俯冲陆壳和洋壳对华北克拉通中生代岩石圈地幔改造的氧同位素记录

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摘 要: 来自华北克拉通山东省中生代镁铁质岩石及地幔包体的橄榄石氧同位素组成显示,早白垩世岩石圈地幔主要受到了来自俯冲的华南陆壳不同组分的改造作用,包括镁铁质下地壳和长英质上地壳组分以及少量的海相沉积碳酸盐岩,而晚白垩世的岩石圈地幔则受到了来自俯冲的太平洋板块的改造。早白垩世受俯冲陆壳改造的岩石圈地幔橄榄石相对正常地幔高 $\delta^{18}O$ (6.0‰~7.2‰),而晚白垩世被俯冲洋壳改造的局部地幔则相对正常地幔低 $\delta^{18}O$ (4.1‰~5.3‰)。板块俯冲作用是导致华北克拉通岩石圈地幔破坏的重要深部机制,三叠纪华南陆壳深俯冲导致了华北克拉通地幔强烈富集相容组分而转变为易熔的岩石圈,早白垩世大规模幔源岩浆的侵位很可能与俯冲大陆板片的整体断离或拆离作用相关;晚中生代以来的太平洋俯冲作用则引发了岩石圈地幔的置换和增生作用,形成了目前新、老地幔共存的格局。

关键词: 地幔改造作用; 氧同位素; 橄榄石; 中生代; 华北克拉通
中图分类号: P597^{+}.2 文献标识码: A 文章编号: 1000-6524(2013)05-0593-11

The modification of the lithospheric mantle beneath the North China Craton by subducted continental and oceanic crust: Oxygen isotopic records of olivine

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Abstract: Oxygen isotopic records from olivine crystals in Mesozoic mafic rocks and xenoliths in Shandong Province indicate an important contribution of both subducted continental crust and oceanic crust to the modification of the lithospheric mantle beneath the North China Craton (NCC). The early Cretaceous lithospheric mantle that has higher $\delta^{18}O$ (6.0‰~7.2‰) than normal mantle was mainly metasomatized by melts/fluids derived from the subducted Yangtze crustal rocks, which included the lower mafic and upper felsic components with subordinate marine carbonates. In contrast, some low-MgO peridotite xenoliths in the late Cretaceous lithospheric mantle that has lower $\delta^{18}O$ (4.1‰~5.3‰) than normal mantle were ascribed to the modification of subducted oceanic crust that had been hydrothermally altered prior to the subduction. The incorporation of recycling crustal rocks into the lithospheric mantle through plate subduction was an important mechanism for the modification and destruction of the lithospheric mantle beneath the NCC, e.g., the introduction of the fertile continental crustal components led to the refertilization of the lithospheric mantle that made it more fusible in response to thermal perturbation. The large-scale early Cretaceous mafic magmatism in NCC resulted probably from the breakoff

收稿日期: 2013-06-05; 修订日期: 2013-08-15
基金项目: 国家自然科学基金资助项目(90914009, 41121002)
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or detachment of the entire subducted continental slab. The subduction of the paleo-Pacific Ocean since late Mesozoic has exerted a significant impact on the mantle replacement and accretion, resulting in the coexistence of "old" and "newly accreted" mantle domain beneath the NCC.

Key words: mantle modification; oxygen isotopes; olivine; Mesozoic; NCC

华北克拉通东部显生宙以来发生了强烈的岩石圈减薄作用，不仅表现在岩石圈厚度从早奥陶世的约200 km减薄到现今的70~80 km，而且其岩石圈地幔性质也由化学成分难熔、Sr-Nd同位素富集转变为现今的化学成分饱满而Sr-Nd同位素组成类似于大洋型的地幔(Fan and Menzies, 1992; Fan *et al*., 2000; Menzies *et al*., 1993, 2007; Xu, 2001; Zheng *et al*., 2001, 2006; Zhang *et al*., 2002, 2004)。

中生代是连接古生代和新生代的纽带，期间华北克拉通经历了强烈的镁铁质岩浆活动、构造变形和成矿作用，标志着强烈的岩石圈减薄。来自中生代(主体为早白垩世)镁铁质火成岩的岩石学、元素-同位素地球化学资料反映华北克拉通的岩石圈地幔存在强烈的元素和同位素不均一性(图1, Zhang *et al*., 2002, 2004; Fan *et al*., 2007)。克拉通内部，包括太行山、鲁西地区的早白垩世超镁铁-镁铁质火成岩显示出EM1特征的Sr-Nd-Pb同位素组成(Guo *et al*., 2001, 2003; Zhang *et al*., 2004; Chen *et al*., 2004; Wang *et al*., 2006)，反映熔融源区具富集LREE, Rb/Sr比值中等，低Th、U但高Th/U比值的特征，与大陆下地壳相似。华北克拉通东南缘包括大别-苏鲁地区同时代超镁铁-镁铁质火成岩的Sr-Nd-Pb和C-O稳定同位素的研究结果显示出类似EM2的特征，其熔融地幔源区被认为受到了来自俯冲华南陆壳流体或熔体的改造(Jahn *et al*., 1999; Guo *et al*., 2001, 2004, 2013a, 2013b; Zhang *et al*., 2002, 2003; Xu *et al*., 2004; Fan *et al*., 2004; Zhao *et al*., 2005; Gao *et al*., 2008; Yang *et al*., 2012a, 2012b)。

晚白垩世期间山东省境内零星分布了镁铁质火山岩，由东至西包括青岛劈石口玄武岩脉(约82 Ma)、胶州大西庄玄武岩(约74 Ma)和莒南玄武质角砾岩(约67 Ma)(Yan *et al*., 2003; Ying *et al*., 2006; Zhang J *et al*., 2008)。这些晚白垩世玄武岩在地球化学上具有与洋岛玄武岩(OIB)类似的主量(低SiO_2、富MgO和碱)、微量元素(Nb-Ta正异常和Pb负异常)组成，在Sr-Nd同位素组成上也总体与OIB相似(Yan *et al*., 2003; Ying *et al*., 2006; Zhang J *et al*., 2008)，也与华北东部乃至中国东部新生代玄武岩非常相似(Zhang *et al*., 2009; Xu *et al*., 2012)。

近年来笔者对山东地区早、晚白垩世镁铁质岩石中的橄榄石开展了原位氧同位素研究，其结果显示，早白垩世无论是侵位的橄榄辉长岩/苏长岩，还是玄武岩中的橄榄石都具有相对正常地幔橄榄石高$\delta^{18}O$的特征(Guo *et al*., 2013a, 2013b; Xu *et al*., 2013; Yang *et al*., 2012a, 2012b)，而晚白垩世玄武岩中的橄榄石捕虏晶和地幔包体橄榄石则显示出相对正常地幔低$\delta^{18}O$的特点(Guo *et al*., 2013c)。由于橄榄石为镁铁质岩浆早期分离结晶的矿物，能有效记录初始幔源岩浆的氧同位素组成(Bindeman *et al*., 2004; Garcia *et al*., 2008; Eiler *et al*., 2011; Gurenko *et al*., 2011)，因此橄榄石显示出的氧同位素差异反映了中生代不同时期华北克拉通岩石圈地幔受到了不同氧同位素组成的再循环物质改造，其中早白垩世岩石圈地幔主要受到了来自华南陆壳物质的改造作用，晚期则主要受到了俯冲的太平洋板片的改造作用。俯冲地壳物质引起的岩石圈地幔富集和交代作用是华北克拉通岩石圈改造和破坏的主要机制。

