crust have been proposed as the sources of parental magmas to pyroxenites (Griffin et al., 1984; Medaris et al., 1995; Becker, 1996; Xu, 2002), in order to account for their compositional diversity. However, there is increasing evidence of more complex petrogenesis for some pyroxenites, involving direct solid-state recycling of subducted lithosphere (Allegre and Turcotte, 1986) and metasomatism origin via melt-peridotite reactions (Garrido and Bodinier, 1999; Liu et al., 2005; Sobolev et al., 2005). In particular, pyroxenites of metasomatic origin have been considered as the dominant source of some intraplate basalts, including OIB (Herzberg, 2006) and continental basalts (Liu et al., 2008; Zhang et al., 2009). Some pyroxenites are characterized by high aluminous content, and the presence of Al-rich phases (sapphirine and corundum) and positive Eu anomalies. For those compositionally resembling kimberlite-borne eclogites (Jacob, 2004), they are generally regarded as solid-state recycled crustal rocks (Allegre and Turcotte, 1986), assuming that they experienced metamorphism with plagioclase-rich, low-pressure

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cumulates or residues as their protoliths (Kronpobst et al., 1990; Morishita et al., 2004; Obata et al., 2006; Ulianov et al., 2006).

This paper reports the petrological, elemental and Sr–Nd–O isotopic composition of a suite of garnet-bearing pyroxenite xenoliths from Jiaohe, northeastern China. High Al_2O_3 contents, positive Eu and Sr anomalies in both bulk rocks and minerals, and the unusual O isotopic disequilibrium between clinopyroxene and garnet/spinel lead to the conclusion that the Jiaohe pyroxenites were originally formed as oceanic cumulate gabbros, that were later transformed via subduction to garnet pyroxenites in the mantle.

2. Geological background and petrography of pyroxenite xenoliths

Northeast China in the eastern part of the Paleozoic Central Asian Orogenic Belt (Fig. 1) is a composite fold belt formed by amalgamation of several minor blocks during subduction and collision between the Siberian craton and the North China craton (Jahn et al., 2000). In this region, there are widespread Phanerozoic granitic rocks with low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and positive $\epsilon_{\text{Nd}}(t)$ values, suggesting a juvenile crustal origin for a significant proportion of the granites (Jahn et al., 2000). In addition, intense and widespread alkaline basaltic activity took place during Cenozoic time, and abundant mantle-derived xenoliths were discovered in several volcanic fields. The Jiaohe volcanic field near the Dun–Mi fault in central Jilin Province is an example (Fig. 1). Late Cenozoic basalts including basanite, alkaline olivine basalt (2–24 Ma, Wang, 1996) are widespread in Dashihe, Jiaohe city. Abundant fresh xenoliths of 5 to 15 cm in diameter were discovered in an olivine quarry at Yiqisong. The xenoliths from this locality include spinel peridotites and garnet-bearing pyroxenites. Peridotite xenoliths range from fertile lherzolite through clinopyroxene-poor lherzolite to highly depleted harzburgite and are

characterized by variable enrichment of incompatible elements (Yu et al., 2009). Hf isotopic data suggest a Mesoproterozoic formation age for the mantle lithosphere beneath Jiaohe (Yu et al., 2009).

The xenoliths investigated in this study are garnet websterite and clinopyroxenite (Table S1). Their typical mineral assemblage is clinopyroxene (cpx, 34.6–73.6%), orthopyroxene (opx, 0–30.5%), garnet (grt, 8.1–50.2%), spinel (sp, 0–10.2%). In some cases, rare tiny olivines are also present (Table S1). Most of the Jiaohe pyroxenites have a granoblastic metamorphic texture with a coarse grain size (6–10 mm). Some (e.g., YQX-18) show clear modal layering, indicative of partially preserved cumulate textures. Large or small size spinels usually have a garnet rim (Fig. 2a). Most garnets in pyroxenites are kelyphized; rare fresh relicts are only observed in YQX-12. Most samples show exsolution of spinel and garnet lamella (with spinel in core) in clinopyroxenites (Fig. 2b, c). Exsolution of garnet and orthopyroxene lamellae in two different directions are also observed in clinopyroxenes. Locally, clinopyroxene, garnet and spinel form aggregates with a fine grained and xenomorphic texture (Fig. 2d), suggesting that they may have been formed by breakdown of former minerals.

3. Results

A description of analytical methods used in this study is found in [supplementary online materials](#).

3.1. Mineral chemistry, equilibrium temperature and pressure estimates

Major element compositions of minerals from representative pyroxenites are given in Table S2. None of the investigated minerals show compositional zoning. Clinopyroxenes have a wider range of Mg#

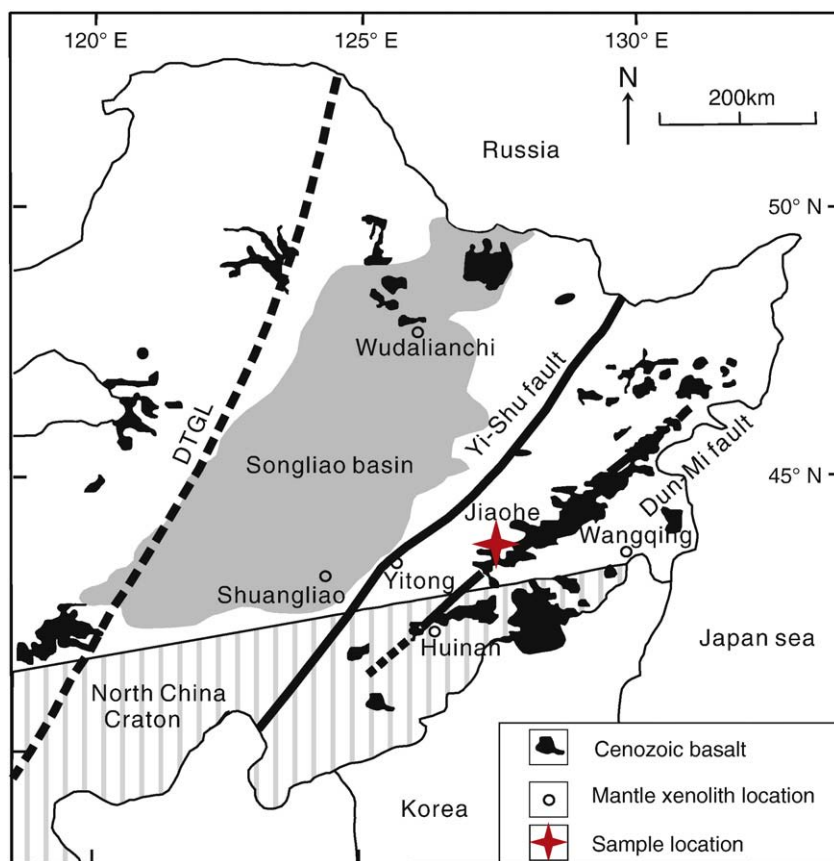


Fig. 1. A sketch map showing the simplified tectonic framework of northeastern China and location of the studied area. Mantle xenolith locations in northeastern China are also shown. The xenoliths in this study were collected from Jiaohe. DTGL: Daxinganling–Taihangshan gravity lineament, Yi–Shu fault and Dun–Mi fault represent Yilan–Shulan fault zone and Dunhua–Mishan fault zone, respectively.

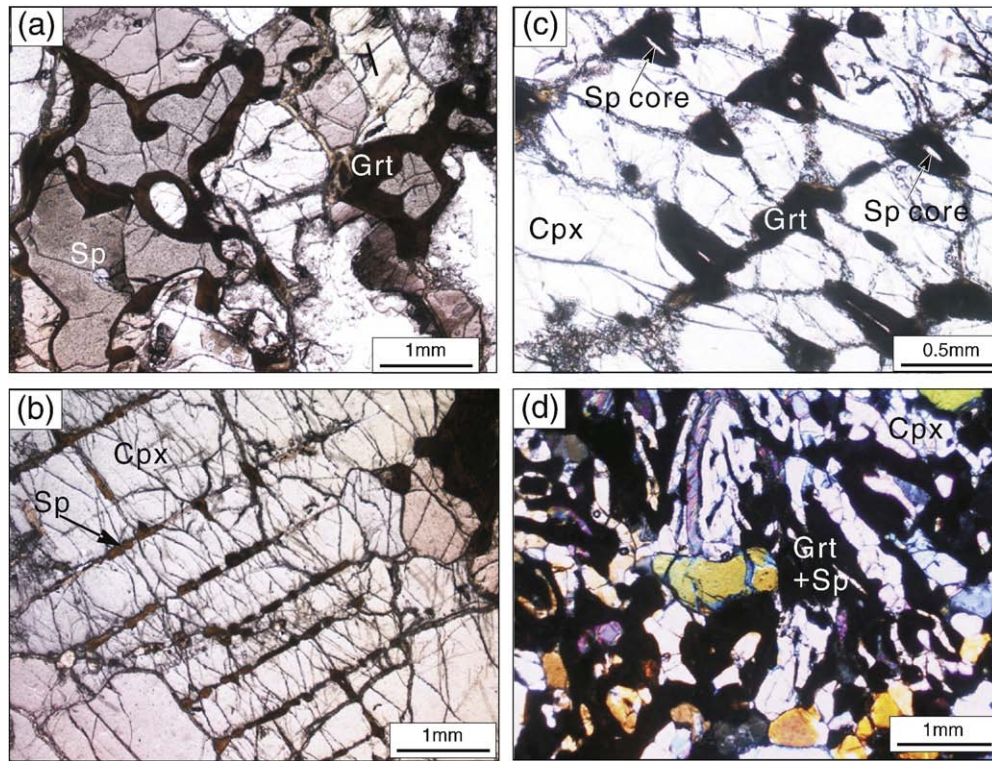


Fig. 2. Photomicrograph showing textures observed in Jiaohe pyroxenite xenoliths. (a) Large grain size of spinels rimmed by garnet. (b) Exsolution lamellae of spinel in clinopyroxenes. (c) Enlarged photomicrograph of (b) shows exsolution lamellae of spinel also rimmed by garnet. (d) Mineral aggregates (including clinopyroxenite, garnet and spinel) show fine grained and xenomorphic texture.

