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对“龙游石榴石角闪岩是退变榴辉岩吗?”质疑的回复

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摘要 《科学通报》2015年第13期发表了我们对浙江龙游地区石榴石角闪岩的研究成果(陈相艳等, 2015). 文章发表后, 引起了南京大学于津海和舒良树两位老师的质疑, 其认为石榴子石周围不存在典型的“白眼圈”, 也不存在典型的后成合晶结构, 同时华南加里东期的构造环境也不会形成榴辉岩, 即于津海和舒良树两位老师认为龙游石榴石角闪岩不是榴辉岩退变的产物. 对此, 我们结合详细的野外观察、显微镜下岩相学和矿物化学分析, 认为该石榴石角闪岩是榴辉岩退变的产物, 可以作为华夏加里东碰撞造山的证据.

关键词 石榴石角闪岩, 退变榴辉岩, 碰撞造山, 华南

2015年《科学通报》第60卷第13期发表了我们对浙江龙游地区石榴石角闪岩的研究成果[1]. 我们认为它是榴辉岩退变质产物, 这一鉴别为华夏早古生代碰撞造山提供了重要证据. 文章发表后, 南京大学于津海老师和舒良树老师(以下简称“于和舒两位老师”)对这一认识提出了质疑[2]. 我们非常欢迎于和舒两位老师的质疑, 争议有益于对科学问题的解决. 现就他们的质疑回复如下.

1 退变榴辉岩的定名

退变榴辉岩的定名是结合岩相学和矿物化学分析得出的.

首先, 该石榴石角闪岩(退变榴辉岩)中石榴子石变斑晶可分为两类: 一部分颗粒较小, 呈集合体分布, 颗粒外围都具有长石+石英“白眼圈”(图1(a)), 并非于和舒两位老师认为的“大多数集合体边上没有文中提到的白眼圈结构”; 另一部分石榴子石颗粒较大, 孤立存在, 也具有长石+石英的“白眼圈”(图1(a)). 需要说明的是, “白眼圈”作为典型的降压结构, 其矿物组合中并非一定要有铁镁矿物[3,4](图1(b), (c)). 此外, 该石榴石角闪岩中石榴子石边部的反应结构有多种类型, 不仅具有长石和石英的“白眼圈”, 石榴子石降压分解形成的角闪石+斜长石组合的锯齿边也大量存在(图1(d)~(f)). 白眼圈和锯齿边中的斜长石成分变化很大, 但是以富An为主(51.8~84.7), 这种成分不平衡表明其在减压过程中没有达到平衡.

其次, 由于减压导致绿辉石分解, 形成单斜辉石和富钠斜长石组成的交生结构(图2). 这种交生结构与已报道的华北和高喜马拉雅退变榴辉岩中指示的绿辉石减压分解形成的后成合晶结构完全一致[5,6]. 而且, 单斜辉石中的斜长石成分以相对贫An为主, 即$An_{38.5\sim46.1}$, 与白眼圈和锯齿边中的成分明显不同. 同时, 根据交生结构回算的绿辉石成分中硬玉含量为25%~30%. 因此, 结构证据和矿物成分支持了这

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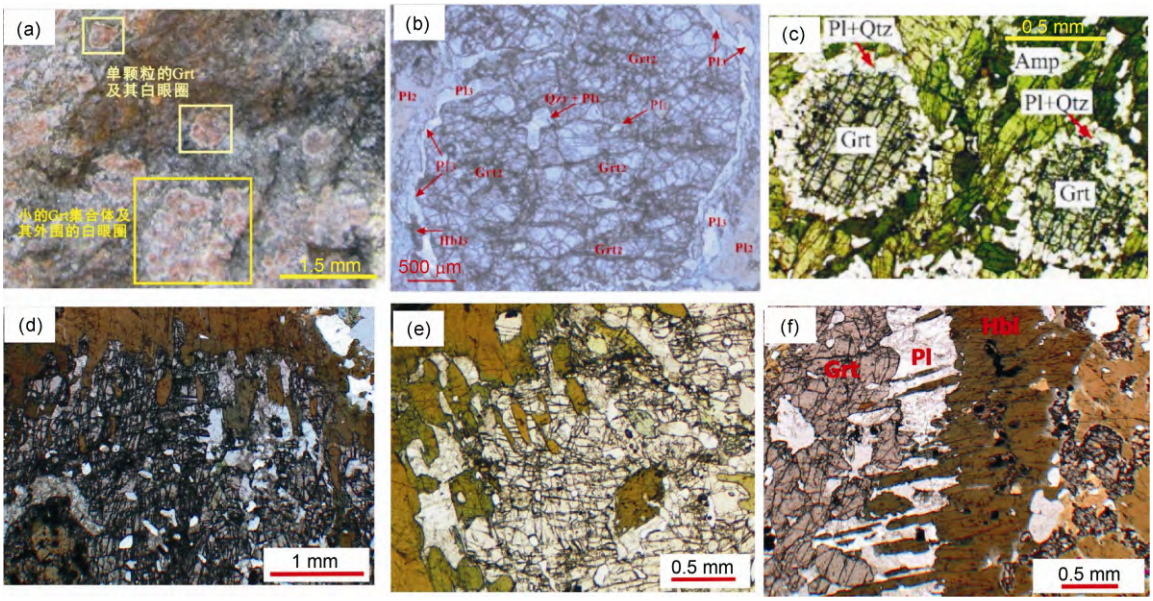

