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# 武功山杂岩高滩组沉积时代与物源特征:来自含榴云母石英片岩锆石U-Pb年龄与稀土元素组成的新证据

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**摘　要:** 武功山地区高滩组是华南板块分布较为广泛的早古生代地层之一,经历了绿片岩相-角闪岩相变质,其沉积时代限定与物源性质确定对客观重建华南板块早古生代地壳演化过程具有重要的意义.本文利用LA-ICP-MS对高滩组中的含榴云母石英片岩进行了碎屑锆石U-Pb测年与稀土元素分析,获得含榴云母石英片岩最年轻一组碎屑锆石年龄为524±12 Ma,结合区域上高滩组被早古生代约462 Ma花岗岩侵入的地质关系,初步限定武功山地区高滩组的沉积时代为524~462 Ma.高滩组含榴云母石英片岩碎屑锆石U-Pb年龄变化于3 622~497 Ma之间,最主要的年龄峰值为956 Ma,4个次要的年龄峰值分别为2 456 Ma、1 644 Ma、850 Ma与524 Ma.对比扬子、华夏陆块早古生代沉积岩系的碎屑锆石年龄图谱,发现高滩组与华夏陆块早古生代地层具有相似的物源特征,指示早古生代期间武功山地区属于华夏陆块的组成部分.

**关键词:** 武功山杂岩;高滩组;含榴云母石英片岩;锆石U-Pb定年;地球化学.

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# Depositional Timing and Provenance Characteristics of the Early Paleozoic Gaotan Formation in the Wugongshan Area, Jiangxi Province: New Evidence from Detrital Zircon U-Pb Dating and Rare Earth Element Compositions of Garnet-Bearing Mica Quartz Schist

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**Abstract:** The Gaotan Formation, which has undergone greenschist to amphibolite facies metamorphism, is one of the most widely distributed Early Paleozoic strata units in the Wugongshan complex of Jiangxi Province. Depositional timing and provenance of the Gaotan Formation is vital for probing the Early Paleozoic crustal evolutionary of the Wugongshan complex. In

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this paper, LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) was used to analyze the zircon U-Pb ages and rare earth element compositions of bearing-garnet micas quartz schist in the Gaotan Formation of the Wugongshan complex. The age of the youngest group of detrital zircons from the garnet-bearing micas quartz schist is 524±12 Ma, combined with geological relationship which the Gaotan Formation was intruded by the ca. 462 Ma granites in the Wugongshan complex, it is speculated that the depositional timing of the Gaotan formation is 524－462 Ma. Detrital zircon U-Pb ages of the Gaotan Formation range from 3 622 Ma to 497 Ma, with the main age peak of 956 Ma and four secondary age peaks of 2 456 Ma, 1 644 Ma, 850 Ma and 524 Ma, respectively. By comparing the detrital zircon ages of the Early Paleozoic sedimentary rocks in the Yangtze and Cathaysia blocks, the provenance characteristics of the Gaotan Formation are similar to the Early Paleozoic strata in the Cathaysia block, indicating that the Wugongshan complex was a part of the Cathaysia block during the Early Paleozoic.

**Key words:** Wugongshan complex; Gaotan Formation; garnet-bearing micas quartz schist; zircon U-Pb dating; geochemistry.