1 区域地质背景概述

华北克拉通是中国大陆最古老的陆块，其地壳最早年龄为3.8 Ga(Liu *et al*., 1992)，岩石圈地幔的年龄为2.8 Ga(Gao *et al*., 2002; Zhang H F *et al*., 2008)。其主要由东、西两大古陆块组成，中间为华北克拉通早元古代过渡造山带(图1a)(Zhao *et al*., 2001)。克拉通周缘为古生代和中生代造山带，其北缘为中亚造山带，南缘为秦岭-大别-苏鲁造山带。

中生代，尤其是早白垩世期间，华北克拉通发生了强烈的岩浆活动、构造伸展变形-变质作用和大规模金属成矿作用。在鲁西地区包括济南辉长岩体、邹平镁铁质火山-侵入杂岩、沂南、淄博、莱芜等地的

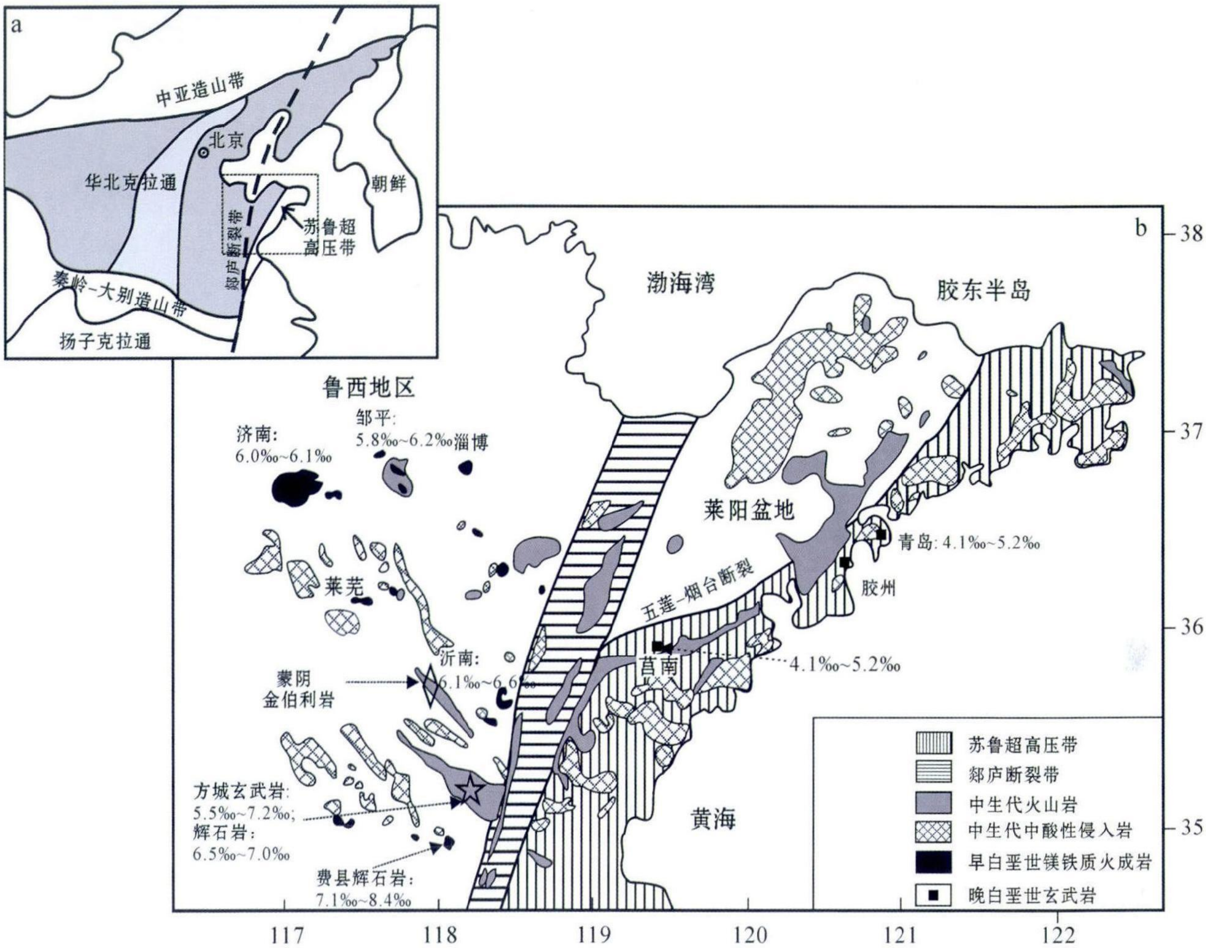

图 1　华北克拉通山东省中生代镁铁质火成岩分布图

Fig. 1　Distribution of Mesozoic mafic rocks in Shandong Province of the North China Craton

图中所标数字为橄榄石的 $\delta^{18}O$ 值, 资料来源: 济南辉长岩 (Yang *et al*., 2012a; Guo *et al*., 2013b); 费县玄武岩中辉石岩包体 (Xu *et al*., 2013); 方城玄武岩及辉石岩包体 (Guo *et al*., 2013a); 沂南辉长岩 (Yang *et al*., 2012b); 邹平辉长岩 (Yang *et al*., 2012a; 作者未发表数据); 莒南和青岛玄武岩地幔包体和橄榄石捕虏晶 (Guo *et al*., 2013c)

The numbers denote the $\delta^{18}O$ values of olivine crystals from mafic magmas or xenoliths; data sources: Jinan gabbros (Yang *et al*., 2012a; Guo *et al*., 2013b); pyroxenite xenoliths in Feixian basalts (Xu *et al*., 2013); Fangcheng basalts and pyroxenite xenoliths (Guo *et al*., 2013a); Yinan gabbros (Yang *et al*., 2012b); Zouping gabbros (Yang *et al*., 2012a and unpublished data); peridotite xenoliths in Junan and Qingdao basalts (Guo *et al*., 2013c)

辉长岩、辉长闪长岩, 还有费县和方城高镁玄武岩; 在鲁东地区的莱阳盆地出露了广为分布的玄武岩、玄武粗安岩、基性脉岩、煌斑岩等。晚白垩世期间沿着五连-烟台断裂带有零星的玄武岩喷发, 从东到西包括青岛、胶州和莒南玄武岩, 并含有地幔捕虏体。

2　早白垩世镁铁质岩浆橄榄石的氧同位素组成

2.1　济南和邹平辉长岩

济南辉长岩主要由橄榄苏长岩和辉长岩组成 (Guo *et al*., 2001, 2013b), 主要矿物包括橄榄石、紫苏辉石、普通辉石、斜长石组成。通过对橄榄石的原位氧同位素和激光氟化法分析, 获得其 $\delta^{18}O$ 值为 6.0‰~6.1‰ (Guo *et al*., 2013b), 相对 Yang 等 (2012a) 获得的济南和邹平岩体橄榄石的 $\delta^{18}O$ 值变化范围略小 (5.8‰~6.6‰), 但整体上较地幔橄榄石的 $\delta^{18}O$ 值 (5.1‰~5.4‰) 高 (Chazot *et al*., 1997), 反映其熔融地幔源区受到了来自再循环富 ^{18}O 地壳物质的贡献。邹平辉长岩橄榄石的原位 $\delta^{18}O$ 值为 5.4‰~6.3‰, 平均值为 5.8‰, 与激光氟化法分析的橄榄石单矿物 $\delta^{18}O$ 值相一致(作者未发表数

