科学通报
快 讯
《中国科学》杂志社
SCIENCE CHINA PRESS

石榴子石: 麻粒岩地体进变质记录的档案库

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2022-07-28 收稿, 2022-10-03 修回, 2022-10-05 接受, 2022-10-08 网络版发表
国家自然科学基金(41890834, 41702196)资助

摘要 麻粒岩地体是否可以保留进变质记录是变质岩石学中的一个难点课题, 相关研究很是薄弱. 这主要源于麻粒岩地体本身的变质记录具有明显信息不对称性: 它们的矿物组合和矿物成分一般被认为代表了峰期变质或退变质阶段的信息, 几乎没有进变质信息. 但是这种习惯性认识需要谨慎对待. 来自华北克拉通晋冀交界地区麻粒岩地体的变质作用研究结果表明, 石榴子石在一定程度上可以作为“抗温抗压容器”, 保留麻粒岩峰期之前的部分进变质记录. 通过对泥质麻粒岩的求证性研究和石榴基性麻粒岩的探索性研究, 证实了研究区麻粒岩的进变质信息可以像基因片段一样部分地烙印在岩石中石榴子石的结构(如矿物包裹体群的分布型式、组合)和某些成分环带中. 有时, 即使主量元素生长环带很难保存, 某些微量元素环带仍然可以抵抗峰期和退变质阶段的改造. 它们促使石榴子石成为麻粒岩地体进变质信息的重要档案库. 该研究表明, 高温变质作用并不一定可以将麻粒岩地体中石榴子石多世代生长信息完全重置, 同时也指示利用石榴子石核部成分计算麻粒岩峰期变质条件需要谨慎.

关键词 麻粒岩地体, 进变质, 石榴子石, 多世代生长

麻粒岩地体是否可以保存进变质记录是变质作用研究中的一个难点课题，一直以来很少有研究．这主要与麻粒岩地体的变质记录具有不对称性有关，峰期之前变质信息易于被高温重置而几乎不保留，现存矿物组合和矿物成分常常反映了峰期变质或退变质阶段的信息[1]．这种特征明显不同于中、低级变质岩的记录，与麻粒岩相变质温度高，反应速率和扩散速率快有关．相平衡模拟结果认为麻粒岩的矿物组合应该代表接近固相线之上的矿物组合[2]．极少保存进变质信息几乎成为麻粒岩变质作用研究的一种习惯性假设，如文献中多数麻粒岩地体的P-T轨迹极少有进变质阶段P-T矢量[1,3]．然而这种习惯性假设需要谨慎对待．

华北克拉通中北部晋冀交界地区广泛出露古元古代麻粒岩地体，代表性岩石为泥质麻粒岩(孔兹岩系)和石榴基性麻粒岩，是解读早前寒武纪变质作用及其构造过程的理想研究对象．然而，由于多阶段变质叠加强烈，峰期前变质记录薄弱，造成对峰期前的视地热梯度、P-t历史(俯冲速率)和T-t历史(升温速率)等知之甚少，制约了对古元古代变质-构造过程及其动力学背景和机制的理解．近年来，我们对研究区两类麻粒岩的进变质历史进行了一些初步工作：针对作为麻粒岩相变质表壳岩的泥质麻粒岩开展了求证性研究，因为这类岩石必然经历过从地表埋深(或俯冲)至深部的进变质阶段．然而这段信息是否像前述的习惯性假设一样被完全重置以至于无法保留，还是有迹可循？研究结果表明，泥质麻粒岩并非达到完全均一化，部分矿物(如石榴子石)仍然保留了多世代生长信息．根据泥质麻粒岩的研究思路，我们进一步对研究区出露典型的岩墙状或透镜体状(原岩被认为是辉长岩)的石榴基性麻粒岩开展了探索性研究，旨在厘清它们有无从地壳浅部到深部的构造过程，结果发现其中的石榴子石记录了这些岩石升温升压的进变质信息．它们为华北克拉通古元古代晋冀活动带的俯冲-聚

引用格式: 吴佳林, 翟明国. 石榴子石: 麻粒岩地体进变质记录的档案库. 科学通报, 2022, 6
Wu J L, Zhai M G. Garnet: The archive of prograde metamorphic records of granulite-facies terranes (in Chinese). Chin Sci Bull, 2022, 67, doi: 10.1360/TB-2022-0799

合过程提供了直接的变质作用记录. 本文对这些阶段性研究成果予以介绍，希望在麻粒岩变质作用的研究中引起关注.

