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华北地幔橄榄岩捕虏体的矿物组成特征与成因意义

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摘要: 地幔橄榄岩捕虏体是起源于地幔的岩浆在上升过程中携带的岩石圈地幔的碎块, 因此是岩石圈地幔的直接样品, 具有地球深部的探针之称, 为岩石圈地幔特征与演化研究提供了关键信息。本文综述了华北克拉通地幔橄榄岩捕虏体的岩石类型、矿物组成特征与成因意义, 并指出熔体改造(熔-岩反应)在华北东部岩石圈地幔从克拉通型转变为大洋型的过程中所起的重要作用; 华北中部和西北部边缘地区既有大量古老、难熔的残留地幔, 也有相对年轻的、具有大洋型特征的饱满地幔, 反映了熔体对古老岩石圈地幔长期改造的结果。参与地幔改造作用的熔体有多个来源, 包括再循环的古老地壳、蚀变洋壳和大洋沉积物等。地幔改造作用发生的时间、期次及其对岩石圈地幔的影响机制有待进一步研究。

关键词: 地幔橄榄岩捕虏体; 矿物组成; 熔-岩反应; 岩石圈地幔; 华北克拉通

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Mineral composition characteristics and genetic significances of mantle peridotite xenoliths in the North China Craton

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Abstract: Mantle peridotite xenoliths are fragments of the lithospheric mantle which were carried by the mantle-derived magmas in their ascent process. Therefore, they are direct samples of the lithospheric mantle and are known as probes for the deep Earth. They can provide key information for studying the characteristics and evolution of the lithospheric mantle. This article summarizes the rock types, mineral composition characteristics, and genetic significances of mantle peridotite xenoliths in the North China Craton, and points out that the mantle modification by melts (melt-rock reaction) played an important role in the modification process of lithospheric mantle beneath the eastern part of the North China Craton from typically cratonic type to oceanic type. There are a large amount of ancient and refractory residual mantle, as well as relatively young and oceanic-type fertile mantle in the central part and northwestern margin of North China Craton, reflecting the long-term modification of ancient lithospheric mantle by various melts. The melts involved in the mantle modification process were derived from multiple sources including the recycled ancient crust, altered oceanic crust, and oceanic sediments. Further researches should be focused on the timing and stages of the mantle modification and its influencing mechanisms on the lithospheric mantle beneath the North China Craton.

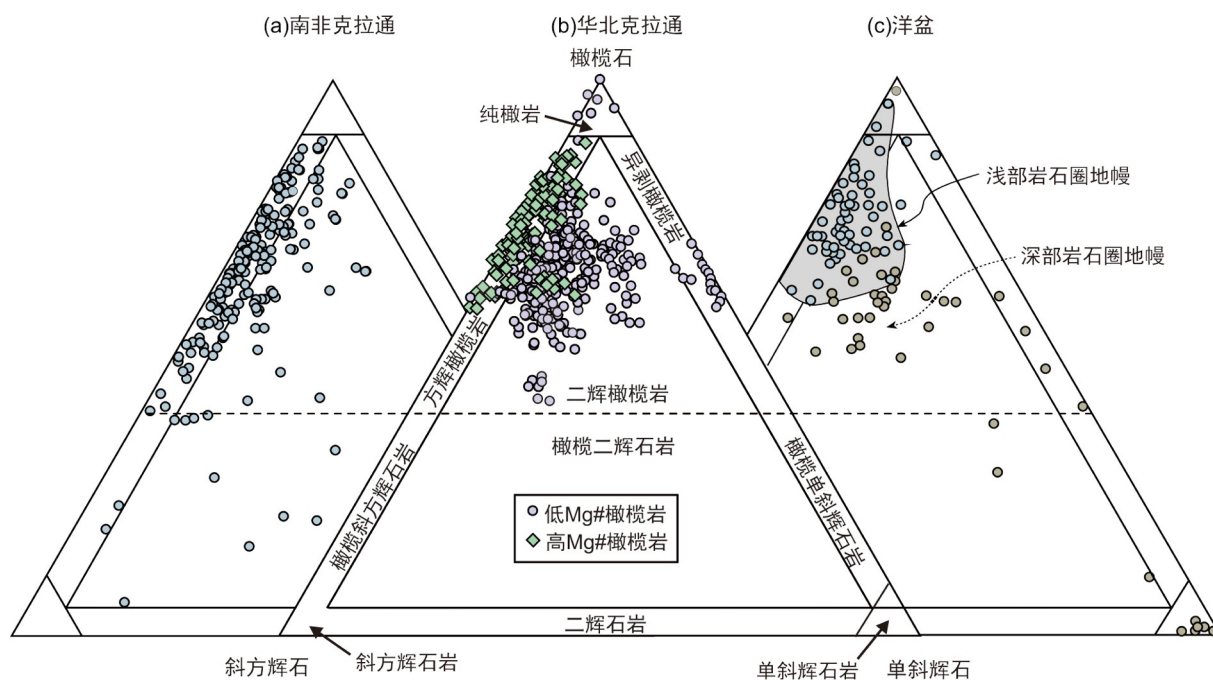
Keywords: mantle peridotite xenolith; mineral composition; melt-rock interaction; Lithospheric mantle; North China Craton