图 1 “白眼圈”结构和石榴子石边部的锯齿边. (a) 颗粒较小、聚集分布的石榴子石和大颗粒、孤立存在的石榴子石边部都具有白眼圈; (b) 石榴子石边部Pl_3构成的白眼圈[3]; (c) 石榴子石边部的Pl+Qtz构成的白眼圈[4]; (d)~(f) 石榴子石边部具有Hbl+Pl组合的锯齿边. Pl, 斜长石; Qtz, 石英; Grt, 石榴子石; 余同

Figure 1 The presence of plagioclase coronas and symplectites of hornblende+plagioclase around garnets. (a) The presence of plagioclase coronas around both single and clustered garnets; (b) the presence of plagioclase coronas around garnet[3]; (c) the presence of plagioclase+quartz coronas around garnets[4]; (d)–(f) symplectites of hornblende+plagioclase around garnets

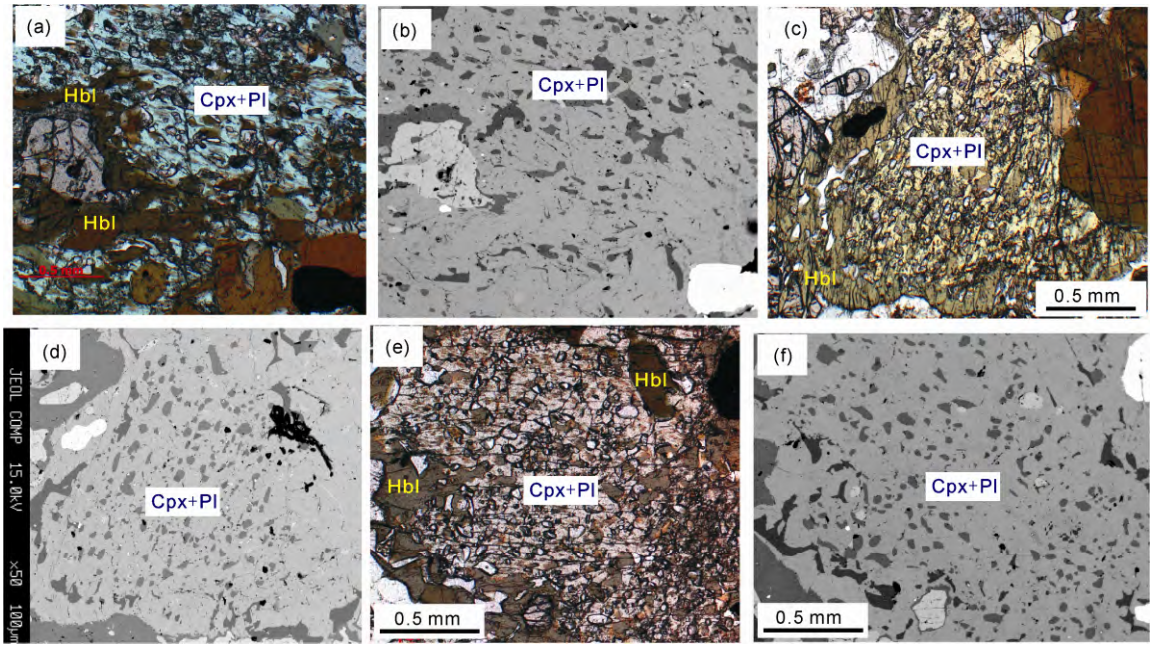

图 2 龙游石榴石角闪岩中不同样品中的Cpx+Pl后成合晶及对应的BSE图像. (a), (b) Cpx+Pl交生结构显微照片及对应的BSE图像, 部分Cpx已退变为Hbl, 2013SC12-1; (c), (d) Cpx+Pl交生结构显微照片及对应的BSE图像, 部分Cpx已退变为Hbl, 2013SC12-4; (e), (f) Cpx+Pl交生结构显微照片及对应的BSE图像, 部分Cpx已退变为Hbl, 2013SC12-4. Cpx, 单斜辉石

Figure 2 Microphotographs of clinopyxene+plagioclase symplectites (or intergrowth) and their corresponding BSE images of Longyou garnet amphibolites. (a), (b) Microphotographs of clinopyxene+plagioclase symplectites (or intergrowth) and its corresponding BSE image, part of the clinopyxene was replaced by hornblende, 2013SC12-1; (c), (d) microphotographs of clinopyxene+plagioclase symplectites (or intergrowth) and its corresponding BSE image, part of the clinopyxene was replaced by hornblende, 2013SC12-4; (e), (f) microphotographs of clinopyxene+plagioclase symplectites (or intergrowth) and its corresponding BSE image, part of the clinopyxene was replaced by hornblende, 2013SC12-4

些“包裹”在单斜辉石中的斜长石不是筛状变晶，而是后成合晶，两者可能构成了原来绿辉石假象，但与一般后成合晶不同的是单斜辉石为单晶，而不是多晶集合体，其原因很可能是后成合晶之后的变质重结晶叠加. 此外，岩石中也不存在原生斜长石，斜长石都以后成合晶和白眼圈的形式存在.

岩石中没有绿辉石并不影响退变榴辉岩的定名，华北太古宙退变榴辉岩[7]、华北恒山退变榴辉岩[5]、东喜马拉雅不丹西北部“麻粒岩化榴辉岩”[6]同样没有残余的绿辉石. 于和舒两位老师认为，文中构成绿辉石假象的Cpx+Pl交生结构与典型退变榴辉岩中的交生结构不符. 对此，我们需要说明的是，即便是典型的退变榴辉岩，其Cpx+Pl交生结构也具有多种形态[5~7]，因此，该石榴石角闪岩与典型退变榴辉岩Cpx+Pl的绿辉石假象仅仅是形态的差异，矿物组合和结构没有本质区别.

对于于和舒两位老师对石榴子石核部不是富镁石榴子石以及后成合晶结构中斜长石的Ab含量仅为53~60的质疑，在原文中已经有清楚的阐述(和原岩成分有关)[1]. 另外，于和舒两位老师对后成合晶结构中石英的存在提出了质疑，变质反应绿辉石+石英=透辉石+钠长石虽然消耗了石英，由于后成合晶结构中石英含量较少，根据化学反应平衡很有可能是未消耗完的石英，或是与退变过程中流体中硅饱和有关，因此，石英的存在并不影响后成合晶结构的识别. 此外，由于石榴子石在退变过程中发育近于平行的裂理，斜长石+石英包体并非进变质包体，其形成主要与受石榴子石局部成分域控制的减压有关[8].

2 退变榴辉岩是原地产物，与华南变质环境协调一致

于和舒两位老师对石榴石角闪岩的来源提出两种可能的模式：一种为“构造混杂”模式，另一种为冰川作用搬运带来的外来岩块. 在“构造混杂”模式中，他们根据坑中一系列无根的由蛇纹岩、辉长岩、花岗岩等构成的混杂岩中的剪切面理、拉伸线理和*XZ*面上的运动学标志，确定出一条上盘岩块朝SE方向逆冲的韧性剪切带. 我们认为，这些“构造混杂”的构造形迹记录了它的折返及后期改造的过程，和碰撞造山形成的榴辉岩折返过程是一致的. 于和舒两位老师在排除了“构造混杂”就位模式后，提出了“冰川”模式. 但在这一地区没有发现任何其他冰川的证据.