晋冀交界地区的大同和怀安两地孔兹岩系中泥质麻粒岩的矿物组合为石榴子石、矽线石、钾长石、斜长石、石英、黑云母、金红石和钛铁矿等，被解释为代表了温度峰期或接近峰期的矿物组合. 相平衡模拟和金红石Zr温度计研究表明，峰期变质温度可达880~900°C，甚至达到>900°C[4~6]. 如此高温变质条件下，很难相信其会保留进变质信息，石榴子石相对均一的主量元素成分特征似乎也支持了这种观点[7,8].

详细的观察发现，泥质麻粒岩中石榴子石内部矿物包裹体群在分布型式、种类及矿物组合上呈带状有规律分布，构成特征的结构环带：核部为筛状变晶结构，以石英为主；幔部包裹体较少，有少量石英，靠近边部出现蓝晶石、(多硅)白云母、钾长石组合；边部包裹体出现针柱状矽线石(图1(a))，更多信息见文献[4,5,9]. 这些不同组合的矿物包裹体群对应于多个变质阶段，支持石榴子石的多世代生长(图1(b))[4,5,9]. 石榴子石的主量元素呈均一化(图1(c))，而某些重稀土元素从核部至边部表现出明显的钟状环带，强烈富集于核部(图1(d)). 石榴子石主量与微量元素的这种脱耦现象与高温条件下二价主量元素的扩散速率较某些三价微量元素快0.5~1.5个数量级有关[10]，因而重稀土元素更有潜力记录石榴子石的生长信息，如图1(d)中Yb的环带对应于进变质过程中石榴子石对重稀土元素的强烈结晶分异作用[11].

综上，尽管主量元素成分发生了高温均一化，石榴子石的结构环带和重稀土元素环带仍然能够支持石榴子石伴随进变质作用连续生长，为探索研究区泥质麻粒岩的进变质历史提供了直接的岩石学和矿物化学证据. 在此基础上，根据不同世代石榴子石的残余包裹体矿物组合、生长体积，结合相平衡模拟半定量地确定了麻粒岩进变质阶段的P-T矢量(图1(e))[4,9].

通过这项研究，本文得出一个初步认识：与进变质信息消失殆尽的基质矿物相比，石榴子石像一个“抗温抗压容器”，其中的矿物包裹体群及某些扩散速率较缓慢的微量(如重稀土)元素，更有潜力保留早期变质历史. 因此，对石榴子石开展详细研究较基质矿物更有益于揭示麻粒岩的进变质历史.

研究区石榴基性麻粒岩主要以岩墙状或透镜体状产出于晚太古代花岗质片麻岩中，原岩被认为是深成岩[13]，目前从构造上很难确定它们是否存在从地壳浅处到深处的经历[14]. 有无进变质历史对理解这些石榴基性麻粒岩的构造过程尤为重要[14]. 然而，关于它们是否存在进变质过程的矿物学和岩石学证据鲜有报道与研究. 基于泥质麻粒岩的研究思路，我们对研究较为成熟的经典地区——怀安和北恒山的石榴基性麻粒岩分别开展了进变质历史的探索性研究.

与泥质麻粒岩一样，两地石榴基性麻粒岩中部分石榴子石表现出了类似的结构环带：核部包裹体较多，出现石英、斜长石、单斜辉石和磷灰石，有时有普通角闪石，含钛矿物为榍石和钛铁矿；幔部包裹体较少，有少量石英、单斜辉石或斜长石；靠近边部出现金红石包裹体，最边部呈港湾状，发生明显分解，最外侧形成斜方辉石+斜长石后成合晶或冠状体，内侧靠近石榴子石边部形成角闪石+斜长石±黑云母±钛铁矿后成合晶(图2(a)~(c))[15~18].