$[Mg/(Mg + Fe)_{at} = 0.85\text{--}0.93]$ compared to those in Jiaohe peridotites. Clinopyroxenes are augite according to their relative low contents of Jadeite end-member (7.7–15.1%). Orthopyroxenes display a similarly wide range of Mg# (0.84–0.91). Spinels are rich in Al_2O_3 (up to 67.95 wt.%) and poor in Cr_2O_3 (0.68–1.66 wt.%). Only one sample (YQSX-18) contains olivines which show a slightly lower Mg# (0.889) than those in peridotites. Garnet is compositionally homogeneous, characterized by high Al, Mg contents, and moderate Ca abundances (Table S2).

Equilibrium temperatures and pressures were calculated using the Ca-in-opx thermometer and barometer of Brey and Kohler (1990). Most Jiaohe pyroxenites are equilibrated at 1.1–1.8 GPa at 892–1007 °C (Table S1), corresponding to a depth of 36 to 60 km.

3.2. Major elements

Major element abundances and their CIPW norms are listed in Table 1 and illustrated in Fig. 3 in which SiO_2 and CaO against MgO. Worldwide pyroxenite and oceanic gabbro data in literature are also shown for comparison. The Jiaohe pyroxenites plot in the domain shared by mantle pyroxenites and oceanic gabbros. They differ from pyroxenites of high-pressure cumulative origin in having distinctly high Al_2O_3 contents (12.16–17.39 wt.%) (Fig. 3c), so that they resemble aluminous pyroxenites and gabbroic rocks. TiO_2 contents range from 0.06 to ~2 wt.%, similar to the range for oceanic gabbros, but lower than the majority of mid-ocean ridge basaltic glasses. There is a positive correlation between Ni and MgO in pyroxenites (Fig. 3d). The ranges of Ni and Cr abundances are large, similar to observations in other pyroxenites (Suen and Frey, 1987; Xu, 2002). Both high Mg# (up to 0.88) and high Ni contents (up to 1000 ppm) are indicative of olivine-accumulation in the protoliths.

The predominant components in the CIPW norms of the Jiaohe pyroxenites are albite, anorthite, olivine and diopside (Table 1), which suggests a gabbroic precursor. Despite the high abundance of olivine

and feldspar in the norm (16–32%, and 36–50%, respectively, Table 2), no olivine and feldspar is observed for these xenoliths.

3.3. Trace element compositions

3.3.1. Bulk rocks

The most striking features of the Jiaohe pyroxenites trace element geochemistry are the pronounced positive Eu (Eu/Eu^* is up to 1.39; Table 1) and Sr anomalies, which are largely absent in pyroxenite xenoliths from eastern China (Ho et al., 2000; Xu, 2002; Liu and Xu, 2006). Specifically, trace element compositions in the Jiaohe pyroxenites vary with the rock types (garnet websterites versus clinopyroxenites; Fig. 4).

Garnet websterites display a fractionated MREE–HREE pattern with a positive slope and have relatively high HREE contents ($Yb_n = 6\text{--}10$) (Fig. 4a, b). All of these samples show variable incipient enrichment in LREE and high abundances of incompatible elements. Positive Eu and Sr anomalies are present in the samples with relatively low HREE contents (YQSX-18, YQSX-19 and BSK-2). However, Eu anomalies are absent in other websterites (YQSX-4, YQSX-13 and BSK-12) which have higher HREE contents. These samples possess pronounced positive Sr anomaly.

Garnet clinopyroxenites show LREE- and LILE-enriched and flat HREE patterns (Fig. 4c). Compared to the garnet websterites, they have relatively lower HREE contents ($Yb_n = 1\text{--}6$) and more variable REE abundance. Positive Eu and Sr anomalies are more pronounced in clinopyroxenites than in websterites.

3.3.2. Clinopyroxene and garnet

High Al contents and positive Eu and Sr anomalies are typical characteristic of plagioclase-bearing rocks. As a consequence, plagioclase might be expected to be present in the Jiaohe pyroxenites but none has been found. However the norm includes a high fraction of feldspar suggesting that it was present prior to high-grade metamorphism. In

Table 1
Major (%) and trace element (ppm) compositions of whole rock pyroxenites from Jiaohe.

	YQXS-2	YQXS-4	YQXS-7	YQXS-10	YQXS-12	YQXS-13	YQXS-18	YQXS-19	BSK-2	BSK-3	BSK-4	BSK-11	BSK-12	BSK-13
SiO ₂	46.40	49.00	45.79	47.45	46.00	47.89	46.40	44.47	45.90	45.99	46.16	46.10	46.45	46.93
MgO	20.05	16.87	16.13	12.15	19.47	13.79	20.28	20.34	15.91	14.79	15.66	15.61	16.67	16.13
TiO ₂	0.13	0.32	0.21	0.25	0.06	0.25	0.20	0.18	0.26	0.23	0.16	0.15	0.37	0.59
Al ₂ O ₃	15.60	12.16	15.89	16.37	15.70	14.30	13.94	17.39	15.06	14.58	14.47	14.55	14.09	13.19
Fe ₂ O ₃	5.76	5.23	4.27	7.03	5.21	6.65	5.72	6.27	7.32	7.67	5.81	5.80	5.42	7.13
MnO	0.11	0.13	0.10	0.12	0.12	0.13	0.11	0.13	0.13	0.12	0.11	0.10	0.14	0.16
CaO	10.54	14.47	15.93	14.47	10.45	14.35	11.37	9.38	12.48	12.63	13.92	13.85	13.89	12.86
Na ₂ O	0.72	0.96	0.83	1.21	0.45	1.07	0.66	0.56	0.94	1.29	0.83	0.83	1.00	1.04
K ₂ O	0.14	0.20	0.22	0.23	0.37	0.28	0.05	0.20	0.14	0.22	0.27	0.27	0.12	0.23
P ₂ O ₅	0.02	0.04	0.05	0.06	0.04	0.03	0.01	0.03	0.06	0.04	0.07	0.07	0.05	0.08
Total	99.46	99.39	99.43	99.33	97.87	98.74	98.76	98.96	98.19	97.55	97.45	97.33	98.19	98.34
Mg#	89.0	88.3	89.8	80.1	89.7	82.9	89.2	88.3	83.5	81.8	86.3	86.2	87.7	84.1
<i>CIPW</i>														
Or	0.83	1.21	1.32	1.36	2.25	1.67	0.32	1.22	0.85	1.31	1.63	1.66	0.70	1.37
Ab	6.12	8.24	0.87	10.37	3.92	9.23	5.65	4.84	8.17	11.25	7.21	7.23	8.65	9.00
An	39.34	28.57	39.36	39.05	40.77	34.02	35.56	45.04	37.36	34.43	36.09	36.33	34.41	31.37
Di	10.55	34.53	31.65	26.58	9.62	30.49	17.17	1.59	20.43	23.89	27.46	27.04	28.25	26.52
Hy	13.91	8.29		4.29	17.33	6.51	12.69	12.84	7.49	2.29	3.55	3.76	1.58	8.12
Ol	27.67	17.28	21.97	16.17	24.74	16.04	26.90	32.64	23.40	24.52	22.27	22.20	24.35	20.70
Mt	1.29	1.17	0.95	1.57	1.18	1.50	1.29	1.41	1.66	1.75	1.33	1.32	1.23	1.61
Ne			3.37											
Il	0.25	0.61	0.40	0.49	0.11	0.48	0.40	0.35	0.51	0.45	0.30	0.29	0.73	1.15
Ap	0.05	0.10	0.11	0.13	0.09	0.07	0.04	0.08	0.14	0.10	0.18	0.18	0.12	0.19
Sc	31.6	60.9	41.4	41.0	47.8	52.8	41.6	57.6	42.4	37.5	30.4	39.4	68.5	53.9
V	93	383	229	172	96	291	185	145	188	172	121	179	367	53.9
Cr	2856	1042	1246	690	2059	929	2187	4598	998	936	918	1536	650	811
Co	62.7	46.2	45.9	53.5	50.4	51.4	62.2	61.7	53.9	55.4	52.2	51.1	44.0	43.6
Ni	726	506	724	226	551	372	822	599	394	407	298	529	580	568
Cu	48.3	11.3	44.7	28.3	33.3	65.7	50.8	35.8	94.3	45.2	30.8	63.8	32.2	49.8
Zn	42.1	27.7	50.5	32.5	33.9	21.7	46.0	41.6	48.7	32.6	32.0	25.4	45.3	24.6
Ga	9.8	8.9	11.5	13.9	7.5	12.3	9.3	9.0	9.2	11.2	10.8	9.3	10.1	10.3
Ba	23.6	9.4	10.6	27.4	13.3	76.1	7.8	30.2	24.3	42.3	9.4	121.0	6.2	14.6
Rb	1.72	1.57	1.80	2.39	5.26	5.37	0.93	2.40	0.97	2.69	1.17	5.09	1.05	2.27
Th	0.14	0.10	0.14	0.25	0.16	0.20	0.11	0.23	0.14	0.11	0.21	0.12	0.12	0.19
U	0.06	0.07	0.08	0.13	0.09	0.09	0.03	0.10	0.06	0.08	0.12	0.06	0.06	0.10
Nb	2.11	1.04	1.50	2.83	2.38	1.60	0.90	2.51	2.14	1.26	2.47	1.01	1.69	1.19
Ta	0.15	0.05	0.08	0.16	0.14	0.09	0.05	0.15	0.18	0.06	0.13	0.05	0.10	0.06
La	1.57	1.27	1.48	2.51	1.71	1.64	0.97	2.14	1.43	1.72	2.05	3.12	1.27	2.33
Ce	2.63	2.93	3.04	4.68	2.97	3.43	2.35	4.32	2.76	3.45	3.77	5.77	2.51	3.70
Pr	0.35	0.46	0.42	0.61	0.36	0.48	0.37	0.55	0.37	0.47	0.50	0.73	0.32	0.48
Sr	100	210	207	102	156	69	68	92	137	95	189	72	143	380
Nd	1.57	2.58	2.10	2.85	1.44	2.22	1.94	2.41	1.83	2.27	2.01	2.84	1.61	2.51
Zr	8.6	16.6	11.3	17.8	9.2	13.4	11.8	19.8	26.2	21.3	26.1	12.3	24.8	35.5
Hf	0.24	0.57	0.32	0.51	0.23	0.47	0.35	0.53	0.58	0.48	0.48	0.29	0.52	0.77
Sm	0.41	0.95	0.67	0.88	0.33	0.75	0.63	0.63	0.64	0.62	0.53	0.69	0.54	1.07
Eu	0.21	0.40	0.29	0.40	0.16	0.32	0.30	0.26	0.28	0.28	0.25	0.26	0.24	0.45
Ti	924	2347	1439	1900	372	1781	1514	1201	1602	1411	1210	1100	1779	2347
Gd	0.53	1.64	0.96	1.16	0.39	1.26	0.93	0.90	0.86	0.73	0.58	0.78	1.18	1.61
Tb	0.10	0.37	0.19	0.22	0.07	0.31	0.20	0.18	0.20	0.15	0.11	0.14	0.30	0.39
Dy	0.63	2.71	1.18	1.40	0.49	2.33	1.42	1.34	1.43	1.04	0.65	0.83	2.39	2.82
Ho	0.14	0.67	0.24	0.30	0.11	0.58	0.33	0.31	0.34	0.23	0.15	0.20	0.69	0.72
Y	3.22	15.64	5.46	7.01	2.56	13.95	7.87	7.61	9.96	6.52	4.12	5.94	19.40	19.60
Er	0.38	1.96	0.59	0.81	0.29	1.75	0.96	0.95	1.04	0.61	0.40	0.61	2.14	2.05
Tm	0.05	0.31	0.08	0.12	0.04	0.27	0.15	0.15	0.15	0.09	0.05	0.08	0.33	0.32
Yb	0.37	2.19	0.50	0.77	0.29	1.98	1.02	1.09	1.01	0.61	0.36	0.60	2.18	2.02
Lu	0.06	0.35	0.08	0.12	0.05	0.33	0.17	0.18	0.14	0.09	0.04	0.09	0.33	0.30
Eu/Eu*	1.39	0.99	1.11	1.21	1.34	1.01	1.21	1.06	1.16	1.28	1.37	1.07	0.92	1.04