据),略低于济南辉长岩的橄榄石,但高于正常地幔橄榄石的 $\delta^{18}O$ 值(Chazot *et al.*, 1997)。

2.2 方城玄武岩及辉石岩包体

我们对方城玄武岩及其辉石岩包体中的橄榄石开展了原位氧同位素分析,方城玄武岩中橄榄石的Fo值变化较大,甚至最高可达93;其 $\delta^{18}O$ 值变化在5.5‰~7.2‰之间;相对于玄武岩中的橄榄石斑晶,辉石岩橄榄石的 $\delta^{18}O$ 值变化较小,在6.5‰~7.0‰之间(Guo *et al.*, 2013a)。总体上,无论是玄武岩中的橄榄石斑晶还是辉石岩中的橄榄石,总体较地幔橄榄石的 $\delta^{18}O$ 值高。最近Xu等(2013)报道了费县辉石岩橄榄石的原位氧同位素组成也显示出高 $\delta^{18}O$ 的特点。类似地,Yang等(2012b)报道了沂南辉长岩橄榄石的激光氟化法氧同位素组成,也具有相对地幔橄榄石高 $\delta^{18}O$ 的特点。

总体上,华北陆块早白垩世镁铁质岩石中橄榄石氧同位素反映的岩石圈地幔以相对正常地幔富集 ^{18}O 为特征,显示其受到了再循环富 $\delta^{18}O$ 地壳物质的改造作用(图2)。

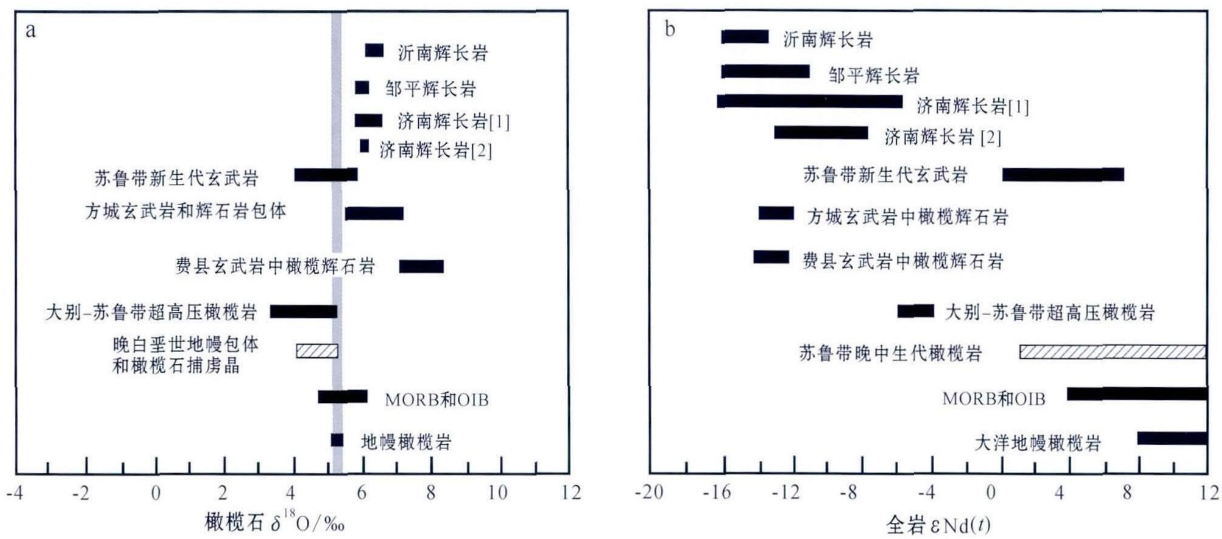

图2 白垩纪山东地区镁铁质岩石橄榄石的 $\delta^{18}O$ 值和全岩 $\varepsilon Nd(t)$ 对比图

Fig. 2 Comparison between $\delta^{18}O$ of olivine and whole-rock $\varepsilon Nd(t)$ of the Cretaceous mafic rocks and xenoliths in Shandong Province

除苏鲁带超高压橄榄岩外,其它资料来源同图1:大别-苏鲁带超高压橄榄岩(Zhang *et al.*, 1998; Zheng *et al.*, 2003);地幔橄榄岩(Chazot *et al.*, 1997);MORB和OIB(Harmon and Hoefs, 1995; Eiler *et al.*, 1997).

data sources are the same as in Fig. 1 except for: Dabie-Sulu UHP peridotites (after Zhang *et al.*, 1998; Zheng *et al.*, 2003); normal mantle peridotite (after Chazot *et al.*, 1997); MORB and OIB (after Harmon and Hoefs, 1995; Eiler *et al.*, 1997)

3 晚白垩世镁铁质岩浆中地幔捕虏体橄榄石的氧同位素组成

我们选择晚白垩世莒南和青岛玄武岩中的橄榄石捕虏晶和地幔包体橄榄石开展了原位氧同位素研究。

3.1 莒南玄武岩橄榄石捕虏晶和地幔包体橄榄石

莒南玄武岩橄榄石的Fo值变化在88.7~89.5之间,考虑到寄主玄武岩为Si不饱和岩浆,其 $Mg^{\#}$ 在66~71之间,由岩浆自身结晶的橄榄石Fo值应在70~80之间,因此这些自形程度高的橄榄石为捕虏晶,而不是斑晶。原位氧同位素分析显示其 $\delta^{18}O$ 值变化在4.1‰~5.3‰之间,平均值为4.7‰(Guo *et al.*, 2013c),相对正常地幔橄榄石的 $\delta^{18}O$ 值(5.1‰~5.4‰)明显偏低(Chazot *et al.*, 1997)。地幔包体橄榄石的Fo值变化在87.5~88.4之间,总体相对正常地幔橄榄岩(熔融残留体的Fo值通常>90)低,其 $\delta^{18}O$ 值变化在4.5‰~5.3‰之间,平均值为5.0‰(Guo *et al.*, 2013c),略低于地幔橄榄石的 $\delta^{18}O$ 值。

3.2 青岛玄武岩中地幔包体橄榄石

该玄武岩中地幔包体橄榄石具典型的碎斑结构,Fo值变化在89.0~89.9之间,与前人报道的低

MgO 橄榄岩成分相当 (Zhang *et al*., 2011), 其 $\delta^{18}O$ 值变化在 4.2‰~5.3‰之间, 平均值为 4.9‰ (Guo *et al*., 2013c), 低于地幔橄榄石的 $\delta^{18}O$ 值。

总体上, 晚白垩世地幔包体橄榄石和玄武岩的橄榄石捕虏晶都显示出相对正常地幔低 $\delta^{18}O$ 特点(图 2), 暗示其成因存在再循环高温蚀变洋壳的贡献。