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状斑晶出现。新鲜岩石为黑绿色或橄榄绿色。地幔橄榄岩中的橄榄石一般为镁橄榄石和贵橄榄石, 辉石为斜方辉石和单斜辉石; 少量矿物有石榴石、云母、斜长石等; 副矿物为铬尖晶石、钛铁矿以及其他金属矿物。橄榄石的含量可占40%~90%。根据橄榄石的含量, 橄榄岩可分为纯橄岩和辉石橄榄岩。按辉石种类和含量, 橄榄岩可进一步划分为方辉橄榄岩(主要由橄榄石和斜方辉石组成)、单斜辉石橄榄岩(又称异剥橄榄岩, 主要由橄榄石和单斜辉石组成)、二辉橄榄岩(单斜辉石和斜方辉石两者含量近于相等)。如果岩石中的矿物以辉石为主, 则称为辉石岩(图2)。



数据来源: 南非克拉通和洋盆橄榄岩^[18], 华北克拉通橄榄岩^[6-43]; 底图据文献^[18,44]修改。

图2 华北与南非克拉通橄榄岩捕虏体以及深海橄榄岩类型对比

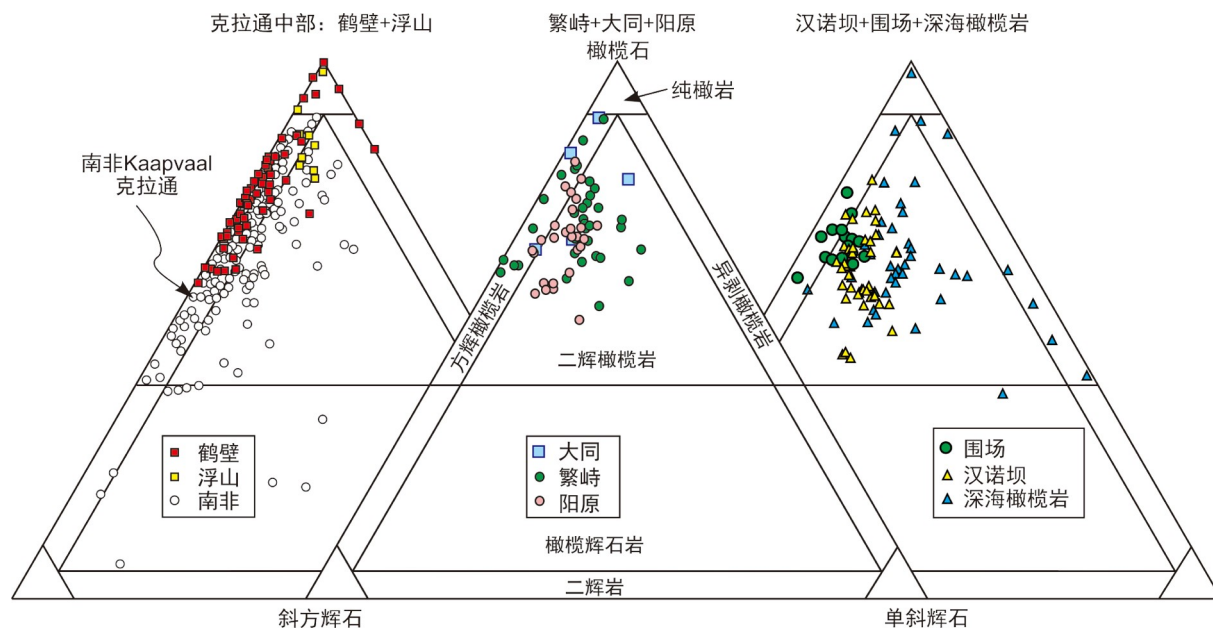
Fig. 2. Comparison of rock types among peridotite xenoliths from the Kaapvaal Craton in South Africa (a), the North China Craton (b), and peridotites from oceanic basins (c)