Note: $Eu/Eu^* = Eu_n / (Sm_n \times Gd_n)^{0.5}$, where the subscripted n indicates the values are normalized to chondrite.

order to determine which mineral carries the positive Eu anomaly, garnet and clinopyroxene from four samples (YQXS-18, YQXS-2, YQXS-10 and YQXS-12) are analyzed by laser-ablation ICP-MS (Table S3). Both garnet and clinopyroxene have positive Eu and Sr anomalies (Fig. 5), showing that the positive Eu anomaly in whole rocks is an intrinsic feature of the Jiaohe pyroxenites.

Two types of REE pattern are distinguished for clinopyroxene. Clinopyroxenes from three clinopyroxenites (YQXS-2, YQXS-10 and YQXS-12) display a convex-upward REE pattern with a maximum at Eu (Fig. 5b). They also show significant Zr and Hf depletion (not shown). The depletion of HREE in clinopyroxene may be due to partitioning into co-existing garnet (35–50%). Specifically, clinopyroxenes from YQXS-2

and YQXS-12 show incipient enrichment in elements more incompatible than Ce. Garnets from these clinopyroxenites show a relatively flat HREE pattern with a relatively low HREE contents ($Yb_N = 1-9$; Fig. 5b). These garnets are also depleted in LREE (but with incipient enrichment in La and Ce for YQXS-12) with Ce_N varying from 0.1 to below the detection limit.

The minerals from the websterite sample YQXS-18 show a different REE pattern. Cpx in this sample possesses an almost flat REE pattern, but with pronounced depletion in HFSE and Ba. Garnets from this sample show a fractionated MREE–HREE and high HREE contents ($Yb_N = 40$). It is noted that sample YQXS-18 contains only 8% garnet, compared to over 30–50% garnet in other samples.

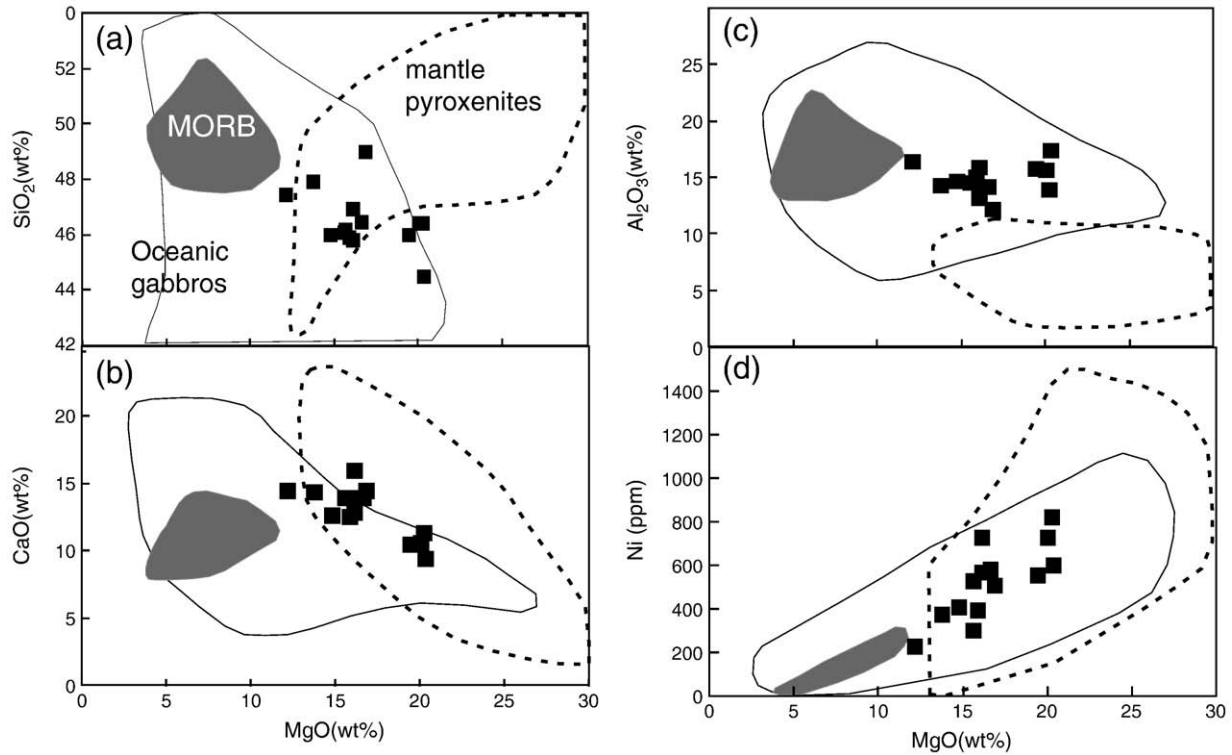


Fig. 3. a–d: Bulk major element plots for the Jiaohe pyroxenites (black squares) compared with oceanic gabbros (solid line), MORB (dark grey) and mantle-derived cumulative pyroxenites (dashed lines). The fields of MORB and Oceanic gabbros are taken from Jacob (2004). The field of mantle pyroxenites is defined on the basis of composition of pyroxenite xenoliths from eastern China (Ho et al., 2000; Xu, 2002; Liu and Xu, 2006). The Jiaohe pyroxenites are distinct from mantle cumulative pyroxenites by showing significantly higher Al₂O₃ contents, and from MORB by lower SiO₂, and higher MgO. They compositionally resemble oceanic gabbros.

3.4. Sr–Nd–O isotopes

The Jiaohe pyroxenites have ⁸⁷Sr/⁸⁶Sr ranging from 0.7032 to 0.7041 and ¹⁴³Nd/¹⁴⁴Nd ranging from 0.5128 to 0.5130 (Table 2). These variations are significantly less than those displayed by peridotite xenoliths from the same locality (⁸⁷Sr/⁸⁶Sr = 0.7026–0.7072; ¹⁴³Nd/¹⁴⁴Nd = 0.5126–0.5134; Yu et al., 2009). However, their ¹⁴³Nd/¹⁴⁴Nd ratios are higher than those of Cenozoic basalts from NE China (¹⁴³Nd/¹⁴⁴Nd = 0.5126–0.5128; Xu et al., unpublished data).