4　华北克拉通中生代岩石圈地幔的改造机制

中生代镁铁质岩石的橄榄石氧同位素组成可以明显分为两类: ¹ 早白垩世镁铁质侵入岩和玄武岩, 其橄榄石的 $\delta^{18}O$ 值明显高于正常地幔橄榄岩; ④晚白垩世玄武岩中橄榄石捕虏晶和地幔包体橄榄石, 其 $\delta^{18}O$ 值明显低于正常地幔橄榄岩(图 2a、图 3)。尽管目前对于地幔氧同位素组成是否存在不均一性仍存在不同认识 (Zhang *et al*., 2000), 但来自大量的地幔包体、岛弧玄武岩和洋岛玄武岩的橄榄石氧同位素分析显示, 俯冲地壳物质的再循环能导致地幔的氧同位素组成不均一。由于地幔对流和软流圈的化学-热侵蚀作用以及氧同位素的扩散分馏效应, 地幔的氧同位素组成不均一性难以长时间被保存下来。Zheng (2012) 提出俯冲隧道的构造模式, 认为俯冲地壳物质在狭长的俯冲隧道内与岩石圈地幔发生反应, 如源自不同性质的俯冲地壳流体/熔体-橄榄岩反应将能形成具差异性氧同位素组成的地幔源区: ¹ 当被俯冲的物质主要为富 ^{18}O 的沉积物或大陆长英质中上地壳, 其析出流体或脱水熔体-地幔反应将形成富 ^{18}O 的地幔源区 (Bindeman *et al*., 2005; Gurenko *et al*., 2011); ④如果被俯冲的是主要由镁铁质岩石组成的下地壳 (如未蚀变大洋下地壳), 由于其 $\delta^{18}O$ 值与正常地幔差别较小, 被改造的地幔源区则 ^{18}O 富集微弱或不明显 (Kempton and Harmon, 1992); ㈣ 当被俯冲的是受到高温蚀变的低 $\delta^{18}O$ 洋壳, 被改造的地幔源区将显示出相对低 $\delta^{18}O$ 的特征 (Gregory and Taylor, 1981; Putlitz *et al*., 2000)。因此, 中生代华北岩石圈地幔显示出的不同 $\delta^{18}O$ 特点反映其受到的改造过程存在差别。

4.1　早白垩世岩石圈地幔属性与大规模熔融

对于早白垩世华北克拉通岩石圈地幔, 其富集的 ^{18}O 以及 Sr-Nd-Hf 同位素特征主要是受到了再循环陆壳物质的改造。综合方城、费县玄武岩和辉

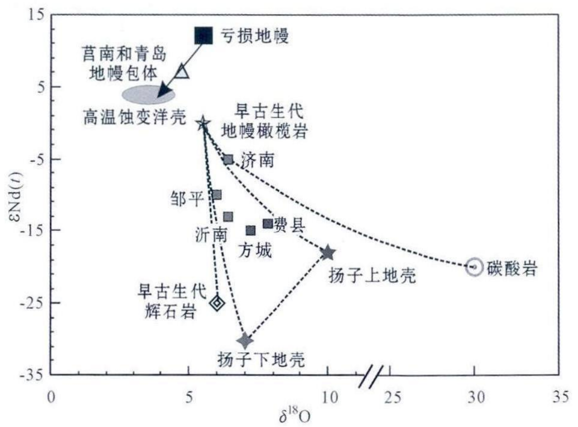

图 3　中生代镁铁质岩石的全岩 εNd(*t*)-$\delta^{18}O$ 协变关系

Fig. 3　Covariation between and whole-rock εNd(*t*) $\delta^{18}O$ of olivine

指示不同地区镁铁质岩浆熔融源区可能形成机制的概念性模型, 显示在沂南、方城和费县等具有 EM2 型同位素特征的早白垩世岩浆熔融源区存在俯冲的华南上地壳组分的贡献; 数据来源: 早古生代岩石圈地幔 (Yang *et al*., 2009), 早古生代辉石岩包体 (Zhang J *et al*., 2008), 华南上下地壳(Guo *et al*. 2013a 及其中参考文献), 碳酸岩 (Ying *et al*., 2004; Guo *et al*., 2013b); 其它数据同图 1 和 2; 高温蚀变洋壳根据氧同位素分馏原理推测

A conceptual model for the formation of the mantle source of the Cretaceous mafic magmas and peridotite xenoliths is showed. It is indicated that the mantle source for the Yinan, Fangcheng and Feixian mafic magmas contained an important component of subducted Yangtze upper crust. The data sources are the same as in Fig. 1 except for: early Paleozoic lithospheric mantle (after Yang *et al*., 2009); pyroxenite xenoliths (after Zhang J *et al*., 2008); Yangtze upper and lower crust (after Guo *et al*., 2013a and references therein); carbonatite (after Ying *et al*., 2004; Guo *et al*., 2013b). The O and Nd isotopic compositions of the hydrothermally altered oceanic crust are arbitrarily assumed in accordance with the oxygen isotope fractionation

石岩中橄榄石的 O 和全岩 Sr-Nd-Hf 同位素组成, 结果显示俯冲华南大陆的上下地壳都参与了岩石圈地幔的改造 (Zhang *et al*., 2002; Xu *et al*., 2013; Guo *et al*., 2013a), 通过橄榄石氧同位素组成估算的费县、方城地区岩石圈地幔的 $\delta^{18}O$ 值在 7.0‰左右, 远高于正常地幔的 5.5‰; 而更靠近华北克拉通内部的济南和邹平岩体, 其来源岩石圈地幔的 $\delta^{18}O$ 值在 5.8‰~6.2‰之间 (Yang *et al*., 2012a; Guo *et al*., 2013b), 可能与来自俯冲的华南表壳海相沉积物析出的碳酸岩熔体(熔体比例为 0.2%~1%)交代作用有关。来自沂南、莱芜等地辉长岩橄榄石的 $\delta^{18}O$ 值在 5.8‰~6.5‰之间, 所对应的地幔源区的 $\delta^{18}O$ 值在 6.3‰~6.8‰之间 (Yang *et al*., 2012b)，反映随着距离俯冲带变远，靠近克拉通内部，其早白垩世地幔源区受到俯冲陆壳的改造程度降低，这与 Sr-Nd-Hf 同位素所反映的特点相一致(Zhang *et al*., 2004，图 1)。

俯冲陆壳物质及其衍生的长英质熔体由于富集易熔组分、不相容元素和 LREE，因此这些再循环地壳物质的大量加入将形成交代辉石岩。这些富含不相容元素、LREE 和易熔组分的辉石岩的熔点远小于橄榄岩，因此在对流软流圈的热烘烤或化学-热侵蚀作用下将率先发生部分熔融作用，形成富镁的幔源岩浆，如方城和费县玄武岩和济南、邹平、沂南等辉长岩。尽管目前对于早白垩世岩石圈的减薄存在争议，但由于重力不稳定性，俯冲大陆板片的整体断离或拆离作用可能是导致加厚岩石圈垮塌和去根的重要机制。近年来对中生代地幔包体的含水性研究也显示，中生代地幔具有与现代岛弧可类比的高含水性(Xia *et al*., 2013; Guo *et al*., 2013a)，因此俯冲古太平洋板块析出流体是导致早白垩世岩石圈地幔软化和不稳定的原因之一(Windley *et al*., 2010)。外来俯冲洋壳析出的水促进了加厚岩石圈的不稳定性而发生断离或拆沉作用，诱发了大规模地幔部分熔融。