由华北克拉通地幔橄榄岩捕虏体的研究可知, 产于华北古生代金伯利岩中的地幔橄榄岩捕虏体主要由橄榄石和斜方辉石组成, 岩石类型主要为方辉橄榄岩(图2中的高Mg#橄榄岩), 橄榄岩中橄榄石的Fo值为91~94^[60,68], 具有难熔的组成特征。这与世界上典型的克拉通(如图2a中的南非Kaapvaal克拉通, 其岩石圈地幔主要由难熔的方辉橄榄岩组成)具有相似的特征, 指示华北古生代具有典型的克拉通型岩石圈地幔; 而与大洋型岩石圈地幔(主要由饱满的二辉橄榄岩组成)有着明显的区别(图2)。

2 华北克拉通中部地区中-新生代地幔橄榄岩捕虏体矿物组成特征

河南鹤壁地区位于华北克拉通中部, 该区新生代玄武岩携带的橄榄岩捕虏体可分为两类: 高Mg#橄榄岩($Fo > 91$)和低Mg#橄榄岩($Fo < 91$)。其中, 具有高Mg#特征($Fo > 92$)的橄榄岩捕虏体通常被认为是古老岩石圈地幔的残留^[7,24,69]; 与鹤壁相邻的河北浮山闪长岩中的地幔橄榄岩捕虏体被认为是该区晚中生代古老岩石圈地幔的残留^[11]。鹤壁具有低Mg#特征的橄榄岩代表新生岩石圈地幔组分^[6], 部分橄榄岩捕虏体中含有交代矿物金云母^[70], 推测这些低Mg#橄榄岩很可能是高Mg#橄榄岩与熔体反应转变而来的, 代表被改造了的古老岩石圈地幔。鹤壁玄武岩中高Mg#橄榄岩占主

体的事实 (图3) 指示华北克拉通中部鹤壁地区岩石圈地幔主要为残留的古老地幔, 而被改造的二辉橄榄岩地幔比较有限^[10,12]。



数据来源: 南非克拉通和深海橄榄岩^[18], 鹤壁^[6-10], 浮山^[11], 繁峙^[8,9,12,13], 大同^[8], 阳原^[8,13-16], 汉诺坝^[8,17-22], 围场^[23]; 底图修改自文献^[10,18,44]。

图3 华北中部晚中生代-新生代地幔橄榄岩捕虏体的岩石类型

Fig. 3. Triangular diagrams of rock types of the Late Mesozoic-Cenozoic mantle peridotite xenoliths in the central part of the North China Craton

山西繁峙地区的地幔橄榄岩捕虏体包括尖晶石相的二辉橄榄岩和方辉橄榄岩, 它们也可分为高Mg#和低Mg#两类, 其中前者占绝大多数 (图3)。方辉橄榄岩因为具有难熔的矿物组成 ($Fo > 91$), 与全球典型克拉通地幔橄榄岩相似; 而且, 繁峙橄榄岩的Re-Os同位素数据给出了古元古代、甚至太古代的熔体抽取年龄^[8,13]; Gao等^[71]研究认为华北克拉通古老岩石圈地幔的形成时间为2.7 Ga, 在大约1.9 Ga和220 Ma左右发生了两次地幔置换作用。上述证据表明, 繁峙方辉橄榄岩捕虏体代表华北中部残留的古老地幔; 二辉橄榄岩捕虏体中的橄榄石具有较低的Fo (< 91), 与华北克拉通东部新生的岩石圈地幔具有相似性。山西大同的地幔橄榄岩捕虏体与繁峙地区的橄榄岩的矿物组成具有很大的相似性^[8], 表明大同地区也存在古老岩石圈地幔的残留。