Oxygen isotope compositions of the four analyzed samples show the following $\delta^{18}\text{O}$ ranges: garnet = 5.1 to 5.6‰; clinopyroxene = 4.5 to 5.4‰; orthopyroxene = 5.2 to 5.8‰; spinel = 5.1 to 5.2‰ (Table 2). O isotope appears to vary with rock types, with the lowest $\delta^{18}\text{O}$ value coming from garnet clinopyroxenites and the highest from garnet websterites.

Despite the overall limited $\delta^{18}\text{O}$ variation, the Jiaohe pyroxenites show significant O isotopic disequilibrium, in contrast with ubiquitous O isotopic equilibrium for mantle xenoliths (Mattey et al., 1994). While

the $\delta^{18}\text{O}$ values for Jiaohe garnets (5.1–5.6‰) are close to normal mantle peridotite values ($5.3 \pm 0.2\text{‰}$), $\delta^{18}\text{O}$ in the Jiaohe cpx (4.5–5.4‰) is significantly lower than the average mantle pyroxene values (5.7‰, Mattey et al., 1994). It is known that at mantle temperatures clinopyroxene has elevated ¹⁸O relative to both garnet and spinel (Mattey et al., 1994; Zheng, 1997; Schulze et al., 2000; Jacob, 2004). However, the negative $\Delta^{18}\text{O}_{\text{cpx-grt}}$ fractionation is observed in the Jiaohe pyroxenites (Fig. 6a), pointing to O isotope disequilibrium between garnet and pyroxene. Likewise, there is also O isotopic disequilibrium between cpx and spinel, as indicated by negative $\Delta^{18}\text{O}_{\text{cpx-sp}}$ values (Fig. 6b). Specifically, spinels are anomalously enriched in $\delta^{18}\text{O}$, compared to the normal mantle values (~4.8‰).

4. Discussion

Gonzaga et al. (2010) summarized similarities and differences between eclogites and garnet pyroxenites. Garnet pyroxenites are characterized by low Al and high Mg contents, lack of Sr and Eu anomalies, and relatively homogeneous O isotope compositions identical to peridotitic mantle. In contrast, eclogites show high Al and low Mg contents, positive Sr and Eu anomalies and heterogeneous Sr–Nd–O isotopes that lie beyond the range of mantle-derived melts. These authors thus enhanced the previous argument that eclogites and garnet pyroxenites are not identical in origin, with garnet pyroxenites being high temperature derivatives of melts in equilibrium with mantle peridotite, and eclogites being linked to the subduction of slab basalt and gabbro precursors which may be hydrothermally altered. Interestingly, the data presented in this paper place the Jiaohe garnet pyroxenites at an intermediate position between these two extremes. Specifically, the Jiaohe samples show compositional and isotopic affinities more akin to the eclogites. The following discussion focuses on the formulation of a petrogenetic model for the Jiaohe pyroxenites.

Table 2

Whole rock Sr–Nd and mineral O isotope compositions of the Jiaohe pyroxenites.

Sample	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	$\delta^{18}\text{O}$ SMOW (‰)				
			Grt	Cpx	Sp	Opx	Bulk rock ^a
YQSX-2	0.703547 ± 5	0.512909 ± 14					
YQSX-4	0.703898 ± 4	0.513029 ± 9					
YQSX-7	0.703913 ± 3	0.512972 ± 10					
YQSX-10	0.704140 ± 4	0.512848 ± 16	5.08	4.91			5.08
YQSX-12	0.703926 ± 5	0.512785 ± 18	5.26	5.13	5.19	5.16	5.12
YQSX-12			5.18				
YQSX-13	0.703667 ± 7	0.513080 ± 14	5.56	4.53			4.94
YQSX-18	0.703161 ± 6	0.512947 ± 16					
YQSX-19	0.704149 ± 4	0.512847 ± 13	5.45	5.36	5.16	5.81	5.45

^a Reconstructed in terms of modes and $\delta^{18}\text{O}$ of minerals.

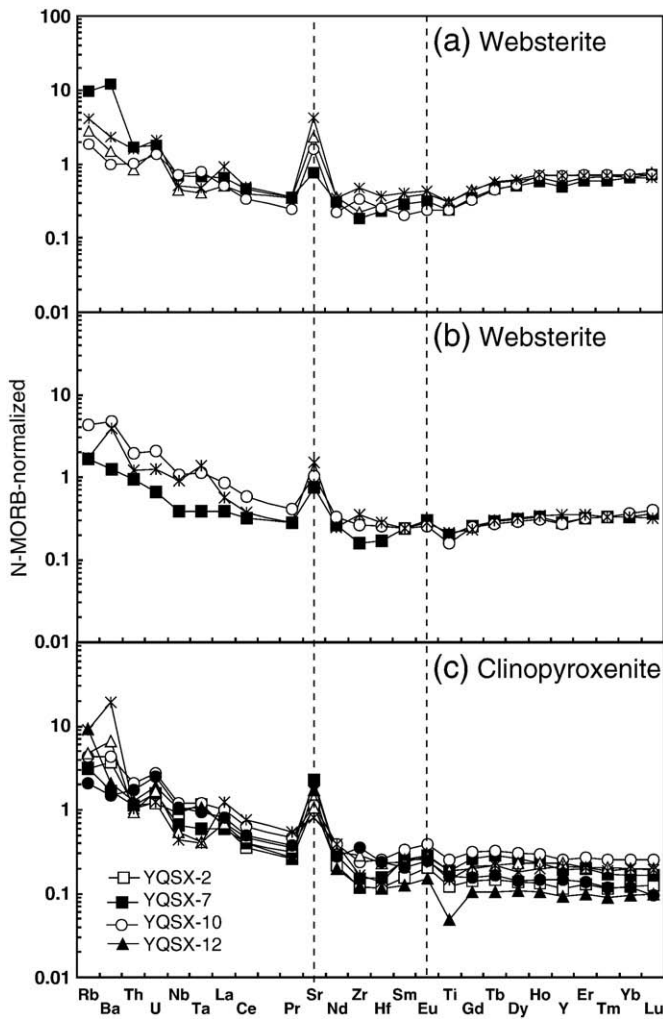


Fig. 4. Trace element abundances in whole rocks of Jiaohé pyroxenites. Normalization values are from Sun and McDonough (1989).

4.1. Contamination by host basalts?

Bulk analyses show variable incipient enrichment in LREE and incompatible elements in the Jiaohé pyroxenites, in contrast to the LREE-depleted patterns exhibit by their constituent minerals (Figs. 4 and 5). This suggests that the Jiaohé xenoliths may be infiltrated by the host basalt. Nevertheless, this contamination by host basalt seems to have only affected the highly incompatible elements in the Jiaohé pyroxenites, and not the moderately incompatible elements such as Eu and Sr. This argument is built on the following considerations: (a) positive Sr and Eu anomalies in bulk rocks cannot be due to contamination by the host basalt because they are not found in the host basalts but are present in the constituent minerals (cpx and grt); (b) Sr–Nd–O isotopes are different in the host basalt and pyroxenite xenoliths. Consequently the observed Sr and Eu anomalies and Sr–Nd–O isotopes can be used to constrain the petrogenesis of these rocks.

4.2. Gabbroic cumulative protoliths of the Jiaohé pyroxenites

Garnet pyroxenites are commonly interpreted as high temperature derivatives of melts in equilibrium with mantle peridotite (Downes, 2007; Gonzaga et al., 2010), or as a metasomatic product of the reaction between felsic melts and peridotites (Garrido and Bodinier, 1999; Liu et al., 2005; Sobolev et al., 2005). Although the high Mg# (0.80 to 0.88) and Ni content of the Jiaohé pyroxenites are

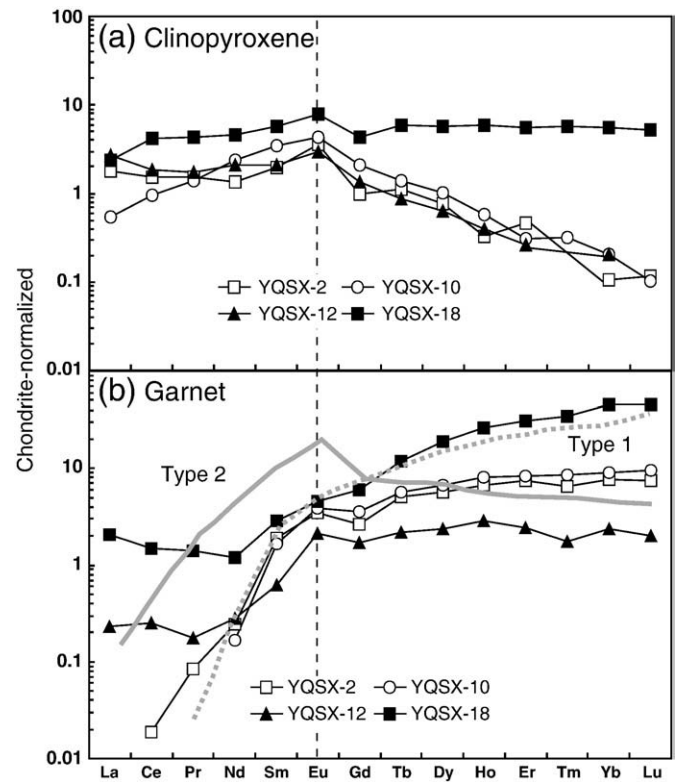


Fig. 5. REE patterns of clinopyroxenes and garnets from the Jiaohé pyroxenites. The grey and dashed grey lines in (b) represent two typical types of REE patterns for garnet from eclogitic xenoliths (Jacob, 2004).

consistent with the first interpretation, their significantly higher Al contents (Fig. 3), compared with typical cumulate pyroxenites from mantle melts argues against an origin from crystallized primary melts or their cumulates. In fact, the Jiaohé pyroxenites are compositionally similar to cumulate gabbros (Fig. 4). Moreover, they have a granoblastic metamorphic texture. Some mineral aggregates show a fine grained, xenomorphic texture (Fig. 2), suggesting that the present minerals may have been formed by breakdown of former minerals. This metamorphic origin is further supported by high abundance of normative olivine and feldspar in the Jiaohé pyroxenites (Table 1), which are absent in the rocks.

