浙江龙游石榴角闪岩的岩石学特征与构造意义

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摘要 鉴于国内部分学者最近提出的“浙江龙游石榴角闪岩乃华夏地块加里东期碰撞榴辉岩退变而成”这一问题, 在野外地质调查的基础上, 我们对龙游地区的石榴角闪岩开展了岩相学、矿物化学、年代学及全岩地球化学等方面的研究. 结果表明, 少数以包裹体状存在于石榴子石和单斜辉石内部的斜长石为钙长石, 而分布于单斜辉石和石榴子石周围的斜长石其An值在44~66之间, 没有发现指示绿辉石分解形成的富钠斜长石(钠长石或更长石); 锆石CL图像显示, 除存在变质成因的小颗粒锆石外, 还存在较多具有明显核环构造的大颗粒锆石. 经U-Pb年代学测试, 其锆石核部年龄的加权平均值为 879 ± 11 Ma, 和邻区陈蔡地区变角闪岩的原岩年龄一致; 而其变质环及小颗粒锆石的加权平均年龄为 446 ± 5 Ma. 全岩地球化学分析显示, 龙游石榴角闪岩的原岩属于基性岩浆岩(SiO_2 含量为46.8%~48.2%), 微量元素特征具有E-MORB的地球化学亲缘性. 依据龙游石榴角闪岩的有效全岩成分和EPMA分析结果, 并结合观测到的矿物组合, 建立了 P - T 视剖面图, 该图揭示龙游石榴角闪岩至少经历过3期次变质阶段, 分别为温压条件为0.67~0.75 GPa/685~719 的进变质作用阶段, 温压条件为0.91~0.97 GPa/766~782 的峰期变质阶段和温压条件为~0.68 GPa/~767 的退变质作用阶段(同时用传统温压计获得退变温压条件为0.66~0.67 GPa/720~740). 无论哪一个变质阶段, 其变质压力都只是中压而没有达到高压. 结合区域背景综合分析, 我们认为龙游石榴角闪岩的成因演化过程为: 新元古代古华南海洋扬子陆块俯冲→引发弧后拉张→导致幔源岩浆上涌结晶, 形成E-MORB型基性岩→志留纪时遭受强烈的区域中高级变质作用, 遂形成龙游石榴角闪岩.

关键词 华夏地块, 浙江龙游, 石榴角闪岩, P - T 视剖面图, 新元古代, 早古生代

华夏和扬子两个陆块在新元古代发生碰撞拼合, 形成了统一的华南大陆^[1~5]. 在经历了南华纪裂解事件和随后的陆内裂谷沉积作用之后, 华南从震旦纪开始进入稳定的陆缘滨海-浅海-斜坡相沉积环境. 发生在早古生代晚期的构造-岩浆事件, 使华夏陆块发生了强烈的板内挤压变形、同构造岩浆与变质作用. 虽然对华南造山带大规模的早古生代花岗质岩浆活动、绿片岩-角闪岩相乃至麻粒岩相变质作用的动力学机制尚有争论, 但如下的野外地质事实: 没有早古生代大洋蛇绿岩、弧岩浆岩和具鲍玛序列的浊积岩,

也没有大规模幔源组分的添加, 更没有高压/低温变质岩^[1,2,6], 清楚指示华南早古生代的地质背景与发育大洋蛇绿岩与超高压变质岩的阿尔卑斯山、中亚造山带、雅鲁藏布江等典型增生型、碰撞型造山带显著不同. 此外, 华夏陆块虽然广泛发育志留纪花岗岩, 但绝大多数为S型, 极少或缺少幔源组分, 也不具备俯冲-碰撞型花岗岩带的线状分布特征, 而是呈面型展布^[2]. 据此, 人们提出了华南加里东期褶皱带属于板内造山带的认识^[3,7~11](图1).