## 0 引言

武功山杂岩位于华夏陆块北缘与江南造山带中南缘之间,经历了长期而复杂的构造演变历史,具有丰富而多样的岩石组合与构造特征.多期多阶段的构造运动使得武功山杂岩一直吸引着地学界的目光,因此武功山杂岩也成为客观恢复华南板块重大地质事件演变的重要地区(杨树锋等,1995; 舒良树,2006, 2012; 郑永飞和张少兵,2007; Shi *et al.*, 2020).在早期的研究过程中,前人对武功山杂岩的构造演化历史、岩浆活动年代学与地球化学特征有了较为深入的理解(Shu *et al.*, 1998; 吴富江等,2001;楼法生等,2005;舒良树,2006;Wang *et al.*, 2015;刘细元等,2016),尤其是前人对武功山杂岩开展了系统的构造解析和构造年代学研究,并提出武功山杂岩是一个晚中生代花岗岩穹窿伸展构造(Faure *et al.*, 1996; Shu *et al.*, 1998).这些认识与成果,可以让人们更加系统地了解武功山杂岩的构造演化与岩浆活动发展历程.但前人对武功山新元古代-早古生代浅变质地层的沉积时代与物质来源、变质-变形演化历史了解较少(Wang *et al.*, 2015; Yao *et al.*, 2017).且不同学者对武功山及其周缘地区早古生代变质地层的时代与物质来源提出了不同的认识(Shu *et al.*, 2008; Wang *et al.*, 2012).鉴于此,本文以武功山地区高滩组中含榴云母石英片岩为对象,通过碎屑锆石 LA-ICP-MS U-Pb测年与稀土元素分析,探讨其沉积时代与物源特征,为客观恢复武功山杂岩早古生代构造演化及其物源区前寒武纪地壳构造演化提供新约束.

## 1 地质背景与样品描述

华南板块位于欧亚大陆东部、太平洋西缘,北隔中部造山带与华北板块相望,西与松潘-甘孜地体、羌塘地体接壤,南西侧与印支地体相邻,南东侧则为西太平洋构造区(图 1a).华南板块东西向延伸 2 000 km 以上,南北向延伸 1 800 km 以上,具有复杂的岩石矿物组合和构造特征(舒良树, 2012; Zhao and Cawood, 2012).目前普遍认为,华南板块是由扬子陆块与华夏陆块碰撞拼合形成,二者之间是一条走向近 NE-SW 的新元古代造山带——江南造山带(图 1b; 舒良树,2006, 2012).

武功山杂岩位于华南板块新元古代江南造山带南侧(图 1),呈椭圆状,其东西向长轴从萍乡延伸至新余约 100 km,南北向短轴从宜春延伸至安福约 50～60 km,经历了加里东期、印支期、燕山期等多期次构造-岩浆活动(Wang *et al.*, 2015).研究表明,武功山杂岩由 3 个构造单元构成,包括核部、滑脱褶皱带和伸展盆地(图 1).核部单元主要由奥陶纪晚期、侏罗纪晚期花岗岩体及中等变质的早古生代残留体组成.奥陶纪花岗岩体普遍发生变质-变形作用,具有眼球状、条带-条纹状构造.片麻理产状基本围绕岩体边界呈面型环状分布,片麻理产状一般向外倾斜,倾角一般在 20°～30°之间.滑脱褶皱带主要沿脆性层和韧性层之间的滑动面形成,主要分布于武功山杂岩的北部和南部.滑脱褶皱带上盘以脆性变形为特征,下盘以韧性变形为特征,在中生代花岗岩周围常常分布糜棱岩化板岩-千枚岩-片岩和片麻岩.在武功山杂岩北部与南部,一系列的野外构造与结构表明其北部向北滑动,南部向南运动(Faure *et al.*, 1996; Shu *et al.*, 1998).伸展盆地主要包括南边的安福盆地和北边的萍乡盆地,它们属于半地堑盆地,主要由晚泥盆世至早三叠世的灰岩、砂岩和泥岩充填(图 1).