Obata et al. (2006) proposed a simple method of identifying gabbros by using MgO-normalized in oxide ratio plots for major elements analyses. It has been demonstrated that cumulus gabbros which originally precipitated from basaltic magmas at low pressure are characterized by a clear linear trend between Al_2O_3/MgO (and CaO/MgO) and SiO_2/MgO . The Jiaohé pyroxenites define a linear correlation in Fig. 7, which is virtually same as those for pyroxenites and eclogites from Beni Bousera and the Czech Republic, whose precursors are gabbroic cumulates (Obata et al., 2006). In contrast, data for mantle pyroxenites of high-*P* cumulative origin are more scattered and tend to plot below the “gabbro” correlations (Fig. 7). We thus conclude that the Jiaohé pyroxenites were primarily formed as cumulus gabbros, which were later transformed to garnet pyroxenites in the mantle. This interpretation is in agreement with positive Eu and Sr anomalies in these rocks, which are indicative of accumulation of plagioclase in the gabbros.

4.3. Continental or oceanic provenance?

The equilibrium pressures of the Jiaohé pyroxenite (1.3–1.5 GPa, Table S1) is significantly greater than the Moho pressure (~1.0 GPa, Xu et al., 1989). This implies recrystallization in the upper mantle, despite the crustal origin of these samples. This requires a mechanism

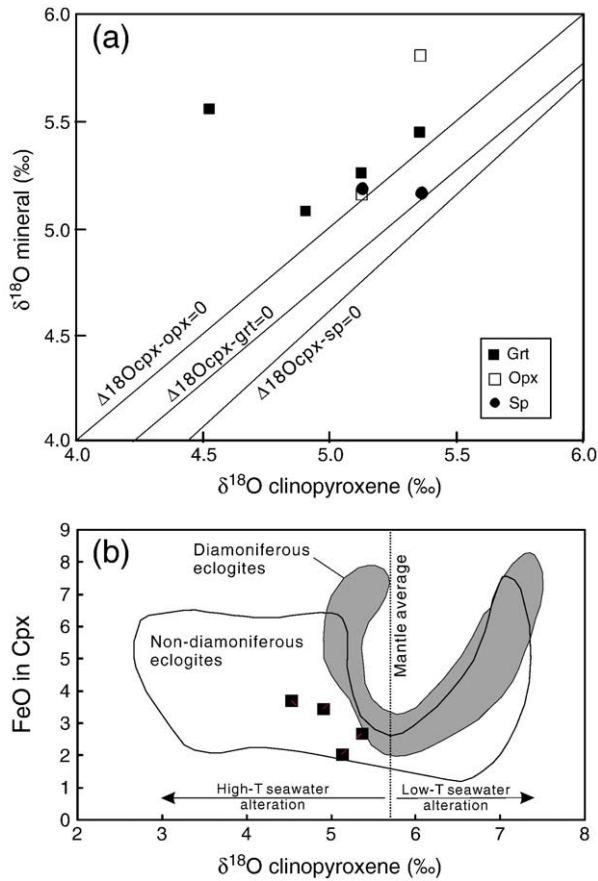


Fig. 6. (a) Oxygen isotope compositions of mineral separates. Equilibrium lines are after Matthey et al. (1994) and Zheng (1997). (b) Correlation between $\delta^{18}\text{O}$ and FeO in clinopyroxenes from the Jiaohe pyroxenites. The fields for diamondiferous and non-diamondiferous eclogites are taken from Jacob et al. (1998). The dashed line denotes the average $\delta^{18}\text{O}$ of mantle peridotites (Matthey et al., 1994). Two arrows indicate variation in $\delta^{18}\text{O}$ of oceanic crust during seawater alteration at low and high temperatures.

by which crustal materials were recycled into the mantle. Such a process must have been accompanied by a pressure increase as evidenced by garnet enclosing spinel (Fig. 2). Delamination of the continental crust and subduction of the oceanic crust are two probable scenarios. Both mechanisms are associated with a pressure-increase, but they imply significantly different tectonic setting under which the gabbroic cumulates were generated.

4.3.1. Delamination of continental lower crust

In this case, the Jiaohe pyroxenites may represent underplated basaltic magmas/cumulate at the base of the continental crust, which were transformed to garnet pyroxenites via metamorphism and founded into the mantle. This model is attractive, because delamination of the mafic lower crust has been proposed for the lithospheric evolution in eastern China (Xu et al., 2002; Gao et al., 2004). A similar model has been preferred by Ulianov et al. (2006) for the aluminous pyroxenite xenoliths from east Africa. However, this interpretation does not seem applicable for the Jiaohe case for the following reasons. (1) Underplated samples from eastern China (e.g., Hannuoba and Yingfengling) generally show lithologies that range from granulite and pyroxenites, and an extreme variation in radiogenic isotopic composition ranging from depleted to enriched mantles, reflecting significant interaction of underplated basalts with pre-existing continental crust (Xu, 2002; Yu et al., 2003; Huang et al., 2004). This contrasts with the rather narrow isotope compositions of the Jiaohe pyroxenites (Table 2). (2) In eastern China, the delamination models are proposed largely for the genesis of Mesozoic magmas (Xu et al., 2002; Gao et al., 2004), which have

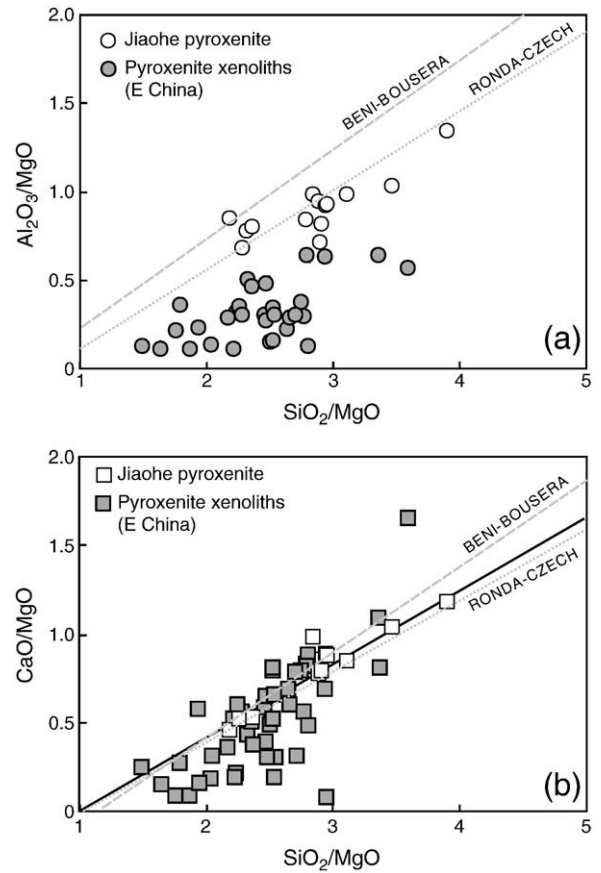


Fig. 7. (a) $\text{Al}_2\text{O}_3/\text{MgO}$ and (b) CaO/MgO versus SiO_2/MgO for the Jiaohe pyroxenites. Mantle-derived cumulative pyroxenites from eastern China (grey symbols) are shown for comparison. Grey dashed lines represent compositional trends for pyroxenites from Beni-Boussera and eclogite-garnet pyroxenites from Ronda and Czech Republic (after Obata et al., 2006).

enriched Sr–Nd isotopes, consistent with the involvement of delaminated mafic crust with enriched lithospheric mantle components. Although the age of the Jiaohe pyroxenites remains unconstrained, their relatively depleted isotopic signature argues against this interpretation. (3) In addition to the high Sr and low Nd isotopic ratios, contamination of basaltic magmas by the continental crust could increase $\delta^{18}\text{O}$ values and generate negative Eu and Nb anomalies. Obviously this model cannot account for the absence of Nb anomalies, positive Eu anomaly and the overall low $\delta^{18}\text{O}$ values (4.8–5.1‰) in the studied samples.

4.3.2. Subduction of the oceanic crust

The oceanic crust is compositionally diverse, with MORB-type basalts overlying gabbroic/ultramafic cumulates. If pyroxenites are derived from the solid-state recycling of oceanic crust, as proposed by Allegre and Turcotte (1986), their average compositions should be similar to those of the bulk oceanic crust; some of them should have MORB compositions, and some should be plagioclase cumulates. As illustrated in Fig. 3, the Jiaohe pyroxenites do not resemble MORB basalts, but are compositionally similar to oceanic gabbros and kimberlite-hosted eclogites. These rocks are distinct from the common alkali basalt-hosted pyroxenites by their unusually high Al_2O_3 contents, a feature commonly taken as evidence for low-pressure crystallization of plagioclase-rich protoliths (Jacob, 2004; Morishita et al., 2004; Ulianov et al., 2006). The gabbroic protoliths hypothesis for the Jiaohe xenoliths is supported by their trace element compositions, which are a powerful tool for investigating concealed evolutionary records in eclogites/pyroxenites and to constrain their possible precursors (Taylor and Neal, 1989; Barth et al., 2001). Positive Eu- and Sr-anomalies and flat HREE pattern are very unusual for garnet-bearing high-pressure

rocks, but are diagnostic of metamorphosed plagioclase-bearing rocks (Mork and Brunfelt, 1988; Barth et al., 2001). The geochemical characteristics of the Jiaohe pyroxenites are therefore consistent with a low-pressure precursor.