在江绍新元古代缝合带南侧的浙江龙游县白石

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图1 研究区所在位置及其主要岩石构造单元(改自文献[12])

Figure 1 Position of the study area and its main petrological tectonic units (revised from Ref. [12])

山头的国道边, 存在一个体积约 20 m^3 、呈孤立滚石面貌出现的石榴角闪岩岩块(图2(a)), 岩石新鲜, 和所在地强烈风化的黑云斜长片麻岩露头形成鲜明对照, 其四周并没有发现同种岩石的露头, 源区不明。最近两年, 国内部分学者^[13-15]对该孤立岩块开展了矿物学、岩石学和年代学等方面的研究, 提出“龙游石榴角闪岩是华夏和扬子地块加里东期碰撞造山形成的高压榴辉岩退变而来”的认识。在大别-苏鲁一带, 即使是包含有榴辉岩透镜体的长英质片麻岩, 全都经历过高压-超高压的变质作用^[16,17]; 如果龙游“退变质榴辉岩”属实, 意义不言而喻, 必是华南地质研究中的一项重大成果。为此, 我们进行了重复研究, 包括实地踏勘与采样、室内测试、梳理比对已经发表的数据和证据等。结果表明, 龙游石榴角闪岩并不具备高压榴辉岩退变质的特征, 其原岩是新元古代辉长岩/辉绿岩, 在早古生代经区域中高级变质作用而形成。多方面的研究结果将在下文一一展示。

1 区域地质背景

龙游地区位于华夏陆块早古生代造山带北东段、

江绍新元古代缝合带南侧(图1)。该区广泛发育新元古代变质岩, 由绢云母千枚岩、云母石英片岩、黑云斜长片麻岩、角闪片岩所组成, 称龙游群^[18], 与浙南龙泉地区的八都群相当^[19]。龙游群之上被晚中生代流纹岩、流纹质火山碎屑岩不整合覆盖, 并被晚中生代花岗岩所侵入。在龙游六连岗-白石山头一带, 分布一些彼此混杂、强烈蛇纹石化的超镁铁岩、辉石岩、硅质灰岩、碧玉岩等新元古代无根构造岩块, 寄主岩为千枚岩、片岩和片麻岩(图1)。野外调查表明, 无论龙游群还是超镁铁-镁铁岩块中均不存在像孤立出现在白石山头路边那样的石榴角闪岩岩块(图2(a))。根据资料, 在龙游石榴角闪岩西侧的江西弋阳地区, 零星出露有志留纪基性麻粒岩相岩石^[20], 在龙游东北侧的陈蔡地区陈蔡群中见有中压变质相形成的泥质高级变质岩^[21,22]。但是, 在龙游石榴角闪岩的四周乃至整个华夏褶皱带, 至今尚没有发现高压-超高压变质岩的报道。

2 岩相学及矿物化学

龙游石榴角闪岩岩块较为新鲜, 粗粒变晶结构,

图2 浙江龙游石榴角闪岩野外及显微镜下照片。(a) 呈滚石状出露的龙游石榴角闪岩露头;(b) 石榴角闪岩中肉眼可识别的呈细粒集合体状产出的石榴子石, 细粒石榴子石之间多为长石、石英充填;(c) 单偏光显微镜下呈粒状集合体产出的石榴子石;(d) 自形石榴子石周围分布的Pl, Qtz, Hbl和Cpx;(e) 呈不规则他形分布于石榴子石边部及裂隙里的中长石和石英;(f) 石榴子石和单斜辉石中同时发现的钙长石包裹体, 以及由单斜辉石核部退变而成的自形角闪石;(g) 以包体形式分布于石榴子石变晶内部的钙长石、角闪石、石英和单斜辉石包体;(h) 分布于石榴子石变晶内部的角闪石、单斜辉石和石英包体, 以及分布于石榴子石外围的中-拉长石、角闪石和石英