河北阳原地区的地幔橄榄岩捕虏体也可分为高Mg#和低Mg#两种类型, 在低Mg#橄榄岩中发现了地幔交代作用的指示矿物金云母和角闪石, 其低Mg#、富铁特征表明阳原地区的岩石圈地幔经历了富铁熔体的改造^[16]。阳原地区高Mg#橄榄岩由于具有难熔的组成特征, 也被认为是本区残留的古老岩石圈地幔, 这些特征与橄榄岩捕虏体所具有的古老的Re-Os同位素年龄相一致^[8,13]。而且, 阳原和繁峙橄榄岩捕虏体具有类似于EM1型富集地幔端元的Sr-Nd同位素组成^[12,14], 进一步指示这些地区存在古老的克拉通型岩石圈地幔。

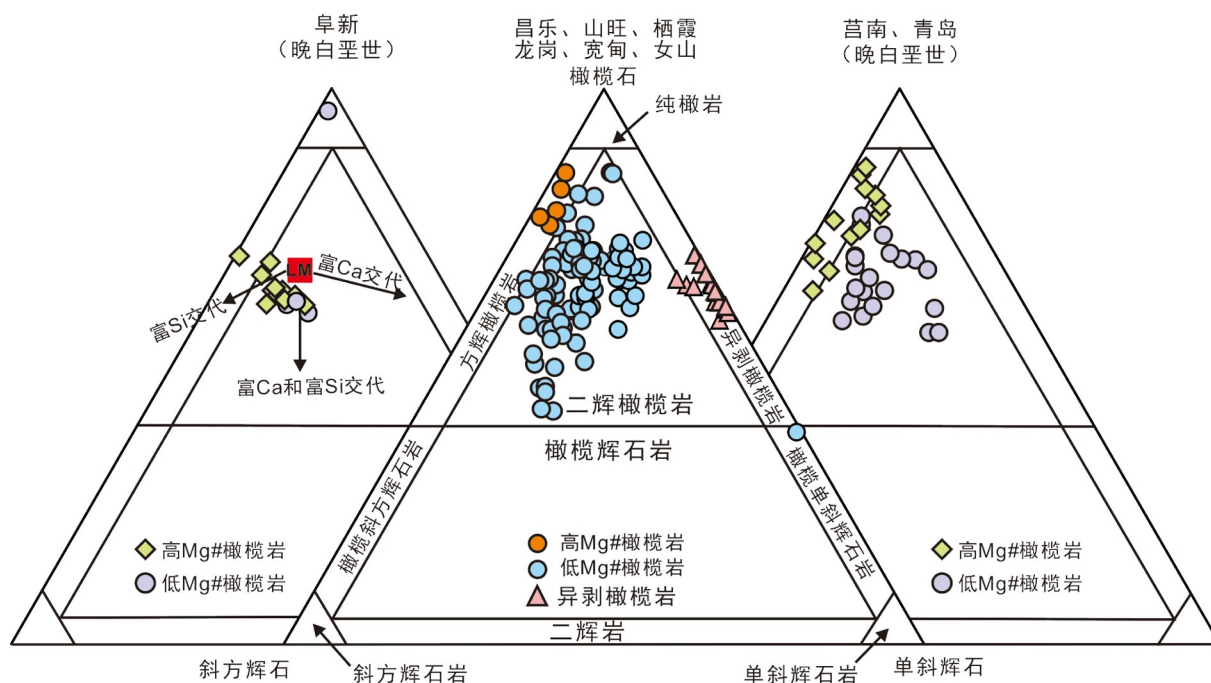
相比之下, 位于华北克拉通中部带北缘汉诺坝地区的地幔捕虏体以饱满的尖晶石相二辉橄榄岩 ($Fo < 91$) 为主, 几乎没有方辉橄榄岩, 其矿物组成明显不同于克拉通型岩石圈地幔的特征 (图3)。汉诺坝橄榄岩的Os同位素数据表明, 华北克拉通中部的古老岩石圈地幔在古元古代 (~ 1.9 Ga) 和中生代 (~ 220 Ma) 曾发生过置换作用^[71]。Rudnick等^[20]认为汉诺坝橄榄岩捕虏体是古元古代原始地幔发生不同程度熔融 (0~25%) 的残余, 近期受到了地幔交代事件的影响。非传统稳定同位素