所选怀安石榴基性麻粒岩中石英、榍石仅出现在石榴子石中，在基质中未见到(图2(a))[16]；而且单斜辉石包裹体与基质中辉石成分明显不同，表现出高铝特征(Al_2O_3高达8%(wt)，基质中一般<3%(wt))[15,17]. 部分石榴子石的锰铝榴石组分呈现从核部至幔部有微弱的钟型分布特征，镁铝榴石组分由核部至幔部升高，尽管该成分环带受扩散作用的影响可能较大，但仍不影响原先石榴子石生长环带的大致样式(图2(d))[17]. 石榴子石的重稀土元素(如Yb)从核部至近边部呈钟型分布，边部因分解作用形成再吸收边；核部重稀土元素含量高于未受再吸收影响的近边部，核部中稀土元素含量低于近边部；边部因受再吸收作用其稀土配分曲线介于核部与近边部之间(图2(f)). 重稀土元素钟型环带样式指示石榴子石生长伴随强烈的结晶分异作用. 同时，核部与近边部中稀土元素含量的差别，指示二者石榴子石生长的变质反应存在差异，可能与石榴子石的生长过程中伴随着富集中稀土元素的普通角闪石的不断消耗有关. 以上证据支持怀安基性麻粒岩中石榴子石核部至幔部形成于进变质升温升压阶段(图2(g))[15,17].

所选北恒山石榴基性麻粒岩中石榴子石核部为筛状变晶结构，含有大量石英，含钛矿物为榍石、钛铁矿；幔部至边部包裹体稀少，出现少量石英、单斜辉石和金红石等，外边部已分解为港湾状(图2(b)). 石榴子石的主量元素表现出典型的生长环带，受扩散作用影响较弱：锰铝榴石组分从核部至幔部呈钟型；镁铝榴石从核部先平缓增加，再急剧增加；钙铝榴石呈马鞍状，先缓慢增加至最高点，再急剧减少(图2(e))[18,19]. 上述结构和成分环带可以解释为石榴子石记录了从早期低温低压阶段$M_{1\text{-}1}$(对应于核部点P0)升温升压至$M_{1\text{-}2}$(对应于点P1)至(接近)峰期阶段($M_{2\text{-}1}$，对应于点P2；峰期$M_{2\text{-}2}$，对应于点P4，即原始石榴子石边部)的过程(图2(c)，(e))，详细分析见文献[18]. 石榴子石现存边界至原始边界(点P4)之间的斜方辉石+斜长石的后成合晶，以及角闪石+黑云母+斜长石的后成合晶，分别代表了近等温降压(M_3)和降温阶段(M_4). 同时，相平衡模拟表明进变质阶段石榴子石的体积随变质温压条件升高而增加，石英则不断消耗[18]. 实际样品中不同世代石榴子石不断生长，体积连续增加，其中的石英包裹体由核部至幔部减少均指示变质P-T条件升高[18]. 结合石榴子石的成分环带、不同世代石榴子石的体积和单斜辉石成分的回算，半定量地估计了北恒山石榴基性麻粒岩的进变质P-T矢量(图2(g))[18].