地幔氧同位素不均一性是否能在岩石圈地幔中得到有效保存是一个长期争议的问题，俯冲隧道模式认为由于地壳富^{18}O 物质的改造能造成地幔的氧同位素不均一(Zheng, 2012)。由于不同深度的地壳的氧同位素组成差异，其中地壳表层的沉积物高度富集^{18}O，中上地壳长英质成分中含有大量的沉积物或变质岩以及由这些原岩熔融形成的花岗质岩石，其 δ^{18}O 值较高，而下地壳主要由基性麻粒岩组成，因此其 δ^{18}O 值较低，但相对正常地幔略高(Eiler *et al*., 2001)。近年来对华北内部及南缘大别-苏鲁造山带的超高压变质岩和中生代火成岩的氧同位素研究显示，被俯冲的华南陆壳具有变化极大的 δ^{18}O 值(Zheng, 2012 及其中参考文献)，但是在中生代镁铁质岩石中普遍观察到相对正常地幔高的 δ^{18}O 值，反映被俯冲并改造华北岩石圈地幔的地壳物质主要为富^{18}O 的中酸性岩石或表壳岩石(Guo *et al*., 2013a)。由于中酸性物质的熔点远低于镁铁质岩石，深俯冲陆壳的选择性熔融(熔融物质主要为被俯冲的中酸性组分，镁铁质组分则残留下来)导致了被交代华北岩石圈地幔具有高的 δ^{18}O 值特征。

在大别地区同时还存在一些低 δ^{18}O 镁铁质岩石(Zhao *et al*., 2005; Dai *et al*., 2011)，它们的熔融源区很可能为俯冲陆壳析出流体改造的华北岩石圈地幔。由于高温热液流体-地幔橄榄岩相互作用，被改造的地幔源区将获得低 δ^{18}O 的特征，如在苏鲁地区发现了低 δ^{18}O 的石榴子石橄榄岩，其 Sr-Nd-O 同位素组成与未受到明显地壳混染的大别地区早白垩世镁铁质岩石相似。

与俯冲隧道模式有所区别的是岩石圈三明治模式(Fan *et al*., 2004)，认为被俯冲的陆壳岩石在折返过程中部分超高压岩石仅折返至冷的岩石圈地幔中，以透镜体或布丁形式存在于岩石圈地幔中。此外早白垩世俯冲板片断离模式认为在陆壳俯冲过程中，相对于俯冲洋壳，俯冲陆壳物质由于相对缺水，因此并未发生大规模的熔融和对华北岩石圈地幔进行改造。在早白垩世期间，由于俯冲板片的重力不稳定性而发生断离作用，使大部分的镁铁质板片再循环到对流软流圈中，而残留的长英质陆壳发生大规模的部分熔融作用对华北岩石圈地幔进行改造并诱发大规模的部分熔融作用(Guo *et al*., 2004)，从而形成了目前所观察到的富^{18}O 的镁铁质岩石，而主要受到热液流体改造的华北岩石圈地幔熔融则形成低 δ^{18}O 的镁铁质岩石。早白垩世板片断离模式则不需要考虑地幔氧同位素组成不均一性的保存问题。

这 3 种构造模式都能较好地解释华北克拉通南缘地幔氧同位素不均一性的保存问题，但在改造的空间分布与规模、岩浆演化和地幔富集机制等方面各有优缺点。如俯冲隧道模式能解释早期的岩浆作用，但其空间规模受到限制，难以解释早白垩世的岩浆大爆发过程；三明治岩石圈构造模式成功地解释了造山带岩浆演化从早期的中酸性向晚期基性演化，但在解释从造山带到华北内部的源区变化趋势上遇到困难；早白垩世板片断离模式能解释同时代的源区富集和岩浆过程，但岩浆的早期演化较少涉及。综合了前人模式的优缺点，我们重新设想了新的演化模式(图 4a～4d)，具体见后面阐述。

4.2 晚白垩世俯冲大洋板片改造作用

在晚白垩世，华北克拉通陆续出现了与现今地幔包体相似的饱满型地幔包体，且这些地幔橄榄岩显示出明显的低 δ^{18}O 特征以及亏损的 Sr-Nd 同位素组成。显然，这些被地幔改造的物质不可能还来自于俯冲的华南陆壳(图 2)。近年来对华北克拉通东南部的新生代玄武岩的氧同位素研究也发现了一些

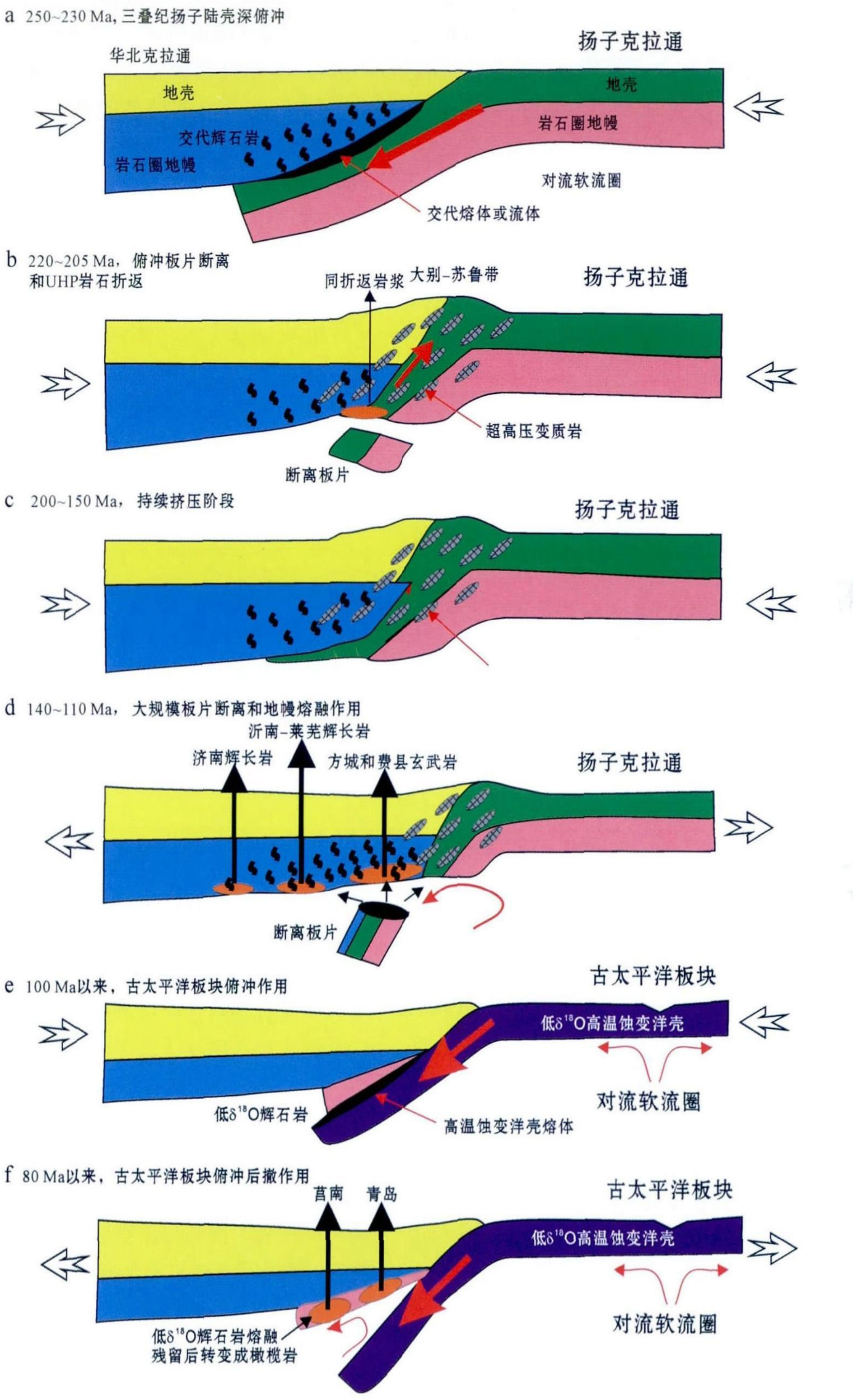

图 4　山东省中生代构造-岩浆作用演化卡通图

Fig. 4　A cartoon showing the possible Mesozoic tectono-magmatic evolution in Shandong Province