(Li、Mg、Fe、Ba和Zn等)地球化学研究表明, 华北中部岩石圈地幔不仅经历了来自软流圈地幔熔体的交代作用, 还经历了来自俯冲的蚀变洋壳和大洋沉积物衍生熔体的改造作用^[21,22,72-74]。例如, 位于华北中部的汉诺坝、繁峙和鹤壁地区的地幔橄榄岩具有极端轻Li同位素组成特征, 暗示它们曾经历来自再循环的蚀变洋壳物质的改造过程^[9,21,75-77]; 橄榄岩异常变化的Mg-Fe-Ca等同位素特征也表明其受到地幔交代作用的影响^[22,43,72,78]; 繁峙新生代玄武岩重的Zn同位素^[79]、轻Ba^[73]和Ca^[80]同位素组成特征也反映了再循环的俯冲物质对地幔组成的改造作用。

综上所述, 华北克拉通中部地区晚中生代-新生代玄武质岩石中地幔橄榄岩捕虏体的矿物组成和年龄特征表明, 华北中部晚中生代-新生代时期仍然保留有古老的岩石圈地幔, 而且该区的古老地幔曾遭受不同来源熔体的多期改造作用^[67,81]。

3 华北东部地区中-新生代地幔橄榄岩捕虏体矿物组成特征

位于辽宁省阜新市碱锅村的碱性玄武岩具有100 Ma的K-Ar年龄, 即为晚中生代火山活动的产物^[82-84], 玄武岩中的地幔橄榄岩捕虏体以二辉橄榄岩为主, 含有少量方辉橄榄岩和纯橄岩(图4)。根据矿物组成特征, 阜新地区的地幔橄榄岩捕虏体可以分为三种类型^[24]: 1) 橄榄石Fo>92的方辉橄榄岩, 代表被改造的难熔古老地幔的残留; 2) 橄榄石Fo为90的二辉橄榄岩, 代表饱满的岩石圈地幔; 3) 橄榄石Fo很低的(大约为86)二辉橄榄岩, 代表岩石圈地幔与熔体或寄主岩反应的产物, 反应熔体具有富Ca和Si的特点, 反映了碳酸岩熔体交代的特征^[24]。由于饱满的二辉橄榄岩占绝大多数, 因此阜新岩石圈地幔在晚中生代以新生岩石圈地幔为主, 即阜新岩石圈地幔在晚白垩世主体上由古老难熔的地幔转变为新生饱满的大洋型地幔, 表明阜新地区岩石圈地幔转变至少发生在晚白垩世, 甚至更早。



数据来源: 阜新^[24], LM表示岩石圈地幔, 昌乐^[25,26], 山旺和栖霞^[20,27-29], 龙岗辉南^[30,31], 宽甸^[32], 女山^[33,34], 莒南^[35], 青岛^[36]; 底图修改自文献^[44]。

图4 华北克拉通东部晚白垩世-新生代地幔橄榄岩捕虏体的岩石类型

Fig. 4. Triangular diagrams of rock types of the Late Cretaceous-Cenozoic mantle peridotite xenoliths in the eastern part of the North China Craton

在山东莒南地区K-Ar年龄为67 Ma的基性脉岩中,发现的地幔橄榄岩捕虏体几乎全部为尖晶石相二辉橄榄岩,没有方辉橄榄岩^[35]。根据矿物组成,莒南橄榄岩捕虏体也可以分为两种类型:低Mg#橄榄岩($Fo < 91.0$)和高Mg#橄榄岩($Fo > 91.0$),其中,低Mg#二辉橄榄岩占绝大多数,仅有少量高Mg#橄榄岩。橄榄岩的矿物组成特征表明,低Mg#橄榄岩代表新生岩石圈地幔,而高Mg#橄榄岩代表受到熔体改造的古老地幔的残留^[35]。