Figure 2 Field and micrographs for Longyou garnet amphibolites. (a) The field outcrop of Longyou garnet amphibolites which show “rolling stone” shape; (b) the granular aggregate garnets, which is visible with the naked eye, are surrounded by quartz and feldspar; (c) granular aggregate of garnets observed by polarizing microscope; (d) the garnet metacryst surrounded by plagioclase, quartz, hornblende, and clinopyroxene; (e) the irregular allotropic plagioclase and quartz in the peripheral part of garnet porphyroblast; (f) the anorthite enclaves distributed in garnet and clinopyroxene, and the hornblende generated from regression of clinopyroxene; (g) the anorthite, hornblende, quartz and clinopyroxene inclusions distributed in garnet porphyroblast; (h) the amphibole, anorthite, quartz and clinopyroxene inclusions in the inner part of garnet, as well as the andesine, labradorite, hornblende and quartz distributed in the outer part of garnet porphyroblast

块状构造。主要由灰黑色的角闪石和红褐色的石榴子石组成, 二者含量大致相等, 均为40%左右。在薄片和背散射图像下可见少量斜长石(钙长石、拉长石和中长石)、石英、单斜辉石和钛铁矿, 分别占7%, 6%, 5%和1%左右。其他矿物如榴石、磁铁矿等总含量远小于1%。石榴子石多呈团块状集合体产出(图2(b), (c))(其矿物缩写据文献[23], 下同), 少数呈较为完整的变晶产出(图2(d))。角闪石、斜长石、石英和辉石多分布于石榴子石集合体的周围以及裂隙中(图2(c)~(e), (g), (h)), 但也有少量呈包裹体状产于石榴子石变晶内部(图2(f)~(h))。

电子探针测试数据表明, 呈包裹体产于石榴子石或辉石变晶内部的斜长石An值高, 为钙长石(表S1-A; 图2(f), (g))。因受到蚀变作用, 在这些钙长石的内部形成了部分高岭石矿物(其成分含量见表S1-F)。呈不规则他形分布于石榴子石和辉石变晶边部或裂隙中的斜长石An值在44~66之间, 属于中长石或拉长石(表S1-A; 图2(e), (h)), 没有发现富钠成分的钠长石或更长石; 对于辉石, 无论是以包裹体形式存在于石榴子石内部还是以变晶形式分布于石榴子

石周围的辉石, 都是次透辉石(表S1-B; 图S1); 角闪石的产状更为多样, 除了自形产出和被石榴子石包裹外, 也有被斜长石和石英包裹的情况, 但不同产状的角闪石之间并不具明显的成分差异(表S1-C; 图S2)。通过对龙游石榴角闪岩薄片的观察, 我们选择了2颗自形程度好、退变程度弱的石榴子石变晶进行了电子探针剖面成分分析和面扫描图像分析。结果显示, 测试的2颗石榴子石均没有十分明显的成分环带特征。如图3及表S1-D可知, 颗粒1剖面AB各成分含量变化范围不大, 其中Alm为56.4%~59.2%, Grs为24.8%~28.9%, Pyp为10.0%~11.1%; 而颗粒2剖面CD各成分变化稍大, 如Alm含量变化范围为53.7%~58.5%, Grs为25.6%~32.9%, Pyp为8.3%~10.8%, 从核部到边部, 该剖面的Mg增加, Ca降低, 指示升温升压的前进变质过程。总体来讲, 两条石榴子石剖面的成分都相对均匀, 并不像阿尔卑斯高压云母片岩^[24]、大别山高压长英质麻粒岩^[25]和塔里木高压基性麻粒岩^[26]中的石榴子石所具有的环带结构那么明显。与2条剖面相对应的面扫描图像特征也印证了这一结论(图4)。

图3 两颗石榴子石变晶的成分剖面

Figure 3 The compositional profiles of two garnet porphyroblasts

图4 两颗石榴子石变晶剖面各自的Fe, Mg, Ca, Mn元素面扫描图

Figure 4 The Fe, Mg, Ca and Mn element surface scan images for two garnet porphyroblasts

3 全岩地球化学

龙游石榴角闪岩的全岩地球化学主量与微量元素分析结果列于表S2, 其全岩 SiO_2 含量为46.8%~48.2%, 属基性岩. 在变质岩原岩类型图解上, 龙游石榴角闪岩样品均落在正变质岩区(图5(a)~(c)), 证明其原岩为基性火成岩.