REE patterns of garnet further constrain the origin of the Jiaohe pyroxenites. Jacob (2004) has identified two types of REE pattern for garnets from eclogitic xenoliths (Fig. 5b). The type I is characterized by LREE-depletion with C_{Ce_N} as low as 0.01 and variably enriched HREE with Lu_N values of up to 70. The type II, which is common amongst coesite, kyanite and/or corundum-bearing eclogite xenoliths, display a nearly flat HREE with $Lu_N < 10$ and positive Eu anomalies. As indicated by Jacob (2004), these type II patterns are very unlike equilibrium REE patterns for garnet from high-pressure rocks that are expected to have high abundances of HREE due to its mineral–melt partitioning characteristics. They are instead interpreted as evidence of a prograde metamorphic reaction from plagioclase to garnet and are used in support of the explanation of the mantle eclogites as subducted oceanic crustal rocks (e.g. Jagoutz et al., 1984; McGregor and Manton, 1986; Jacob et al., 2003). Both types of REE patterns are found in the Jiaohe pyroxenites (Fig. 5c). In particular, the flat HREE patterns and positive Eu anomaly in garnet from garnet clinopyroxenites suggest that garnet was initially not present as a residual or fractionating phase. Rather it may have experienced subsolidus crystallization via metamorphic reactions involving plagioclase, an inference supported by petrographic development of garnet at the expense of spinel (Fig. 2).

Perhaps, the most compelling evidence in favor of recycled ocean crust are the O isotope compositions that deviate from the well defined mantle peridotitic values and fresh MORB (Gregory and Taylor, 1981), but are within the range of O isotope compositions observed in the basaltic sections of ophiolites (see Muehlenbachs, 1986). The significant O isotope fractionations between minerals require low-temperature processes at or close to the surface of the Earth (Hoefs, 2009). It is known that, during the hydrothermal alteration of oceanic crust by circulating seawater, O isotopic fractionation between seawater and basalt is temperature dependent (Gregory and Taylor, 1981; Putlitz et al., 2000). Interaction with seawater at low temperature leads to higher $\delta^{18}\text{O}$ than normal mantle values (the case for MORB upper oceanic crust), whereas interaction with seawater at high temperatures results in $\delta^{18}\text{O}$ lower than the normal mantle values (the case for gabbroic lower oceanic crust).

Therefore, samples from the upper mantle that have $\delta^{18}\text{O}$ which lie outside the mantle range are interpreted either as parts of subducted slabs or as having been contaminated by melts or fluids from subducted slabs. This rationale has been widely accepted in interpreting the provenance of the eclogite xenoliths hosted in kimberlites (Schulze et al., 2000; Jacob, 2004) and of some pyroxenite layers (Pearson et al., 1991).

The reconstructed $\delta^{18}\text{O}$ values for the Jiaohe pyroxenites according to mode and mineral isotope ranges from 4.9 to 5.1‰ (except one with a $\delta^{18}\text{O}$ value of 5.4‰). They are significantly lower than the mantle whole-rock averages ($\delta^{18}\text{O} = 5.5 \pm 0.4\%$; Matthey et al., 1994), and consistent with their gabbroic precursor having been altered by seawater. Though limited, the available O isotope data show disequilibrium between the coexisting minerals in the Jiaohe pyroxenites (Fig. 7). Although $\delta^{18}\text{O}$ in garnet (5.1 to 5.6‰) are similar to mantle garnet averages, co-existing clinopyroxene shows distinctly lighter O isotopes with $\delta^{18}\text{O}$ ranging from 4.5 to 5.1‰ (compared to the mantle average of 5.7‰, Fig. 7a). The negative $\Delta^{18}\text{O}_{\text{gt-cpx}}$ is the reverse of what predicted for equilibrium fractionation in the mantle (Fig. 7; Zheng, 1997). In addition, spinels are also anomalously enriched in heavy O isotopes; their $\delta^{18}\text{O}$ (5.1–5.2‰) are considerably higher than that reported for the lithospheric mantle (~4.8‰, Matthey et al., 1994).

The O isotope disequilibrium observed in the Jiaohe xenoliths is in striking contrast with the common O isotope equilibrium between mantle minerals (Matthey et al., 1994). A rare example for O isotope

disequilibrium comes from spinel lherzolite and pyroxenite xenoliths from the Rio Puerco Volcanic Field, New Mexico, where olivine $\delta^{18}\text{O}$ values are higher (+5.5‰), whereas $\delta^{18}\text{O}$ values for pyroxenes are lower (cpx = +5.1‰; opx = +5.4‰) than normal mantle values. The anomalously low $\delta^{18}\text{O}$ in pyroxenes reflects metasomatism by a silicate melt from subducted altered oceanic crust (Perkins et al., 2006). A similar selective metasomatism model, in which cpx is more suspected to metasomatic fluids whereas garnet is more resistant (Schulze et al., 2000), is however not suitable in the Jiaohe case, given the following considerations:

- There is no correlation between metasomatic indices (e.g., La/Yb) and $\delta^{18}\text{O}$ for the Jiaohe pyroxenites. For example, cpx with the lowest $\delta^{18}\text{O}$ does not show any sign of metasomatic enrichment, whereas cpx with $\delta^{18}\text{O}$ close to the normal mantle values shows variable LREE enrichment. This argues against the role of metasomatism in reducing $\delta^{18}\text{O}$, although metasomatism did occur in the upper mantle underneath Jiaohe (Yu et al., 2009).
- While selective metasomatism can account for the lower $\delta^{18}\text{O}$ in cpx and the unaffected $\delta^{18}\text{O}$ in garnet, it is difficult to explain the higher $\delta^{18}\text{O}$ in spinel. Either low or mantle-like $\delta^{18}\text{O}$ values would be expected in the circumstance of selective metasomatism by altered oceanic crust-derived fluids/melts.
- The reconstructed whole-rock $\delta^{18}\text{O}$ values for the three Jiaohe pyroxenites (4.9–5.1‰) is lower than the typical mantle peridotite values ($\delta^{18}\text{O} = 5.5 \pm 0.4\%$; Matthey et al., 1994). More importantly, variable $\delta^{18}\text{O}$ of cpx from the Jiaohe pyroxenites negatively correlates with FeO in cpx (Fig. 6b), an observation indicative of altered oceanic crust (Jacob et al., 1998). Specifically the low to normal $\delta^{18}\text{O}$ values for the Jiaohe xenoliths are suggestive of high-*T* alteration in the deeper, gabbroic parts of oceanic crust (in contrast to the high $\delta^{18}\text{O}$ values for the upper oceanic crust), which is consistent with plagioclase-rich cumulate protoliths as inferred from the major and trace element compositions.

The assertion that the Jiaohe pyroxenites represent metamorphosed, subducted altered lower oceanic crust is consistent with its evolutionary history as constrained by the mineralogical data. The mineralogical transformation from gabbroic rocks to pyroxenites may have involved two reactions: (1) ol + pl = opx + cpx + sp and (2) opx + cpx + sp = grt + ol (Ulianov et al., 2006). Moreover, exsolution lamellae of spinel and orthopyroxene, spinel rimmed by garnet (Fig. 2) all indicate that this pressure increasing process was accompanied by cooling. Subduction could in principle be a viable process for transporting the gabbroic protoliths to mantle depth. This process has been invoked for pyroxenites from orogenic mafic–ultramafic complexes from several localities, such as Beni Bousera, Ronda, Horoman (Kronpobst et al., 1990; Morishita et al., 2004).

4.4. Oxygen isotope disequilibrium in the Jiaohe xenoliths: causes and implications

The O isotopic disequilibrium exhibited by the Jiaohe pyroxenites is unusual and the cause of this phenomenon deserves further discussion. Why is $\delta^{18}\text{O}_{\text{cpx}}$ lower than, $\delta^{18}\text{O}_{\text{grt}}$ virtually identical to, but $\delta^{18}\text{O}_{\text{sp}}$ higher than the average mantle values for the corresponding mantle minerals? Earlier discussions lead to the conclusion that the Jiaohe pyroxenites represent metamorphosed, subducted altered oceanic crust. During subduction, plagioclase transformed first to spinel then to garnet. Under these circumstances, the O isotope composition of spinel and garnet would be inherited from the plagioclase in gabbroic precursors, provided that the time interval is too short for newly formed minerals to achieve isotopic equilibration under mantle conditions. This interpretation is supported by the similarity of observed O-isotopic fractionations between garnet/spinel and clinopyroxene in the Jiaohe

pyroxenites to plagioclase/cpx fractionation in seawater altered oceanic crust (Fig. 8).