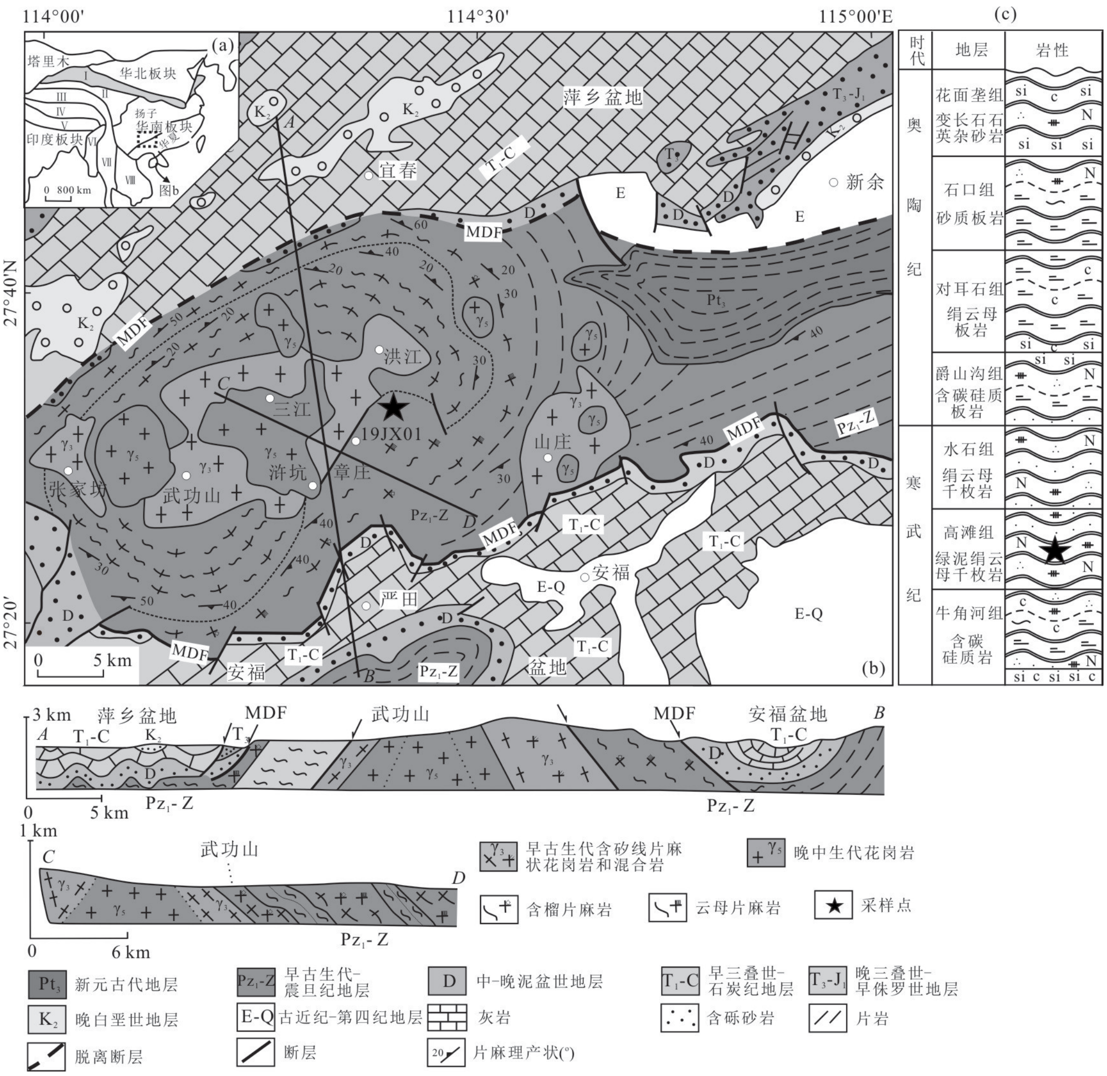


图1　武功山大地构造位置简图(a;修改自 Metcalfe, 2013),武功山区域地质简图(b;修改自 Shu *et al*., 1998),柱状图及采样位置(c;修改自马虎超等,2019)

Fig.1　Sketch map of Wugong mountain geotectonic location (a; modified from Metcalfe, 2013) and simplified geological map of the Wugongshan complex showing sampling localities (b; modified from Shu *et al*., 1998), and histogram (c; modified from Ma *et al*., 2019)