Pearce和Cann^[30,31]指出, 高场强元素Ti, Zr, Nb, Ta和Y在热液、海底蚀变及中高级变质等条件下均具有良好的稳定性, 可作为区分不同构造环境有效的判别因子. 综合运用 $\text{Ti}/100\text{-Zr-3*Y}$ 图解和 Ti-Zr 图解进行地球化学投图可以发现(图5(d), (e)), 龙游石榴角

闪岩均投在与MORB成分相关的构造背景区; 在 $\text{Hf}/3\text{-Th-Ta}$ 图解(图5(f))上, 龙游石榴角闪岩投入E-MORB和板内拉斑玄武岩的构造背景区域. 综合以上图解, 推测龙游石榴角闪岩很可能是由E-MORB型玄武质/辉长质岩石变质而来. 结合区域地质资料, 我们认为这些E-MORB型的基性岩是新元古代古华南洋向扬子陆块俯冲→引起弧后拉张→幔源岩浆向上侵位而形成.

4 锆石U-Pb年代学

龙游石榴角闪岩中的锆石CL图像显示, 这些锆石在形态结构上可划分为截然不同的两类: 第一类

图 5 龙游石榴角闪岩全岩地球化学图解. (a) MnO-TiO₂图解^[27]. (b) MgO-CaO-FeO^T图解^[28]. (c) Zr-MgO图解^[29]; 其中, I, 正变质岩; II, 副变质岩. (d) Ti/100-Zr-3*Y图解^[30]; I, 岛弧玄武岩; II, MORB、岛弧玄武岩或钙碱性玄武岩; III, 钙碱性玄武岩; IV, 板内玄武岩. (e) Ti-Zr图解^[30]. (f) Hf/3-Th-Ta图解^[32]; I, N-MORB; II, E-MORB和板内拉斑玄武岩; III, 碱性板内玄武岩; IV, 火山弧玄武岩. 虚线表示不同类型玄武质岩石的过渡带

Figure 5 Bulk rock geochemical discrimination diagrams for Longyou garnet amphibolites. (a) MnO-TiO₂ diagrams^[27], (b) MgO-CaO-FeO^T diagram^[28], and (c) Zr-MgO diagram^[29], among these figures, I represent orthometamorphite and II represent parametamorphite. (d) Ti/100-Zr-3*Y diagram^[30]; I, Island-arc basalt; II, MORB (middle ocean ridge basalt), island-arc basalt or calc-alkaline basalt; III, calc-alkaline basalt; IV, within plate basalt. (e) Ti-Zr diagram^[30]. (f) Hf/3-Th-Ta diagram^[32]; I, N-MORB; II, E-MORB and within plate tholeiite basalt; III, within plate alkali basalt; IV, volcanic arc basalt. The dotted line means transitional zone of different types of basalt

为颗粒细小且呈圆形或近圆形展布的锆石, 粒径60 μm×100 μm左右(图6- I); 第二类锆石斑晶粗大, 发育明显的核环构造(图6- II), 多数呈长条形, 少数为近圆形, 粒径为80 μm×160 μm 左右.

锆石LA-ICPMS定年结果表明, 第二类锆石的核部显示较高的Th/U比, 如表S3所示, 其范围在0.20~1.23之间, 表明这些核部锆石为岩浆成因. 13个高谐和度的核部年龄定年值在844~904 Ma之间, 这些定年值的加权平均年龄为879±11 Ma(图7), 对应于新元古代板块俯冲-碰撞造山事件^[19,33~35], 表明龙游石榴角闪岩的原岩形成于新元古代. 而对第二类锆石的边部和第一类锆石的年龄测试表明, 除少数几个数据点Th/U比值较高(0.2~3.6)外, 多数锆石的Th/U值都较小(≤0.1), 推测具高Th/U比值的锆石是因变质温度过高引发锆石重结晶形成的. 同样选择高谐和度的定年数据得到15个定年值, 集中于429~460 Ma, 其加权平均年龄为446±5 Ma. 表明龙游石榴角闪岩是新元古代的基性岩在早古生代经变质作用而形成.