低 $\delta^{18}O$ 值的具有 OIB 特征的玄武岩以及华北克拉通东北部代表残留洋壳的低 $\delta^{18}O$ 石榴子石辉石岩包体，其成因与俯冲太平洋板片的参与有关(Zhang *et al*., 2008, 2009; Yu *et al*., 2011; Wang *et al*., 2011; Xu *et al*., 2012)。来自古太平洋板块的运动轨迹和相关俯冲带岩浆记录(Faure and Natal'in, 1992; Guo *et al*., 2007)显示，东亚大陆边缘至少在晚中生代受到了来自太平洋板块的俯冲作用。被俯冲的太平洋地壳岩石经历了高温流体蚀变或变质作用，从而获得了低 $\delta^{18}O$ 的特征(Zhang *et al*., 2009; Yu *et al*., 2010; Xu *et al*., 2012)；俯冲的低 $\delta^{18}O$ 洋壳发生部分熔融，形成低 $\delta^{18}O$ 长英质熔体交代上覆地幔楔橄榄岩，产生低 $\delta^{18}O$ 的地幔源区。地幔楔发生部分熔融作用，其中的低 $\delta^{18}O$ 超镁铁岩，包括交代橄榄岩(Guo *et al*., 2013c)和石榴石辉石岩(Yu *et al*., 2010)熔融产生了低 $\delta^{18}O$ 玄武岩。这些熔融后的低 $\delta^{18}O$ 地幔楔残留体以及上覆的华北古老岩石圈地幔——高镁橄榄岩包体同时被寄主玄武岩捕获带到地表(Ying *et al*., 2006; Zhang *et al*., 2011)。

综合前面的讨论，华北中生代岩石圈地幔的演化可划分为6个阶段(图4)：

(a) 三叠纪华南陆壳俯冲阶段：被深俯冲的华南陆壳(包括长英质的上地壳和镁铁质的下地壳)在俯冲隧道内析出流体或熔体交代上覆的华北岩石圈地幔(Yang *et al*., 2012a)，由于当时的华北岩石圈厚且冷，难以发生熔融形成类似于大洋俯冲带的钙碱性岩浆，这些熔体/流体与地幔橄榄岩发生反应形成了大量的富集 LILE 和 LREE 和亏损 HFSE 的同位素富集辉石岩脉。

(b) 俯冲板片折返阶段：由于俯冲陆壳的密度相对较低和局部的板片断离作用，早先富集的岩石圈地幔发生小比例熔融作用，形成了220~205 Ma的同折返岩浆(Zhao *et al*., 2012)，部分超高压岩石折返到地幔深度呈布丁或透镜体形态，与富集岩石圈地幔构成类似"三明治"的岩石圈结构(Fan *et al*., 2004)。

(c) 持续挤压加厚阶段：受到周边板块相互作用的影响，华北与华南陆块继续发生挤压和岩石圈加厚，导致造山带山根的重力不稳定性。

(d) 板片断离和地幔大规模熔融阶段：大规模的俯冲华南大陆板片和一部分华北岩石圈地幔发生断离作用，断离部分在对流软流圈发生部分熔融形成类似于 adakite 的熔体继续改造上覆的华北岩石圈地幔(Guo *et al*., 2006)，同时软流圈的上涌导致了早先和正在改造的华北岩石圈地幔发生大规模熔融作用，形成了区域上广泛分布的早白垩世镁铁质岩浆。

(e) 古太平洋板块俯冲阶段：晚白垩世以来古太平洋板块向华北克拉通俯冲，受到高温蚀变的低 $\delta^{18}O$ 下部洋壳熔融形成长英质熔体，与上覆地幔橄榄岩反应形成低 $\delta^{18}O$ 橄榄辉石岩。

(f) 古太平洋板块俯冲后撤阶段：俯冲的古太平洋板片发生角度变陡和后撤，在低 $\delta^{18}O$ 橄榄辉石岩与软流圈之间形成了类似板片窗的结构，这些橄榄辉石岩发生部分熔融作用，其残留部分形成了被玄武岩携带到地表的青岛和莒南低 $\delta^{18}O$ 橄榄岩。大洋岩石圈俯冲引起的交代地幔楔增生和"置换"作用可能是华北陆块中新生代岩石圈地幔演化过程的一个重要机制。

5 主要认识

通过对华北克拉通早、晚白垩世镁铁质岩石中的橄榄石氧同位素分析，主要获得了以下主要认识：

(1) 橄榄石的氧同位素研究显示白垩纪不同时期华北克拉通岩石圈地幔存在氧同位素组成差异，早白垩世岩石圈地幔以高 $\delta^{18}O$ 为特征，而晚白垩世岩石圈地幔则出现了低 $\delta^{18}O$ 增生型橄榄岩；

(2) 综合分析橄榄石氧同位素组成和相关的元素-同位素地球化学特征显示，早白垩世岩石圈地幔主要受到了来自俯冲华南陆壳的改造作用，导致了当时的岩石圈地幔富集不相容元素和易熔组分；而晚白垩世岩石圈地幔则受到了来自俯冲大洋地壳的改造，交代地幔楔导致的地幔增生作用可能是华北克拉通现今岩石圈地幔的重要增生方式之一；

(3) 俯冲陆壳和洋壳的共同改造是导致华北克拉通破坏的重要机制之一。

致谢 非常感谢夏群科教授的约稿和赵子福教授与张宏福研究员对本文提出的宝贵意见。

References

Bindeman I N, Ponomareva V V, Bayley J C, *et al*. 2004. Volcanic arc of Kamchatka, a province with high-δ ^{18}O magma sources and large scale $^{18}O/^{16}O$ depletion of the upper crust[J]. Geochimica et Cosmochimica Acta, 68: 841~ 865.

Bindeman I N, Eiler J M, Yogodzinskic G M, *et al*. 2005. Oxygen isotope evidence for slab melting in modern and ancient subduction zone [J]. Earth and Planetary Science Letters, 235: 480~ 496.

Chazot G, Lowry D, Menzies M, *et al*. 1997. Oxygen isotopic composition of hydrous and anhydrous mantle peridotites[J]. Geochimica et Cosmochimica Acta, 61: 161~ 169.

Chen B, Jahn B M, Arakawa Y, *et al*. 2004. Petrogenesis of the Mesozoic intrusive complexes from the southern Taihang Orogen, North China Craton: Elemental and Sr-Nd-Pb isotopic constraints [J]. Contributions to Mineralogy and Petrology, 148: 489~ 501.