晋冀交界地区泥质麻粒岩进变质作用的求证性研究和石榴基性麻粒岩的探索性工作，揭示麻粒岩地体可以在一定程度上保留峰期前的进变质历史. 尽管

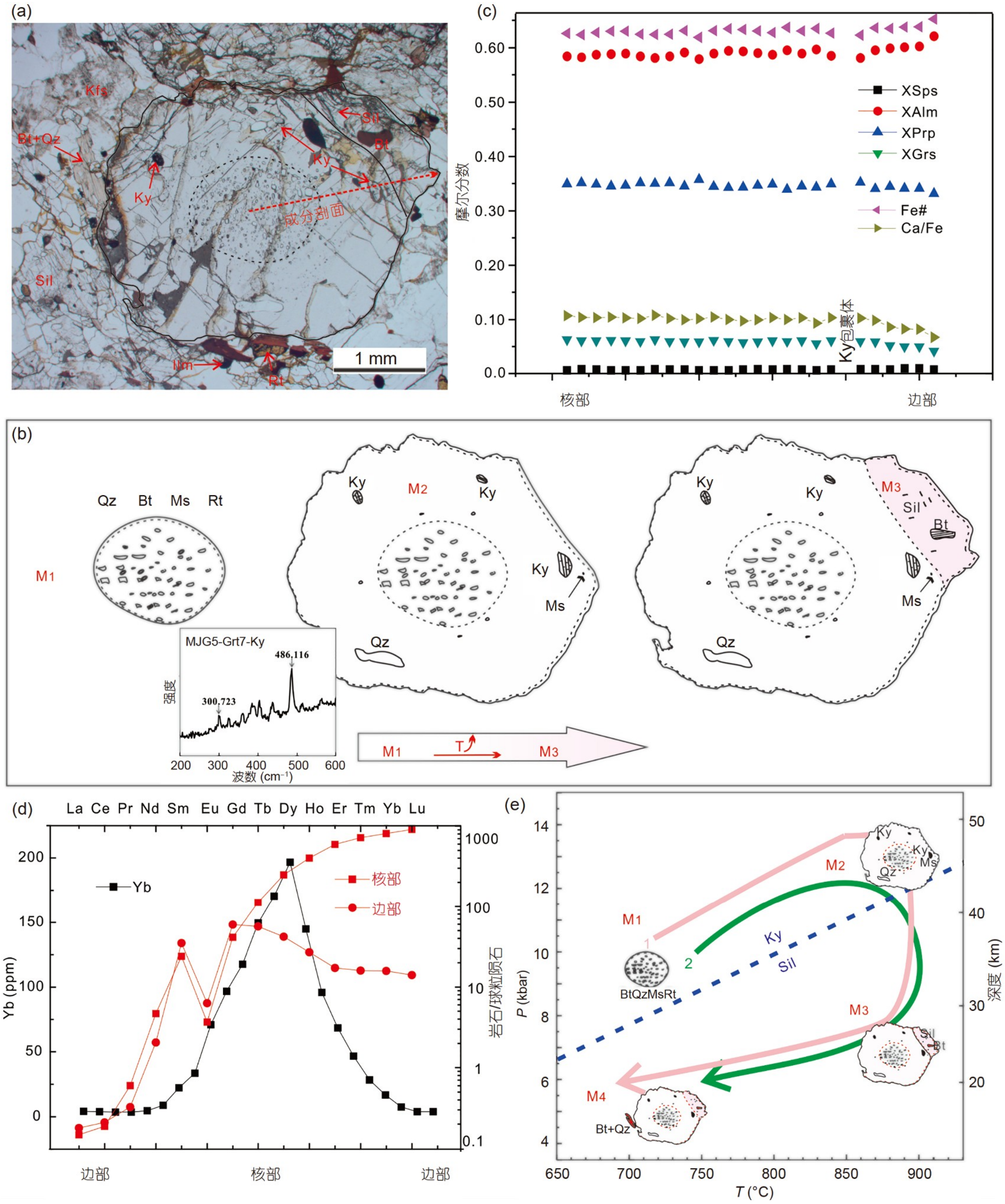

图 1 (网络版彩色)晋冀交界地区泥质麻粒岩中石榴子石的结构、矿物包裹体和成分环带及*P-T*轨迹. (a) 怀安泥质麻粒岩中石榴子石[9], 红色虚线代表成分采集剖面. (b) 从进变质(M_1)、压力峰期(M_2)至温度峰期(M_3)整个升温过程中石榴子石的生长示意图(包含了矿物包裹体组合演变及分布特征、生长体积变化), 代表性蓝晶石拉曼谱峰图[9]. 石榴子石成分环带: (c) 主量元素, 修改自文献[9]; (d) 核部和边部稀土元素配分型式及Yb成分剖面. (e) 泥质麻粒岩*P-T*轨迹及石榴子石的结构演化示意图, 修改自文献[4,12]. 轨迹1: 怀安蔓菁沟, 轨迹2: 大同孤山. 矿物缩写: Grt, 石榴子石; Qz, 石英; Bt, 黑云母; Sil, 矽线石; Kfs, 钾长石; Ky, 蓝晶石; Ms, 白云母; Rt, 金红石; Ilm, 钛铁矿. 1 ppm=1 μg/g

Figure 1 (Color online) Microstructural, mineral inclusions and compositional zoning of garnet grains, and *P-T* paths of pelitic granulites from the junction zone of Shanxi and Hebei provinces. (a) A representative garnet grain of pelitic granulites from Huai'an area[9]. Red dotted line: Locations of composition analysis profile. (b) A sketch map of garnet growth (including development of mineral inclusion assemblages, distribution patterns, and volume accretion) from prograde (M_1), pressure-peak (M_2) to temperature-peak (M_3) stages, and Raman spectrometry of a representative kyanite[9]. Composition zoning of garnet: (c) Major elements profiles, modified after Ref. [9], and (d) rare earth elements distribution patterns of core and rim, and Yb profile from core to rim. (e) *P-T* paths (path 1: Manjinggou, Huai'an; path 2: Gushan, Datong) and microstructural evolution of garnet of pelitic granulites, modified after Refs. [4,12]. Mineral abbreviations: Grt, garnet; Qz, quartz; Bt, biotite; Sil, sillimanite; Kfs, feldspar; Ky, kyanite; Ms, muscovite; Rt, rutile; Ilm, ilmenite. 1 ppm=1 μg/g