山东青岛地区晚白垩世玄武岩的K-Ar年龄约为78 Ma^[85],玄武岩所携带的低Mg#橄榄岩与莒南低Mg#橄榄岩具有相似性,代表新生的岩石圈地幔;高Mg#橄榄岩的组成特征与古老岩石圈地幔相似,代表古老岩石圈地幔的残留^[36]。结合阜新和莒南地区地幔橄榄岩捕虏体的特征,得到如下认识:华北克拉通东部岩石圈地幔的组成和属性在晚中生代发生了重大转变,主体上由古老难熔的克拉通型地幔转变为饱满的大洋型岩石圈地幔^[76,86]。郭锋等^[87]对山东晚白垩世莒南和青岛玄武岩中地幔捕虏体的橄榄石开展了原位氧同位素分析,发现了较多的低 $\delta^{18}O$ 橄榄石,反映了太平洋板块俯冲板片熔体改造的影响。

在华北克拉通东部郯庐断裂沿线及其邻近地区,新生代玄武岩的分布比较集中。而且,该区的新生代玄武岩大多为碱性玄武岩,普遍含有地幔橄榄岩捕虏体,如安徽女山^[33,34]、山东昌乐^[25,26]、山旺和栖霞^[20,27-29],以及辽宁宽甸^[32]和吉林龙岗^[30,31]等地,均发现了大量具有低Fo($Fo < 91$)特征的地幔橄榄岩捕虏体。其中,位于郯庐断裂带内部的山东昌乐-临朐地区的地幔橄榄岩捕虏体具有非常低的Fo值(约83~88)^[26,88]。上述地区地幔橄榄岩的Li^[31,89]、Mg^[25]、Fe^[43,78]和Sr^[90-92]同位素地球化学研究结果和岩石学特征共同表明,在郯庐断裂带沿线,新生代岩石圈地幔主要由类似于大洋型的新生地幔构成,而且近期遭受了再循环的俯冲大洋板片和软流圈等不同来源的熔体的强烈改造作用^[76,90,91]。