Dai L Q, Zhao Z F, Zheng Y F, *et al*. 2011. Zircon Hf-O isotope evidence for crust-mantle interaction during continental deep subduction [J]. Earth and Planetary Science Letters, 308: 224~ 244.

Eiler J M, Farley K A, Valley J W, *et al*. 1997. Oxygen isotope variations in ocean island basalt phenocrysts [J]. Geochimica et Cosmochimica Acta, 61: 2 281~ 2 293.

Eiler J M, Farley K A, Valley J W, *et al*. 2001. Oxygen isotope variations of basaltic lavas and upper mantle rocks[J]. Reviews in Mineralogy and Geochemistry, 43: 319~ 364.

Eiler J, Stolper E M, McCanta M C. 2011. Intra- and intercrystalline oxygen isotope variations in minerals from basalts and peridotites [J]. Journal of Petrology, 52: 1 393~ 1 413.

Fan W M, Guo F, Wang Y J, *et al*. 2004. Late Mesozoic volcanism in the northern Huaiyang tectono-magmatic belt, central China: Partial melts from a lithospheric mantle with subducted continental crust relicts beneath the Dabie orogen? [J]. Chemical Geology, 209: 27~ 48.

Fan W M, Guo F, Wang Y J, *et al*. 2007. Late Mesozoic mafic magmatism from the North China Block: constraints on chemical and isotopic heterogeneity of the subcontinental lithospheric mantle[A]. Zhai M G, Windley B F, Kusky T M, *et al*. Mesozoic Sub-Continental Lithospheric Thinning Under Eastern Asia[C]. Geological Society, London, Special Publications, 280: 77~ 100.

Fan W M and Menzies M A. 1992. Destruction of aged lower lithosphere and accretion of asthenosphere mantle beneath eastern China [J]. Geotectonica et Metallogenia, 16: 171~ 180.

Fan W M, Zhang H F, Baker J, *et al*. 2000. On-craton and off-craton Cenozoic spinel peridotites in eastern China: Similarity and difference [J]. Journal of Petrology, 41: 933~ 950.

Faure M and Natal' in B. 1992. The geodynamic evolution of the eastern Eurasian margin in Mesozoic times[J]. Tectonophysics, 208: 397~ 411.

Garcia M O, Ito E and Eiler J M. 2008. Oxygen isotope evidence for chemical interaction of Kilauea historical magmas with basement rocks[J]. Journal of Petrology, 49: 757~ 769.

Gao S, Rudnick R L, Carlson R W, *et al*. 2002. Re-Os evidence for replacement of ancient mantle lithosphere beneath the North China Craton[J]. Earth and Planetary Science Letters, 198: 307~ 322.

Gao S, Rudnick R L, Xu W L, *et al*. 2008. Recycling deep cratonic lithosphere and generation of intraplate magmatism in the North China Craton[J]. Earth and Planetary Science Letters, 270: 41~ 53.

Gregory R T and Taylor H P. 1981. An oxygen isotope profile in a section of the Cretaceous oceanic crust, Samail ophiolite, Oman: evidence for $\delta^{18}O$ buffering of the oceans by deep (> 5 km) seawater-hydrothermal circulation at mid-ocean ridges[J]. Journal of Geophysical Research, 86: 2 737~ 2 755.

Guo F, Fan W M, Wang Y J, *et al*. 2001. Late Mesozoic mafic intrusive complexes in North China Block: Constraints on the nature of subcontinental lithospheric mantle[J]. Physics and Chemistry of the Earth (A), 26: 759 ~ 771.

Guo F, Fan W M, Wang Y J, *et al*. 2003. Geochemistry of late Mesozoic mafic magmatism in west Shandong Province, eastern China: Characterizing the lost lithospheric mantle beneath the North China Block[J]. Geochemical Journal, 37: 63~ 77.

Guo F, Fan W M, Wang Y J, *et al*. 2004. Origin of early Cretaceous calc-alkaline lamprophyres from the Sulu orogen in eastern China: implications for enrichment processes beneath continental collisional belt[J]. Lithos, 78: 291~ 305.

Guo F, Fan W M and Li C W. 2006. Geochemistry of late Mesozoic adakites from the Sulu belt, eastern China: magma genesis and implications for crustal recycling beneath continental collisional orogens [J]. Geological Magazine, 143: 1~ 13.

Guo F, Nakamuru E, Fan W M, *et al*. 2007. Generation of Palaeocene adakitic andesites by magma mixing; Yanji Area, NE China[J]. Journal of Petrology, 48: 661~ 692.

Guo J T, Guo F, Wang C Y, *et al*. 2013a. Crustal recycling processes in generating the early Cretaceous Fangcheng basalts, North China Craton: New constraints from mineral chemistry, oxygen isotopes of olivine and whole-rock geochemistry[J]. Lithos, 170~ 171: 1~ 16.

Guo F, Guo J T, Wang C Y, *et al*. 2013b. Formation of mafic magmas through lower crustal AFC processes—an example from the Jinan gabbroic intrusion in the North China Block[J]. Lithos, doi: 10. 1016/j. lithos. 2013. 05. 018, in press.

Guo F, Fan W M, Guo J T, *et al*. 2013c. A metasomatized mantle wedge origin for low-δ ^{18}O olivine in late Cretaceous Junan and Qingdao basalts in the Sulu orogen[J]. Chinese Science Bulletin, doi:

10.1007/s11434-012-5607-z.

Gurenko A, Bindeman I and Chaussidon M. 2011. Oxygen isotope heterogeneity of the mantle beneath the Canary Islands: insights from olivine phenocrysts[J]. Contributions to Mineralogy and Petrology, 162: 349~363.

Harmon R S and Hoefs J. 1995. Oxygen isotope heterogeneity of the mantle deduced from global ^{18}O systematics of basalts from different geotectonic settings[J]. Contributions to Mineralogy and Petrology, 120: 95~114.

Kempton P D and Harmon R S. 1992. Oxygen isotope evidence for large-scale hybridization of the lower crust during magmatic underplating[J]. Geochimica et Cosmochimica Acta, 56: 971~986.

Jahn B M, Wu F, Lo C H, *et al*. 1999. Crust-mantle interaction induced by deep subduction of the continental crust: geochemical and Sr-Nd isotopic evidence from post-collisional mafic-ultramafic intrusions of the northern Dabie complex, central China[J]. Chemical Geology, 157: 119~146.

Liu D Y, Nutman A P, Compston W, *et al*. 1992. Remnants of 3800Ma crust in the Chinese part of the Sino-Korean craton[J]. Geology, 20: 339~342.

Menzies M A, Fan W and Zhang M. 1993. Paleozoic and Cenozoic lithoprobes and the loss of > 120 km of Archean lithosphere, Sino-Korean craton, China[A]. Pichard H M, Alabaster T, Harris N B W. Magmatic Processes and Plate Tectonics[C]. Geological Society London, Special Publications, 76: 71~81.

Menzies M A, Xu Y G, Zhang H F, *et al*. 2007. Integration of geology, geophysics and geochemistry: A key to understanding the North China Craton[J]. Lithos, 96: 1~21.

Putlitz B, Matthews A and Valley J W. 2000. Oxygen and hydrogen isotope study of high pressure metagabbros and metabasalts (Cyclades, Greece): implications for the subduction of oceanic crust[J]. Contributions to Mineralogy and Petrology, 138: 114~126.