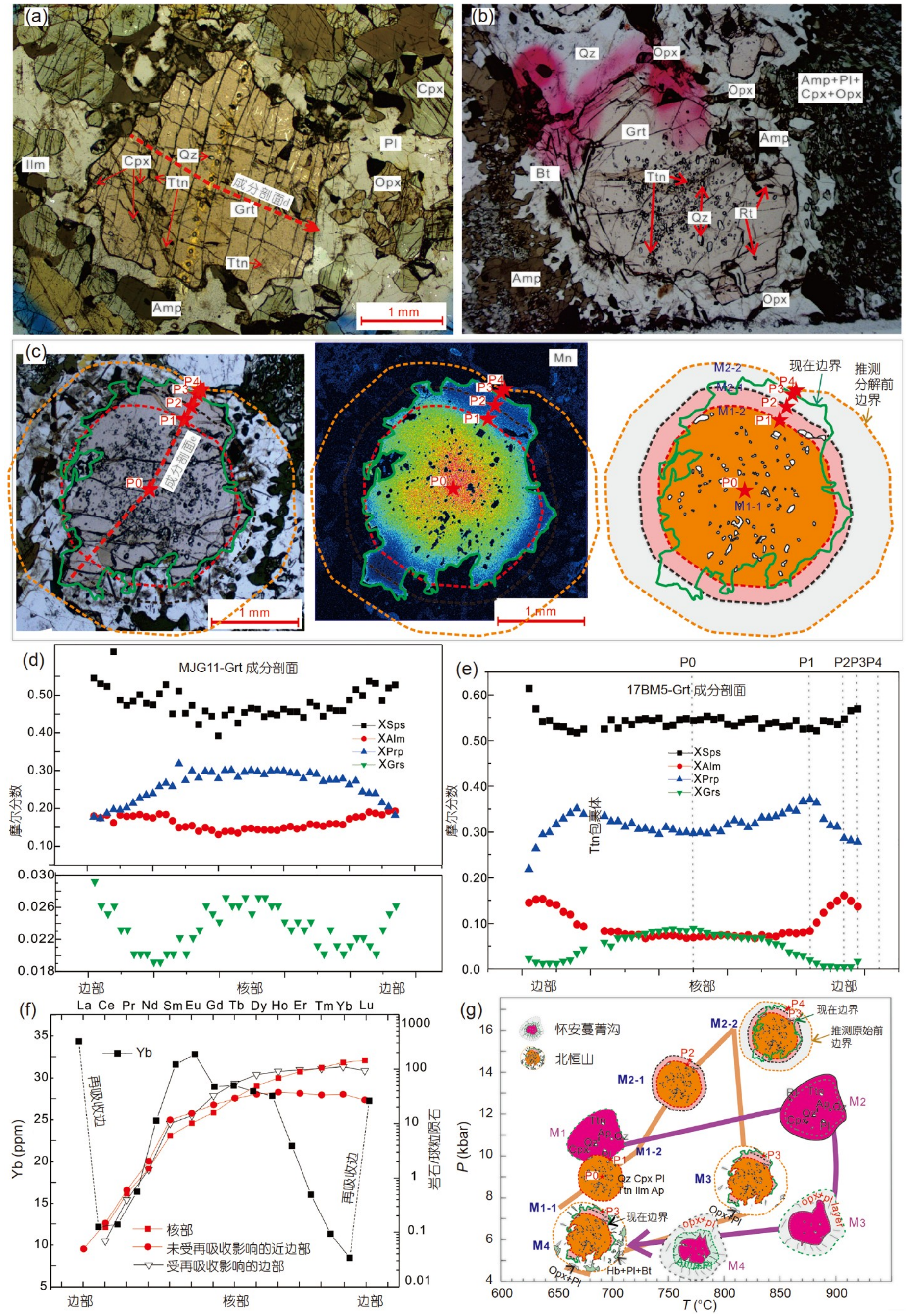

图 2 晋冀交界地区石榴基性麻粒岩中石榴子石的结构、矿物包裹体和成分剖面特征及*P-T*轨迹. (a), (b) 怀安、北恒山地区石榴基性麻粒岩中的石榴子石. (c) 示意了石榴子石从开始生长时(M_{1-1})、进变质晚期(M_{1-2})至(接近)峰期(M_{2-1}和M_{2-2})整个进变质过程中的生长特征(矿物包裹体组合演变及分布特征、成分环带、各阶段生长体积)[18]. (d), (e) 怀安、北恒山石榴子石的主量元素成分剖面, 修改自文献[17,18]. (f) 怀安石榴子石的核部与边部的稀土配分型式及Yb成分环带. (g) 石榴基性麻粒岩*P-T*轨迹及石榴子石的结构演化示意图, 修改自文献[12,17,18], 橙色: 北恒山, 紫红色: 怀安蔓菁沟. 矿物缩写: Cpx, 单斜辉石; Pl, 斜长石; Opx, 斜方辉石; Amp, 角闪石; Ttn, 榍石; Ap, 磷灰石

Figure 2 Microstructural, mineral inclusions and compositional profiles of garnet grains, and *P-T* paths of mafic granulites from the junction zone of Shanxi and Hebei provinces. (a), (b) Representative garnet grains of mafic granulites from Huai'an and northern Hengshan area. (c) A sketch map of garnet growth (including development of mineral inclusion assemblages, distribution patterns, compositional zoning and volume accretion) from prograde (M_{1-1}), late prograde (M_{1-2}) to near pressure-peak (M_{2-1} and M_{2-2}) stages[18]. (d), (e) Major elements profiles of the garnets from Huai'an and northern Hengshan, modified after Refs. [17,18]. (f) Rare earth elements distribution patterns of