5 温压计算

依据龙游石榴角闪岩的有效全岩成分(表S2)和EPMA分析结果(表S1-D, E), 结合样品中现在观测到的矿物组合(包括石榴子石、角闪石、斜长石、石英、单斜辉石和钛铁矿, 并按照40:40:7:6:5:1的体积比算出摩尔比), 算得石榴角闪岩样品的P-T视剖面图(图8). 其中区域M1是基于自形石榴子石剖面CD成分的投图结果, 自该剖面的核部到边部, 钙含量比 $Z(g)=Ca/(Ca+Mg+Fe)$ 逐渐降低, 而镁含量比 $X(g)=Mg/(Ca+Mg+Fe)$ 逐渐升高, 指示升温升压的进变质过程; 该区域对应的进变质作用温压条件为0.67~0.75 GPa/685~719 °C. 区域M2是基于自形石榴子石剖面AB成分的投图区域, 其核部与边部成分的变化并无明显规律; 该区域指示峰期变质的温压条件为0.91~0.97 GPa/766~782 °C. 区域M3是基于退变石榴子石的边部成分的投图结果, 该点对应的温压条件为~0.68 GPa/~767 °C.

结合退变石榴子石边部共生矿物组合Grt+Hbl+

图6 石榴角闪岩锆石CL图像. I, 志留纪变质成因的细小颗粒锆石; II, 发育核环构造的锆石, 核部年龄属新元古代, 环部年龄为志留纪
Figure 6 Zircon CL images of garnet amphibolite. I, Silurian metamorphogenic fine-grained zircons; II, zircons that show core-rim structure with the core and rim showing Neoproterozoic and Silurian ages, respectively

图7 龙游石榴角闪岩锆石U-Pb年龄谐和图
Figure 7 Zircon U-Pb concordia age diagram for Longyou garnet amphibolite

Pl+Qtz的EPMA分析结果(表S1-E), 利用传统温压计方法^[36,37], 算得退变质作用的温压条件为0.66~0.67

GPa/720~740℃, 这一结果与上述 P - T 视剖面图法得到的退变温压数据十分接近。

6 讨论

传统地质温压计方法目前被广泛使用,其理论基础是依据共生矿物组合,建立合适的模式反应,利用平衡常数与温度、压力和矿物成分之间的关系,进而获取变质 P 、 T 条件^[36-38]。但对于高级变质岩,由于其一般都经历了复杂的变质演化历史,发育多阶段矿物组合,多数情况下其峰期矿物组合与现保存的矿物组合并不一致^[39-41],因此,传统地质温压计在确定不同期次矿物组合的平衡和 P - T 条件上有若干不确定性^[42,43]。相对而言,利用以全岩成分为基础的视剖面图,结合矿物成分等值线,不仅可以确定岩石形成的 P - T 条件和轨迹,而且可以通过正演模拟方法了解变质作用演化各阶段的矿物组合特征^[44,45]。

就龙游石榴角闪岩而言,由于退变强烈,变质峰期的矿物组合同样难以确定。虽然在退变程度较弱的石榴子石核部同时发现了钙长石、角闪石、石英和辉石包裹体,但由于石榴子石的出现反映较高压的条件,而钙长石在较高压力环境下不能稳定存在^[46],因此,二者不可能在变质峰期达到平衡。于是,利用视剖面图温压计方法算得的龙游石榴角闪岩变质峰期温压条件显然更为可靠。从龙游石榴角闪岩的 P - T 视剖面图(图8)可以看出,从M1到M2阶段为升温升压的进变质过程,由M2到M3阶段为等温降压的退变质过程,两个阶段的变质作用构成了一个顺时针的 P - T 轨迹,指示龙游榴闪岩的原岩经历了一段挤压造山被埋藏,然后折返抬升的动力学过程。