Wang Y J, Fan W M, Zhang H F, *et al*. 2006. Early Cretaceous gabbroic rocks from the Taihang Mountains: implications for a paleosubduction-related lithospheric mantle beneath the central North China Craton[J]. Lithos, 86: 281~302.

Wang Y, Zhao Z F, Zheng Y F, *et al*. 2011. Geochemical constraints on the nature of mantle source for Cenozoic continental basalts in east-central China[J]. Lithos, 125: 940~955.

Windley B F, Maruyama S and Xiao W J. 2010. Delamination/thinning of sub-continental lithospheric mantle under Eastern China: The role of water and multiple subduction[J]. American Journal of Science, 310: 1250~1293.

Xia Q K, Liu J, Liu S C, *et al*. 2013. High water content in Mesozoic primitive basalts of the North China Craton and implications on the destruction of cratonic mantle lithosphere[J]. Earth and Planetary Science Letters, 361: 85~97.

Xu Y G. 2001. Thermo-tectonic destruction of the Archaean lithospheric keel beneath the Sino-Korean Craton in China: evidence, timing and mechanism[J]. Physics and Chemistry of the Earth(A), 26: 747~757.

Xu Y G, Huang X L, Ma J L, *et al*. 2004. Crust-mantle interaction during the tectono-thermal reactivation of the North China Craton: constraints from SHRIMP zircon U-Pb chronology and geochemistry of Mesozoic plutons from western Shandong[J]. Contributions to Mineralogy and Petrology, 147: 750~767.

Xu W L, Zhou Q J, Pei F P, *et al*. 2013. Destruction of the North China Craton: Delamination or thermal/chemical erosion? Mineral chemistry and oxygen isotope insights from websterite xenoliths[J]. Gondwana Research, 23: 119~129.

Xu Z, Zhao Z F and Zheng Y F. 2012. Slab-mantle interaction for thinning of cratonic lithospheric mantle in North China: Geochemical evidence from Cenozoic continental basalts in central Shandong[J]. Lithos, 146~147: 202~217.

Yan J, Chen J F and Xie Z. 2003. Mantle derived xenoliths in the late Cretaceous basalts in eastern Shandong: New constraints on the timing of lithospheric thinning in east China[J]. Chinese Science Bulletin, 48: 1570~1574.

Yang Q L, Zhao Z F and Zheng Y F. 2012a. Modification of subcontinental lithospheric mantle above continental subduction zone: Constraints from geochemistry of Mesozoic gabbroic rocks in southeastern North China[J]. Lithos, 146~147: 164~182.

Yang Q L, Zhao Z F and Zheng Y F. 2012b. Slab-mantle interaction in continental subduction channel: Geochemical evidence from Mesozoic gabbroic intrusives in southeastern North China[J]. Lithos, 155: 442~460.

Yang Y H, Wu F Y, Wilde S A, *et al*. 2009. In situ perovskite Sr-Nd isotopic constraints on the petrogenesis of the Ordovician Mengyin kimberlites in the North China Craton[J]. Chemical Geology, 264: 24~42.

Ying J F, Zhang H F, Kita N, *et al*. 2006. Nature and evolution of Late Cretaceous lithospheric mantle beneath the eastern North China Craton: Constraints from petrology and geochemistry of peridotitic xenoliths from Junan, Shandong province, China[J]. Earth and Planetary Science Letters, 244: 622~638.

Ying J F, Zhou X H and Zhang H F. 2004. Geochemical and isotopic investigation of the Laiwu-Zibo carbonatites from western Shandong Province, China, and implications for their petrogenesis and enriched mantle source[J]. Lithos, 75: 413~426.

Yu S Y, Xu Y G, Ma J L, *et al*. 2010. 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[J]. Earth and Planetary Science Letters, 297: 413~422.

Zhang H F, Goldstein S L, Zhou X H, *et al*. 2008. Evolution of subcontinental lithospheric mantle beneath eastern China: Re-Os isotopic evidence from mantle xenoliths in Paleozoic kimberlites and Mesozoic basalts[J]. Contributions to Mineralogy and Petrology, 155: 271~293.

Zhang H F, Mattey D P, Grassineau N, *et al*. 2000. Recent fluid processes in the Kaapvaal Craton, South Africa: coupled oxygen isotope and trace element disequilibrium in polymict peridotites[J]. Earth and Planetary Science Letters, 176: 57~72.

Zhang H F, Sun M, Zhou X H, *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 [J]. Contributions to Mineralogy and Petrology, 144: 241~253.

Zhang H F, Sun M, Zhou X H, *et al*. 2003. Secular evolution of the lithosphere beneath the eastern North China Craton: evidence from Mesozoic basalts and high-Mg andesites[J]. Geochimica et Cosmochimica Acta, 67: 4 373~4 387.

Zhang H F, Sun M, Zhou M F, *et al*. 2004. Highly heterogeneous late Mesozoic lithospheric mantle beneath the North China Craton, evidence from Pb-Sr-Nd isotopic systematics of mafic igneous rocks[J]. Geological Magazine, 141: 55~62.

Zhang J, Zhang H F, Kita N, *et al*. 2011. Secular evolution of the lithospheric mantle beneath the eastern North China craton: evidence from peridotitic xenoliths from Late Cretaceous mafic rocks in the Jiaodong region, east-central China[J]. International Geology Review, 53: 182~211.

Zhang J, Zhang H F, Ying J F, *et al*. 2008. Contribution of subducted Pacific slab to Late Cretaceous mafic magmatism in Qingdao region, China: A petrological record[J]. Island Arc, 17: 231~241.

Zhang J J, Zheng Y F and 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 [J]. Lithos, 110: 305~326.

Zhang R Y, Rumble D, Liou J G, *et al*. 1998. Low $\delta^{18}O$, ultrahigh-P garnet-bearing mafic and ultramafic rocks from Dabie Shan, China [J]. Chemical Geology, 150: 161~170.

Zhao G C, Wilde S A, Cawood P A, *et al*. 2001. Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P-T path constraints and tectonic evolution[J]. Precambrian Research, 107: 45~73.

Zhao Z F, Zheng Y F, Wei C S, *et al*. 2005. Zircon U-Pb age, element and C-O isotope geochemistry of post-collisional mafie-ultramafic rocks from the Dabie orogen in east-central China[J]. Lithos, 83: 1~28.

Zhao Z F, Zheng Y F, Zhang J, *et al*. 2012. Syn-Yexhumation magmatism during continental collision: Evidence from alkaline intrusives of Triassic age in the Sulu orogen[J]. Chemical Geology, 328: 70~88.

Zheng J, Griffin W L, O'Reilly S Y, *et al*. 2006. Mineral Chemistry of Peridotites from Paleozoic, Mesozoic and Cenozoic Lithosphere: Constraints on Mantle Evolution beneath Eastern China[J]. Journal of Petrology, 47: 2 233~2 256.

Zheng Y F. 2012. Metamorphic chemical geodynamics in continental subduction zones[J]. Chemical Geology, 328: 5~48.

Zheng Y F, Yang J J, Gong B, *et al*. 2003. Partial equilibrium of radiogenic and stable isotope systems in garnet peridotite during UHP metamorphism[J]. American Mineralogists, 88: 1 633~1 643.

Zheng J, O'Reilly S Y, Griffin W L, *et al*. 2001. Relict refractory mantle beneath the eastern North China Block: significance for lithospheric evolution[J]. Lithos, 57: 43~66.