core and rim, and Yb profile of garnet from Huai'an. (g) *P-T* paths and microstructural evolution of garnet of mafic granulites (orange: northern Hengshan, red purple: Manjinggou, Huai'an), modified after Refs. [12,17,18]. Mineral abbreviations: Cpx, clinopyroxene; Pl, plagioclase; Opx, orthopyroxene; Amp, amphibole; Ttn, titanite; Ap, apatite

多数麻粒岩中石榴子石的主量元素生长环带很难保存, 丢失掉了进变质记录, 但是其中的结构环带和微量元素环带仍然能够抵抗峰期和退变质阶段的改造，它们像基因片段一样保留下来，成为寻找麻粒岩地体进变质记录的重要档案库. 即使最终无法像中-低温变质岩一样获得定量的进变质条件和可靠的*P*-*T*轨迹, 但依然可以通过不同世代石榴子石的体积、残余包裹体矿物组合和其他信息, 结合相平衡模拟可以有效地半定量估算麻粒岩地体进变质阶段的*P*-*T*矢量[9,17,18]. 少数麻粒岩中石榴子石仍然能够大致保留主量元素生长环带(如北恒山地区), 可以有效恢复进变质历史[18,19], 同时亦指示了该岩石在高温条件下驻留时间非常短暂[18,20]. 晋冀交界地区泥质麻粒岩和石榴基性麻粒岩均记录了从地壳浅处埋深或俯冲到深部的过程，为华北中北部古元古代的俯冲-碰撞造山-地壳加厚过程提供了直接的变质岩石学证据.

本文揭示出麻粒岩中石榴子石有可能保留多阶段生长信息，因而估算变质条件时需谨慎判断和选取同一世代相互平衡的矿物成分对. 过去估算麻粒岩峰期变质条件时常常假设石榴子石核部比边部成分更接近于峰期阶段的平衡成分，与石榴子石的主量元素在麻粒岩相峰期变质条件下极其容易均一化，而核部成分在后续冷却退变过程中受扩散影响最弱有关[7,8]. 如果石榴子石主量元素发生均一化，上述假设对使用主量元素温压计获得的结果可能并不会产生重要差别，但是对于扩散较慢的稀土元素构成的矿物对温压计则有可能产生较大的差别. 值得注意的是, 少数麻粒岩地体中石榴子石可能保留了不同构造期次生长的信息，如Liu和Wei[21]提出华北冀东迁安地区的变质杂砂岩中部分石榴子石同时记录了晚太古代超高温麻粒岩相和古元古代高压麻粒岩相两期变质作用. 这无疑使重建麻粒岩地体变质-构造历史复杂化, 因此, 启示研究者需谨慎分析麻粒岩中石榴子石的成因.