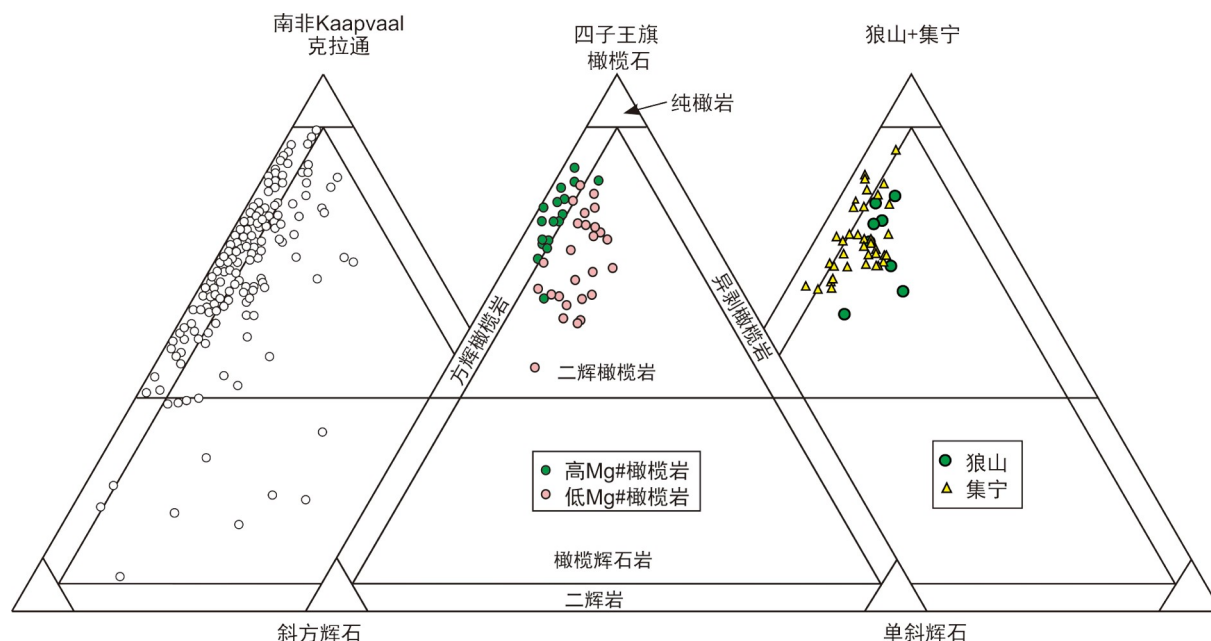
4 华北克拉通西北缘中-新生代地幔橄榄岩捕虏体矿物组成特征

位于华北克拉通西北缘狼山地区的晚白垩世玄武岩^[39,93]、四子王旗^[37,94]和集宁地区的新生代玄武岩^[42,70]中含有的地幔橄榄岩捕虏体也可分为高Mg#($Fo > 91$)和低Mg#($Fo < 91$)两种类型,在数量上以低Mg#二辉橄榄岩为主。高Mg#橄榄岩出现在四子王旗地区,岩石类型主要为方辉橄榄岩(图5)。根据新近的研究结果,华北克拉通西北缘岩石圈地幔也经历了熔体的改造过程。该区具有高Mg#特征的地幔橄榄岩捕虏体也代表古老岩石圈地幔的残留,而具有低Mg#特征的地幔橄榄岩捕虏体则代表经历熔体改造的古老岩石圈地幔,即具有“改造型”岩石圈地幔的特征^[45]。虽然它们具有低Mg#特征,但其Re-Os同位素分析结果却给出了元古宙甚至太古宙的古老年龄,表明华北克拉通西北缘在晚白垩世-新生代仍然存在古老岩石圈地幔的残余,由于经历熔体改造作用,从而具有相对饱满的组成特征^[45]。

考虑到华北克拉通东部晚白垩世-新生代岩石圈地幔主体上是由年轻、饱满的二辉橄榄岩组成,具有类似于大洋型岩石圈地幔的特征,因此可将整个华北东部(太行山重力梯度带以东地区)视为类似于大洋型岩石圈地幔分布区(图1中蓝色填充部分)。由于华北克拉通中部地区既有大量古老地幔的残留,也有古老地幔遭受熔体改造的特征,因此将华北中部带附近的岩石圈地幔视为改造型岩石圈地幔,介于东部类似于大洋型岩石圈地幔和西部(鄂尔多斯陆块)克拉通型岩石圈地幔之间的过渡类型^[44,67]。

5 结语

地幔橄榄岩捕虏体的矿物组成特征可以很好地反映岩石圈地幔的属性及其经历的演化过程。地



数据来源: 南非克拉通^[18], 四子王旗^[37,38], 狼山^[39,40], 集宁^[8,41-43]; 底图修改自文献^[18,45]。

图5 华北克拉通西北缘地幔橄榄岩捕虏体的岩石类型

Fig. 5. Petrological classification diagrams of the Late Cretaceous-Cenozoic peridotite xenoliths from the northwestern margin of the North China Craton

幔橄榄岩捕虏体的研究表明, 多期次强烈的熔体改造作用最终导致华北克拉通东部岩石圈地幔组成特征的重大转变。总体上, 华北古生代具有克拉通型的岩石圈地幔, 而自晚白垩世-新生代以来, 华北克拉通东部岩石圈地幔转变为主要由年轻、饱满的二辉橄榄岩组成、具有类似于大洋型特征的岩石圈地幔。华北中部地幔橄榄岩捕虏体的矿物组成特征表明它们也经历了不同熔体的多期次改造过程, 包括来源于再循环的大陆地壳、大洋地壳和沉积物的衍生熔体, 以及软流圈熔/流体的改造作用。近年来, 以地幔橄榄岩矿物组成特征研究为基础, 岩石学与地球化学、宏观与微区原位研究等多种方法的综合运用, 拓宽了地幔橄榄岩、岩石圈地幔特征与演化过程的研究领域, 加深了对克拉通和岩石圈地幔演化规律的认识。然而, 地幔交代作用发生的时间和期次、交代熔体的规模和作用过程及其对岩石圈地幔演化的影响等相关科学问题还需开展深入研究。由于篇幅所限, 本文主要总结了华北地幔橄榄岩捕虏体矿物组成特征方面的若干研究成果。有关华北克拉通地幔橄榄岩的研究工作已开展40余年, 成果非常丰富, 本文所述内容可能挂一漏万, 敬请各位读者不吝指正。

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