从龙游石榴角闪岩的 P - T 视剖面图可以看出,揭示峰期变质条件的自形、弱退变的石榴子石剖面成分投图区域属于中压环境变质,并没有达到高压。除此之外,由于绿辉石是高压榴辉岩存在标志之一,根据榴辉岩中绿辉石的退变反应式 $\text{Omp} + \text{Qz} = \text{Di} + \text{Ab}$ (即,绿辉石退变会生成钠长石),我们对分布于单斜辉石附近的斜长石矿物做了系统EPMA测试。结果表明,不规则分布在单斜辉石周围呈他形产出的斜长石其An值在44~66之间,为中长石和拉长石;少数作为包裹体存在于单斜辉石内部的斜长石其An值在92~93之间,为钙长石(图2(f)),没有发现富钠的斜长石(钠长石或更长石)。推测那些仅以包裹体状存在于石榴子石和单斜辉石内部的少量钙长石是在进变质过程中形成的,并被随后形成的石榴子石和辉石包裹进而保存下来。进变质过程中有An值在80上下的斜长石的出现(图8)暗示了钙长石存在的可能;再者,如

图8 龙游石榴角闪岩在NCFMASHTO(+H₂O)体系中的 P - T 视剖面图。I示矿物组合grt+hbl+qtz+ilm+rt, II示grt+cpx+hbl+pl+qtz+ilm+rt, III示cpx+hbl+pl+qtz+ilm; 虚线如An80所在虚线代表拉长石等值线, Z(g)和X(g)所在虚线分别为石榴子石中钙和镁元素等值线

Figure 8 P - T pseudosection in the NCFMASHTO(+H₂O) system for Longyou garnet amphibolite. In the figure, serial number I stands for mineral association grt+hbl+qtz+ilm+rt, II stands for grt+cpx+hbl+pl+qtz+ilm+rt, III represents cpx+hbl+pl+qtz+ilm; dotted line, such as An80 located in, stands for isoline of labradorite, dotted line Z(g) and X(g) located in represents calcium and magnesium content isoline of garnet

果当时的环境富水的话,则完全可以结晶出更加富Ca的斜长石。

年代学方面,锆石的CL图像特征揭示,龙游石榴角闪岩的原岩经历过后期变质事件,形成了大量颗粒细小的锆石,并使早先岩浆锆石边部发生变质或重结晶,形成核环构造。锆石核部U-Pb年龄的加权平均值为 879 ± 11 Ma, 变质环部加权平均年龄为 446 ± 5 Ma, 多数早古生代变质锆石或变质环对应的Th/U<0.1(表S3),表明龙游石榴角闪岩是新元古代的原岩在早古生代晚期经变质而成。此外,已获得的地球化学特征揭示(表S2; 图5),龙游石榴角闪岩的原岩为具有E-MORB亲缘性的基性火成岩。Yao等人^[35]报道了位于研究区北东侧陈蔡地区的陈蔡群变角闪岩的锆石U-Pb年龄同样为 879 ± 10 Ma, 且具有相同的、与俯冲相关的地球化学亲缘性,其变质时间也是志留纪(438 ± 3 Ma)。这一变角闪岩与龙游石榴角闪岩在原岩年龄、地球化学、变质时间及变质程度上可对比性高,暗示其具有相似的形成过程。

7 结论

(1) 系统的EPMA分析表明,以包裹体状存在于石榴子石和单斜辉石变晶内部的长石为钙长石,而

分布于石榴子石和单斜辉石外围附近的斜长石An值在44~66之间;没有发现指示绿辉石分解形成的富钠长石(钠长石或更长石),暗示龙游石榴角闪岩不是由高压榴辉岩退变而来。