此外，麻粒岩中石榴子石多世代生长也为利用具有较高封闭温度的石榴子石Lu-Hf等时线年代学方法探索麻粒岩进变质年龄提供了很好的岩石学依据. 华北克拉通大同和胶北地区麻粒岩相变质沉积岩中石榴子石-全岩Lu-Hf等时线年龄约为1.97~1.94 Ga, 被解释为进变质年龄[22,23]. 该方法在一定程度上可以弥补进变质过程中锆石不断分解进入熔体从而难以记录麻粒岩进变质年龄信息的不足[24]. 今后工作中应加强麻粒岩中石榴子石的成因分析，从多方位开展结构、包裹体、主量、微量成分、元素扩散速率和原位Lu-Hf年代学等方面的研究.

致谢 本文主要基于对近期研究成果的凝练, 受益于与多位合作者的讨论, 在此一并表示衷心感谢. 感谢两位审稿专家建设性的建议.

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Summary for “石榴子石: 麻粒岩地体进变质记录的档案库”

Garnet: The archive of prograde metamorphic records of granulite-facies terranes

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Whether granulite terranes can preserve prograde metamorphic records is a perturbing topic in metamorphic petrology, and related research is rare. This is mainly because the metamorphic records of the granulite terranes have information asymmetry. Generally, the mineral assemblages and compositions of granulite-facies rocks are considered to reflect peak and retrograde metamorphism, rather than prograde metamorphism. However, this assumption must be made with caution. Case studies of granulites from the junction area of Shanxi and Hebei province in the North China Craton suggest that garnet could serve as “temperature and pressure resistant containers” under granulite-facies conditions, and retain the evidence of pre-peak metamorphism. For pelitic granulites, their protoliths are supracrustal rocks, and must have undergone prograde metamorphic processes from the Earth's surface to the deep crust. Therefore, a confirmatory study seeking prograde metamorphic records for pelitic granulites from the Huai'an-Datong area was conducted. In the studied pelitic granulites, inclusions in garnet display well-preserved microstructural zoning, with radical zonal distribution patterns: Crowded quartz grains in the core, a few K-feldspar-kyanite-bearing assemblages in the mantle, and some sillimanite flakes in the rim. The major element zoning (here, major endmember proportions X_{Sps}, X_{Alm}, X_{Pyr}, and X_{Grs} are used) of garnet is relatively homogeneous. However, the high rare earth elements (HREEs) exhibit bell-shaped profiles decreasing from the core to the rim. This suggests that even if the major elements of garnet are homogenous due to high-temperature diffusion, microstructural zoning and some trace elements with slow diffusion rates could be protected from peak- and retro-grade high-temperature modification. For garnet mafic granulites, their protoliths are considered as gabbro dykes, and there is no robust evidence of prograde metamorphism from the upper to lower crust; therefore, their tectonic significance is unclear. Here, an exploratory study of prograde metamorphism for garnet mafic granulites from the Huai'an-Hengshan area was conducted based on the study experience of pelitic garnet. In the investigated mafic granulites, garnet also displays a zoned distribution of various mineral assemblages from its center to rim, including quartz- and titanite/ilmenite-bearing assemblages in the core, rutile-bearing assemblages in the outer mantle to the inner rim, and a resorbed rim. Fortunately, garnet of the mafic granulites displays well-preserved compositional growth zoning patterns, with bell-shaped X_{Sps}, increasing X_{Pyr} from core to mantle, and a resorbed rim (X_{Sps}). The HREEs (for example, Yb) show bell-shaped patterns similar to those of the X_{Sps}. Both textural and compositional zoning patterns in the studied mafic granulites documented multiple generations of garnet growth history from the prograde to peak metamorphic stages. These findings provide robust metamorphic evidence for the Paleoproterozoic subduction and assembly of the Jin-Yu Mobile Belt in the North China Craton. The above two case studies suggest that high-temperature granulite-facies metamorphism may not completely reset the multi-generation growth information retained in the garnet. In contrast, minerals in the matrix only record the history of intensive re-equilibration at the peak or rehydration retrogression metamorphism. Thus, garnet is an important archive of prograde metamorphic information. This study further suggests that caution should be exercised when determining the peak P-T conditions of granulites using garnet core compositions.

granulite terrane, prograde metamorphism, garnet, multi-generation growth

doi: 10.1360/TB-2022-0799