Fig. 8 shows a relationship between $\delta^{18}\text{O}_{\text{plagioclase}}$ and $\delta^{18}\text{O}_{\text{pyroxene}}$ in which primary magmatic plagioclase–pyroxene pairs from normal mid-ocean ridge tholeiites plot along a line of slope 1, and mostly cluster around a spot having the $\delta^{18}\text{O}$ coordinates of 5.5‰ and 6.0‰. Seawater alteration of oceanic crust at different temperature, as recorded in ophiolites, would generate significant variation in $\delta^{18}\text{O}$, forming a trend with a slope of 2.3 (Gregory and Taylor, 1981). Specifically, cumulate gabbros from the lower oceanic crust tend to light O isotopes (below the equilibrium fractionation line), whereas altered oceanic basalts tend to have elevated $\delta^{18}\text{O}$ values (above the equilibrium fractionation line). Except for one analysis, both grt–cpx pairs and sp–cpx pairs for the Jiaohe pyroxenites plot along the hydrothermal alteration trend, and along the trend for altered cumulate gabbros (Fig. 8). This characteristic is consistent with the cumulate gabbroic precursor for the Jiaohe pyroxenites, inferred on the basis of major and trace element compositions. The coincidence of garnet–cpx and spinel–cpx fractionation along the plagioclase–cpx fractionation for altered oceanic crust can be understood if the O-isotope compositions of the garnets and spinels were inherited from those of former altered plagioclases. The oxygen isotope inheritance from gabbroic protolith during mineralogical transformation was suggested by Zheng et al. (2002) for eclogitization at Yangkou in the Sulu orogen, east-central China.

Using available data for O diffusion in mantle minerals, the O isotopic disequilibrium between coexisting minerals can provide an estimate on the timescale of metasomatism and/or metamorphism. Rosenbaum et al. (1994) suggested that diffusion of oxygen in olivine and pyroxenes at mantle temperatures is rapid so that negative

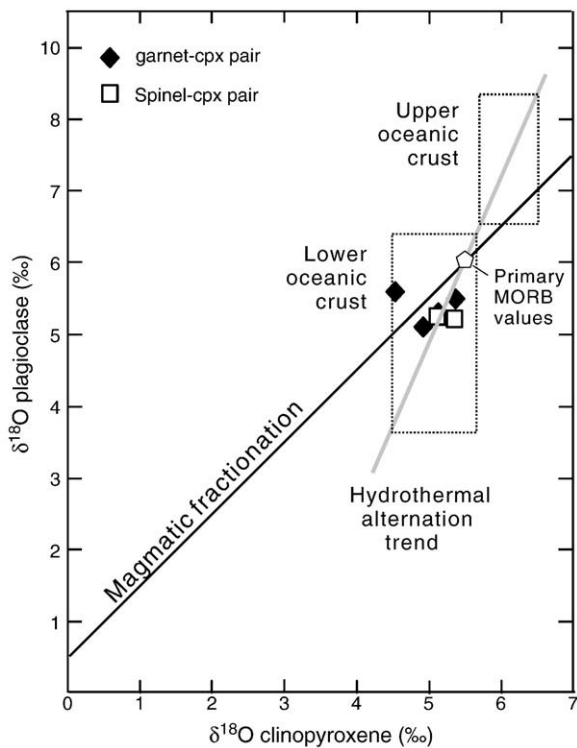


Fig. 8. Plot of $\delta^{18}\text{O}$ of garnet and spinel versus $\delta^{18}\text{O}$ clinopyroxene for the Jiaohe pyroxenites in the $\delta^{18}\text{O}$ plagioclase– $\delta^{18}\text{O}$ clinopyroxene space. The black and grey lines represent equilibrium magmatic fractionation and hydrothermal alteration trend of oceanic crust, respectively (Gregory and Taylor, 1981). Two rectangular boxes outline the isotopic compositions of altered upper and lower oceanic crust. Note that garnet–cpx and spinel–cpx pairs for the Jiaohe pyroxenites are plotted along the hydrothermal alteration trend of oceanic crust. This can be understood if spinel and garnet represent metamorphosed phase of plagioclase from altered oceanic crust.

$\Delta^{18}\text{O}_{\text{px-ol}}$ fractionations are unlikely to be preserved for more than ~10,000 years. On the other hand, Zheng et al. (2003) estimated a duration of 10 to 53 Myr for O diffusion re-equilibration across a diopside crystal with a grain size of 2 mm at 850–800 °C. It follows that for the Jiaohe pyroxenites, O isotopic disequilibrium between the coexisting minerals may have persisted for a few Myr in the source before eruption.

The studied area was an intraplate setting during the late Cenozoic. Two alternatives can be envisaged to rationalize to O isotopic disequilibrium in the Jiaohe pyroxenites with their tectonic setting. (1) Mesozoic subduction of the oceanic crust was stalled somewhere in subcontinental lithospheric mantle (SCLM) where relatively low temperatures would prevent isotopic re-equilibration. Not long before the eruption of the host basalts, this subducted oceanic crust was reactivated in the SCLM prior to delamination or foundering. This process has been suggested by Zhang et al. (2009) to interpret the origin of Cenozoic continental basalts in east-central China. (2) Although Jiaohe is located far from the current subduction zone, there is ample evidence for subduction of Pacific plate underneath the eastern Asian continent. Seismographic studies suggest that the subducted Pacific oceanic slabs have become stagnant within the mantle transition zone and extended subhorizontally westward beneath the East Asian continent (Huang and Zhao, 2006). Therefore, the formation of the Jiaohe pyroxenites is probably related to this subduction process.

5. Conclusions

Garnet pyroxenite xenoliths from Jiaohe, NE China, display petrological, geochemical and isotopic characteristics that are distinct from common basalt-hosted pyroxenites. Their high Al_2O_3 contents and high Mg# resemble that for olivine-bearing cumulative gabbros. A crustal origin from plagioclase-bearing protoliths is further supported by positive Eu and Sr anomalies in both whole rocks and constituent minerals and unusual O isotopic disequilibrium between coexisting minerals. It is proposed that the Jiaohe pyroxenite xenoliths were primarily formed as oceanic cumulate gabbros, which were later transformed to garnet pyroxenites by subduction into the mantle. During this mineralogical transformation, the O isotopes of garnet and spinel inherited those of former plagioclases without isotopic re-equilibration. Therefore, the Jiaohe pyroxenites are interpreted to originate from the metamorphic transformation of gabbroic precursors that underwent high-T seawater-hydrothermal at high temperatures. This interpretation, similar to that for kimberlite-hosted eclogite xenoliths, contrasts with the origin of high pressure cumulate origin widely proposed for the majority of basalt-hosted pyroxenites.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2010.06.043.