(2) 依据龙游石榴角闪岩的有效全岩成分和EPMA分析结果,采用 P - T 视剖面图法计算获得三期变质温压条件,分别是:峰前以升温升压为特征的进变质作用阶段,温压条件为0.67~0.75 GPa/685~719℃;峰期变质温压条件0.91~0.97 GPa/766~782℃;峰后以近等温降压为特征的退变质阶段,温压条件为~0.68 GPa/~767℃,三者共同构成一个顺时针演变的 P - T 轨迹,指示龙游榴闪岩的原岩经历了一个挤压造

山被埋藏,然后折返抬升的动力学过程。

(3) 龙游石榴角闪岩中的锆石普遍发育核环构造,其核部的锆石U-Pb为 879 ± 11 Ma,对应的Th/U值大于0.1;环部和细小颗粒锆石的年龄为 446 ± 5 Ma,对应的Th/U多数小于0.1;表明龙游石榴角闪岩的原岩形成于新元古代(879 Ma),而变质作用发生在早古生代晚期(446 Ma)。全岩地球化学数据揭示,龙游石榴角闪岩的原岩是E-MORB型的基性岩浆岩。结合区域地质背景,重建了该岩石的形成过程:新元古代古华南洋向扬子陆块俯冲→引发弧后拉张→幔源岩浆上涌结晶,形成E-MORB型基性岩;在志留纪,遭受了一系列中高温-中压相变质作用,形成石榴角闪岩。

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Petrological properties and tectonic significance for Longyou garnet amphibolite

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In view of the recent issue proposed by some researchers that “the garnet amphibolite in Longyou county of Zhejiang was retrograded from Caledonian collision-related eclogite”. Based on detailed field geological investigation, we carried out a systematic study including petrography, mineral chemistry, zircon geochronology and bulk rock geochemistry. Our results indicate that, the relatively small amounts of plagioclase which only found in interior of garnet or clinopyroxene metacryst are anorthite, while plagioclase that largely distribute in the outer part of garnet or clinopyroxene metacryst are andesine and labradorite (with their An value within 44–66), and no sodium-rich plagioclase (albite or oligoclase) which imply omphacite decomposition structure are found. The CL images of zircon exhibit obvious core-rim structure. U-Pb dating results indicate that the weighted average age of the zircon core part is 879 ± 11 Ma, with Th/U ratio values ranging from 0.20–1.23 which suggest their magmatic origin; while the age of the rim is 446 ± 5 Ma, and lots of their corresponding Th/U ratio show low values (≤ 0.1), suggesting their metamorphic origin. Moreover, the bulk rock geochemistry feature of garnet amphibolite suggest that its protolith is basic (the SiO_2 content within 46.8%–48.2%), and its trace element exhibit E-MORB geochemical affinity. Based on the effective bulk rock composition and EPMA analysis results, as well as the mineral association we found, the P - T pseudosection for Longyou garnet amphibolite was worked out. And this figure reveals that the Longyou garnet amphibolite at least experienced three stages of metamorphism: the prograde metamorphism stage with P - T condition of 0.67–0.75 GPa/685–719°C; the peak-metamorphism with P - T condition of 0.91–0.97 GPa/766–782°C; and the retrograde metamorphism stage with P - T condition of ~0.68 GPa/~767°C (by traditional P - T thermobarometer, we also get a P - T condition of 0.66–0.67 GPa/720–740°C for retrograde metamorphism stage). Whichever stage, its pressure is medium-pressure but not high-pressure. In combination with regional geological setting, we prefer the following genetic model for Longyou garnet amphibolite: the paleo-South China Ocean subduction under Yantze plate in Neoproterozoic→trigger back-arc extension→mantle-derived magma upwelling and forming E-MORB type basic rocks in Neoproterozoic→medium to high-grade metamorphism in Silurian.

Cathaysia block, Longyou of Zhejiang, garnet amphibolite, P - T pseudosection, Neoproterozoic, early Paleozoic

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补充材料

- 图 S1 辉石分类
- 图 S2 角闪石分类图
- 表 S1 矿物 EPMA 分析结果
- 表 S2 全岩地球化学
- 表 S3 龙游石榴角闪岩锆石年龄

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