我们的野外观察表明，侵入到石榴石角闪岩中的淡色脉体是向下延伸的，脉体的产状与片麻岩的面理产状完全一致(图3)，围岩与其接触关系清晰可见(图3)，而且周围风化的松散岩石，均是片麻岩风化的产物，尽管如此，还保留了完整的面理构造. 1:25万衢州区调资料也记录该石榴石角闪岩为基岩露头或构造岩片[9]. 另外，龙游石榴石角闪岩并非仅出露在白石山头，周坞里另有一个露头[9]，相信随着进一步区调工作的进行，会有更多的露头被慢慢发现. 因此，结合已有地质资料和野外露头特征可以断定，龙游石榴石角闪岩是片麻岩中的“构造岩块”，不是冰川带来的“漂砾”.

已有的研究表明，华夏地区早古生代的变质作用从绿片岩相到麻粒岩相均有发育，且大部分地区为角闪岩相到麻粒岩相变质. 就研究区而言，龙游群以及陈蔡群都经历了早古生代角闪岩相到麻粒岩相的变质. 不是所有榴辉岩的围岩都能和榴辉岩一样记录完整的榴辉岩相变质演化过程[10~12]，因此，这些围岩仅出现角闪岩相或麻粒岩相组合是完全可能的. 此外，于津海等人[13]最近报道的赣东北弋阳早古生代基性麻粒岩的矿物组合与基性麻粒岩典型的矿物组合[14]完全不符. 既无岩相学证据，也无原岩成分支持，将其简单地定为基性麻粒岩显然不合适. 实际上，该矿物组合并不罕见，其原岩可以是含榴紫苏花岗岩，也可以是半泥质岩. 特别指出的是，于津海等在这篇文章中认为华夏是早古生代碰撞造山带，而在质疑我们的文章中，又认为华夏是早古生代陆内造山带.

图 3 龙游石榴石角闪岩露头中的浅色脉及其与围岩接触关系

Figure 3 The leucocratic veins in the Longyou garnet amphibolites and the country rocks around them

3 宏观地质证据也支持华夏地区存在早古生代碰撞造山作用，可以出现榴辉岩相变质条件

于和舒两位老师认为在华夏地区没有早古生代的蛇绿岩、没有显著的陆壳增生以及浅海—半深海环境的沉积岩，和俯冲—碰撞造山模式不一致. 从区域地质分析，华夏在早古生代经历了角闪岩相到麻粒岩相[3,15~17]乃至榴辉岩相的变质、发育了长达2000多千米的北东向岩浆岩带，其中包括一系列碰撞有关的S型花岗岩[18,19]以及加厚下地壳熔融的 I 型花岗岩[20,21]，此外，华夏北缘到扬子南缘发育了典型的早古生代晚期的前陆盆地[22]. 所有这些宏观现象都支持华夏地区在早古生代发生过碰撞造山，有利于形成榴辉岩相变质条件. 早些时候，大多数地质学家认为在华夏早古生代构造演化过程中，没有地幔物质的参与. 这些年在华夏相继发现了早古生代的玄武岩、辉长岩、辉石岩等等[23~25]，充分说明早古生代地幔物质加入到地壳中来的事实.

致谢 于津海和舒良树两位老师对我们的工作进行的评述，使我们有机会再次对这一问题进行思考并做进一步的阐述，魏春景教授对此文进行了详细审阅并提出了建设性修改意见，在此一并表示感谢.

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Reply to “Is the garnet amphibolite in the Longyou a retrograde eclogite?”

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Our paper titled “Retrograde garnet amphibolite from eclogite of the Zhejiang Longyou area: New evidence of the Caledonian orogenic event in the Cathaysia block” was recently published in *Chinese Science Bulletin* (Chen et al., 2015). A comment by Prof. Yu Jinhai and Prof. Shu Liangshu from Nanjing University argued against our conclusions. They suggested that there were no typical coronas of plagioclase+quartz around garnet porphyroblast and omphacite pseudomorph, as indicated by clinopyroxene+plagioclase symplectites (actually intergrowths). Moreover, they argued that the early paleozoic tectonic system, i.e., the intraplate orogeny model, was inconsistent with eclogite-facies metamorphism. In this reply, we once again presented our detailed field investigation, petrographic observations and mineral compositions studies. We carefully and seriously replied their questions one by one. We emphasized that the Longyou garnet amphibolite was a retrograde eclogite, which is genetically related to the Caledonian collisional orogenic event between the South China Block and an unknown block in the process of their assemblage to eastern Gondwana.

garnet amphibolite, retrograde eclogite, collisional orogenic event, South China

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