References

- Allegre, C., Turcotte, D.L., 1986. Implications of a two component marble-cake mantle. *Nature* 323, 123–126.
- Barth, M., Rudnick, R.L., Horn, I., McDonough, W.F., Spicuzza, M., Valley, J.W., Haggerty, S.E., 2001. Geochemistry of xenolithic eclogites from West Africa: part I. A link between low MgO eclogites and Archean crust formation. *Geochim. Cosmochim. Acta* 65, 1499–1527.
- Becker, H., 1996. Crustal trace element and isotopic signatures in garnet pyroxenites from garnet peridotite massifs from Lower Austria. *J. Petrol.* 37, 785–810.
- Brey, G.P., Kohler, T., 1990. Geothermobarometry in four-phase lherzolites II. New thermobarometers, and practical assessment of existing thermobarometers. *J. Petrol.* 31, 1353–1378.
- Downes, H., 2007. Origin and significance of spinel and garnet pyroxenites in the shallow lithospheric mantle: ultramafic massifs in orogenic belts in Western Europe and NW Africa. *Lithos* 99, 1–24.
- Gao, S., Rudnick, R.L., Yuan, H.L., Liu, X.M., Liu, Y.S., Xu, W.L., Ling, W.L., Ayers, J., Wang, X.C., Wang, Q.H., 2004. Recycling lower continental crust in the North China craton. *Nature* 432, 892–897.
- Garrido, C.J., Bodinier, J.L., 1999. Diversity of mafic rocks in the Ronda peridotite: evidence for pervasive melt–rock reaction during heating of subcontinental lithosphere by upwelling asthenosphere. *J. Petrol.* 40, 729–754.
- Gonzaga, R.G., Lowry, D., Jacob, D.E., LeRoex, A., Schulze, D., Menzies, M.A., 2010. Eclogites and garnet pyroxenites: similarities and differences. *J. Vol. Geotherm. Res.* 190, 235–247.
- Gregory, R.T., Taylor Jr, H.P., 1981. An oxygen isotope profile in a section of Cretaceous oceanic crust, Samail ophiolite, Oman: evidence for ^{18}O buffering of the oceans by deep (>5 km) seawater–hydrothermal circulation at mid-ocean ridges. *J. Geophys. Res.* 86, 2737–2755.
- Griffin, W.L., O'Reilly, S.Y., Hollis, J.D., 1984. Ultramafic xenoliths from Bullenmerri and Gnotuk maars, Victoria, Australia: petrology of a sub-continental crust–mantle transition. *J. Petrol.* 25, 53–87.
- Herzberg, C., 2006. Petrology and thermal structure of the Hawaiian plume from Mauna Kea volcano. *Nature* 444, 605–609.
- Hirschmann, M.M., Stolper, E.M., 1996. A possible role for garnet pyroxenite in the origin of the “garnet signature” in MORB. *Contrib. Mineral. Petrol.* 124, 185–208.
- Ho, K.S., Chen, J.C., Smith, A.D., Juang, W.S., 2000. Petrogenesis of two groups of pyroxenite from Tungchihsu, Penghu Islands, Taiwan Strait: implications for mantle metasomatism beneath SE China. *Chem. Geol.* 167, 355–372.
- Hoefs, J., 2009. *Stable Isotope Geochemistry*, 6th edition. Springer-Verlag, Berlin Heidelberg, 285 pp.
- Huang, J.L., Zhao, D.P., 2006. High-resolution mantle tomography of China and surrounding regions. *J. Geophys. Res.* 111, B09305.
- Huang, X.L., Xu, Y.G., Liu, D.Y., 2004. Geochronology, petrology and geochemistry of the granulite xenoliths from Nushan, eastern China: implication for a heterogeneous lower crust beneath the Sino-Korean Craton. *Geochim. Cosmochim. Acta* 68, 127–149.
- Irving, A.J., 1980. Petrology and geochemistry of composite ultramafic xenoliths in alkali basalts and implications for magmatic processes within the mantle. *Am. J. Sci.* 280-A, 389–426.
- Jacob, D., 2004. Nature and origin of eclogite xenoliths from kimberlites. *Lithos* 77, 295–316.
- Jacob, D., Jagoutz, E., Lowry, D., Zinngrebe, E., 1998. Comment on “The origins of Yakutian eclogite xenoliths” by Snyder, G.A., Taylor, L.A., Crozaz, G., Halliday, A.N., Beard, B.L., Sobolev, V.N., Sobolev, N.V. *J. Petrol.* 39, 1527–1533.
- Jacob, D.E., Schmickler, B., Schulze, D.J., 2003. Trace element geochemistry of coesite-bearing eclogites from the Roberts Victor kimberlite, Kaapvaal craton. *Lithos* 71, 337–351.
- Jagoutz, E., Dawson, J.B., Hoernes, S., Spettel, B., Wänke, H., 1984. Anorthositic oceanic crust in the Archean Earth. 15th Lunar Planet. Sci. Conf., pp. 395–396.
- Jahn, B.M., Wu, F.Y., Chen, B., 2000. Massive granitoids generation in Central Asia: Nd isotope evidence and implication for continental growth in the Phanerozoic. *Episodes* 23, 82–92.
- Kronobst, J., Piboule, M., Roden, M., Tabit, A., 1990. Corundum-bearing garnet clinopyroxenites at Beni Bouchera (Morocco): original plagioclase-rich gabbros recrystallized at depth within the mantle? *J. Petrol.* 31, 717–745.
- Liu, J.F., Xu, Y.G., 2006. Mineral chemistry and geochemistry of the two suites of pyroxenite xenoliths in Cenozoic basalts from Yangyuan, Hebei. *Geotectonica et Metallogenia* 30, 52–62 (in Chinese with English abstract).
- Liu, Y.S., Gao, S., Lee, C.T., Hu, S.H., Liu, X.M., Yuan, H.L., 2005. Melt–Peridotite interactions: links between garnet pyroxenite and high-Mg# signature of continental crust. *Earth Planet. Sci. Lett.* 234, 39–57.
- Liu, Y.S., Gao, S., Kelemen, P.B., Xu, W.L., 2008. Recycled crust controls contrasting source compositions of Mesozoic and Cenozoic basalts in the North China Craton. *Geochim. Cosmochim. Acta* 72, 2349–2376.
- Mattey, D., Lowry, D., Macpherson, C., 1994. Oxygen isotope composition of mantle peridotite. *Earth Planet. Sci. Lett.* 128, 231–241.
- McGregor, I.D., Manton, S.R., 1986. Roberts Victor eclogites: ancient oceanic crust. *J. Geophys. Res.* 91, 14063–14079.
- Medaris, L.G., Beard, B.L., Johnson, C.M., Valley, J.W., Spicuzza, M.J., Jelinek, E., Misar, Z., 1995. Garnet pyroxenite and eclogite in the Bohemian Massif: geochemical evidence for Variscan recycling of subducted lithosphere. *Geol. Rundsch.* 84, 489–505.
- Morishita, T., Arai, S., Green, D.H., 2004. Possible non-melted remnants of subducted lithosphere: experimental and geochemical evidence from corundum-bearing mafic rocks in the Horoman Peridotite Complex. *Jpn. J. Petrol.* 45, 235–252.
- Mork, M.B.E., Brunfelt, A.O., 1988. Geochemical comparisons of coronitic olivine gabbro and eclogites - Metamorphic effects and the origin of eclogite protoliths (Flemsoy, Sunnmore, Western Norway). *Norsk Geol. Tidsskrift* 68, 51–63.
- Muehlenbachs, K., 1986. Alteration of the oceanic crust and the ^{18}O history of seawater. *Rev. Mineral.* 16, 425–444.
- Obata, M., Hirajima, T., Svojtka, M., 2006. Origin of eclogite and garnet pyroxenite from the Moldanubian Zone of the Bohemian Massif, Czech Republic and its implication to other mafic layers embedded in orogenic peridotites. *Mineral. Petrol.* 88, 321–340.
- Pearson, D.G., Davies, G., Nixon, P., Greenwood, P., Mattey, D., 1991. Oxygen isotope evidence for the origin of pyroxenites in the Beni Bousera peridotite massif, North Morocco: derivation from subducted oceanic lithosphere. *Earth Planet. Sci. Lett.* 102, 289–301.
- Perkins, G.B., Sharp, Z.D., Selverstone, J., 2006. Oxygen isotope evidence for subduction and rift-related mantle metasomatism beneath the Colorado Plateau–Rio Grande rift transition. *Contrib. Mineral. Petrol.* 151, 633–650.
- Pilet, S., Baker, M.B., Stolper, E.M., 2008. Metasomatized lithosphere and the origin of alkaline lavas. *Science* 320, 916–919.
- Putlitz, B., Matthews, A., Valley, J.W., 2000. Oxygen and hydrogen isotope study of high-pressure metagabbros and metabasalts (Cyclades, Greece): implications for the subduction of oceanic crust. *Contrib. Mineral. Petrol.* 138, 114–126.
- Rosenbaum, J.M., Walker, D., Kyser, T.K., 1994. Oxygen isotope fractionation in the mantle. *Geochim. Cosmochim. Acta* 58, 4767–4777.
- Schulze, D.J., Valley, J.W., Spicuzza, M., 2000. Coesite eclogites from the Roberts Victor kimberlite, South Africa. *Lithos* 54, 23–32.
- Sobolev, A.V., Hofmann, A.W., Sobolev, S.V., Nikogosian, I.K., 2005. An olivine-free mantle source of Hawaiian shield basalts. *Nature* 434, 590–597.
- Suen, C.J., Frey, F.A., 1987. Origins of the mafic and ultramafic rocks in the Ronda peridotites. *Earth Planet. Sci. Lett.* 85, 183–202.
- Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), *Magmatism in the Ocean Basins*: Geol. Soc. Spel. Pub., 42, pp. 313–345.
- Taylor, L.A., Neal, C.R., 1989. Eclogites with oceanic crustal and mantle signatures from the Bellsbank kimberlite, South Africa. Part I: mineralogy, petrography and whole rock chemistry. *J. Geol.* 97, 551–567.
- Ulianov, A., Kalt, A., Petteke, T., 2006. Aluminous websterite and granulite xenoliths from the Chyulu Hills volcanic field, Kenya: gabbro-troctolitic cumulates subjected to lithospheric foundering. *Contrib. Mineral. Petrol.* 152, 459–483.
- Wang, L.C., 1996. The occurrence of Dashihe olivine deposit in Jilin Province. *Chin. J. Changchun Univ. Earth Sci.* 26, 43–46 (in Chinese with English abstract).
- Xu, Y.G., 2002. Evidence for crustal components in the mantle and constraints on the crustal recycling mechanisms: pyroxenite xenoliths from Hannuoba, North China. *Chem. Geol.* 182, 301–322.
- Xu, H., Liu, T., Yang, Y., 1989. Lithospheric dynamics of Northeast China. In: Ma, X.Y. (Ed.), *Lithospheric dynamics atlas of China*. SinoMaps Press, Beijing, 64 pp.
- Xu, J.F., Shinjo, R., Defant, M.J., 2002. Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: partial melting of delaminated lower continental crust? *Geology* 30, 1111–1114.
- Yu, J.H., Xu, X.S., O'Reilly, S.Y., Griffin, W.L., Zhang, M., 2003. Granulite xenoliths from Cenozoic Basalts in SE China provide geochemical fingerprints to distinguish lower crust terranes from the North and South China tectonic blocks. *Lithos* 67, 77–102.
- Yu, S.Y., Xu, Y.G., Huang, X.L., Ma, J.L., Ge, W.C., Zhang, H.H., Qin, X.F., 2009. Hf–Nd isotopic decoupling in continental mantle lithosphere beneath Northeast China: effects of pervasive mantle metasomatism. *J. Asian Earth Sci.* 35, 554–570.
- Zhang, J.-J., Zheng, Y.-F., Zhao, Z.-F., 2009. Geochemical evidence for interaction between oceanic crust and lithospheric mantle in the origin of Cenozoic continental basalts in east-central China. *Lithos* 110, 305–326.
- Zheng, Y.F., 1997. Prediction of high-temperature oxygen isotope fractionation factors between mantle minerals. *Phys. Chem. Miner.* 24, 356–364.
- Zheng, Y.F., Wang, Z.R., Li, S.G., Zhao, Z.F., 2002. Oxygen isotope equilibrium between eclogite minerals and its constraints on mineral Sm–Nd chronometer. *Geochim. Cosmochim. Acta* 66, 625–634.
- Zheng, Y.-F., Yang, J.-J., Gong, B., Jahn, B.-M., 2003. Partial equilibrium of radiogenic and stable isotope systems in garnet peridotite during UHP metamorphism. *Am. Mineral.* 88, 1633–1643.