Ⅰ.中国中部造山带;Ⅱ.松潘-甘孜增生杂岩;Ⅲ.羌塘板块;Ⅳ.拉萨地体;Ⅴ.喜马拉雅地体;Ⅵ.缅甸西部地体;Ⅶ.西布马苏地体;Ⅷ.印度支那地体;MDF.主要断裂带

本次研究的含榴云母石英片岩,分布于武功山杂岩的南侧滑脱褶皱带中,属于寒武系高滩组泥砂质变质岩,取样位置为江西省吉安市安福县章庄乡章庄村东约 2 km 的公路旁.野外露头可见新鲜的含榴云母石英片岩发生强烈的褶皱变形,形成小型的平卧褶皱和滑脱褶皱(图 2).高滩组含榴云母石英片岩(19JX01-1.1、19JX01-3.1)颜色为灰褐色,中细粒鳞片变晶结构,片状构造,其主要由石英(约 50%)、黑云母与白云母(约 30%)、石榴子石(约 2%)以及少量的斜长石组成,副矿物包括锆石、独居石、电气石和钛铁矿.由于受到强烈变形作用影响,镜下可见早期形成的结晶片理发生强烈的褶皱变形,石榴子石一般分布于褶皱核部,并断续定向分布,大致与第二期褶皱轴面平行.

## 2　分析方法

本次采集的高滩组含榴云母石英片岩共 8 kg,在室内先将岩石样品粉碎至 120 目以下,用常规的人工淘洗和电磁选方法富集锆石,再在双目镜下手工逐个精选锆石颗粒,然后经过透射光、反射光和阴极发光成像来判断锆石内部结构.同时在武汉上

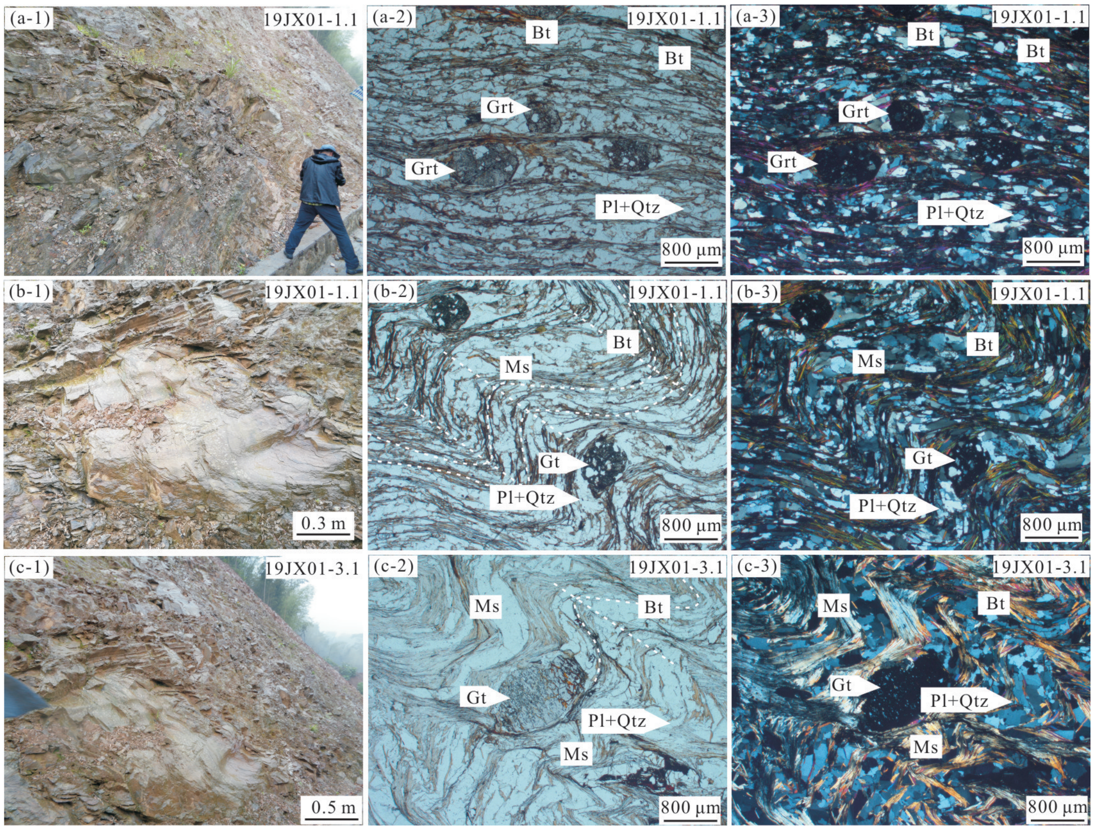


图 2　武功山杂岩高滩组含榴云母石英片岩代表性野外和显微照片

Fig.2　Representative photomicrographs and field photos of garnet-bearing mica quartz schist from the Gaotan Formation in the Wugongshan complex

矿物缩写据沈其韩(2009);a~c.高滩组含榴云母石英片岩主要矿物组合:石英+斜长石+黑云母+白云母+石榴子石;a-1~c-1.露头尺度小型褶皱;a-2~c-2.单偏光镜下显微尺度的挤压褶皱;a-3~c-3.正交偏光镜下显微尺度的挤压褶皱

谱分析科技有限责任公司进行锆石 U-Pb 定年和稀土元素分析,采用 GeoLasPro 激光剥蚀系统进行激光取样.用安捷伦电感耦合等离子体质谱仪(Agilent 7700)采集离子信号强度.测试过程中以标准锆石 91500 为外标,来检验 U-Pb 定年数据质量.微量元素校正标准样品以 NIST 610 为外标,以 Si 为内标(Hu *et al.*, 2011,2012).原始的测试数据经过 ICPMSDATACAL10.0 软件离线处理完成,后续数据处理采用 Origin 8.0 程序,锆石年龄谐和图用 Isoplot 3.2 程序完成(刘平华等,2020).

## 3　分析结果

### 3.1　锆石 U-Pb 年龄

如图 3 所示,含榴云母石英片岩样品(19JX01-1.1 与 19JX01-3.1)的锆石颗粒大多呈灰色,部分呈浅棕色,粒径一般在 75~200 μm 之间.多数锆石呈棱柱状,长短轴之比为 2:1~3:1,指示其经历了近距离的搬运;部分锆石呈圆状和次圆状,表明其经历一定距离的搬运且被不同程度磨蚀.多数锆石发育典型的岩浆振荡环带,并具有相对中等-弱的阴极发光效应,颜色为灰色-灰白色,相应的 Th/U 比值相对偏高,为 0.1~0.4,暗示它们为岩浆结构的碎屑锆石(Belousova *et al.*, 2002).但测点 19JX01-1.1-24 锆石阴极发光图像显示为浑圆状,粒度相对较小,从边部至核部具有相对弱的阴极发光效应,颜色为灰色-灰黑色,内部无明显环带结构,显示出变质重结晶结构的碎屑锆石特征.

本次研究对样品 19JX01-1.1 中的 92 颗锆石进行 U-Pb 测年(附表 1),在锆石 U-Pb 谐和图中,多数测点均具很好的谐和度(图 4),数据落在谐和线上,说明这些年龄可近似代表锆石结晶年龄.大多数锆石的 U 含量在 $66.21\times10^{-6}$~$1\,622.43\times10^{-6}$ 之间,Th 含量在 $25.53\times10^{-6}$~$859.80\times10^{-6}$ 之间,Th/U 值大于 0.1. 92 个锆石的 $^{207}Pb/^{206}Pb$ 年龄分布在 3 622~497 Ma 之间.主要年龄峰值为 965 Ma,次要年龄峰值为 506 Ma、1 600 Ma 与 2 447 Ma

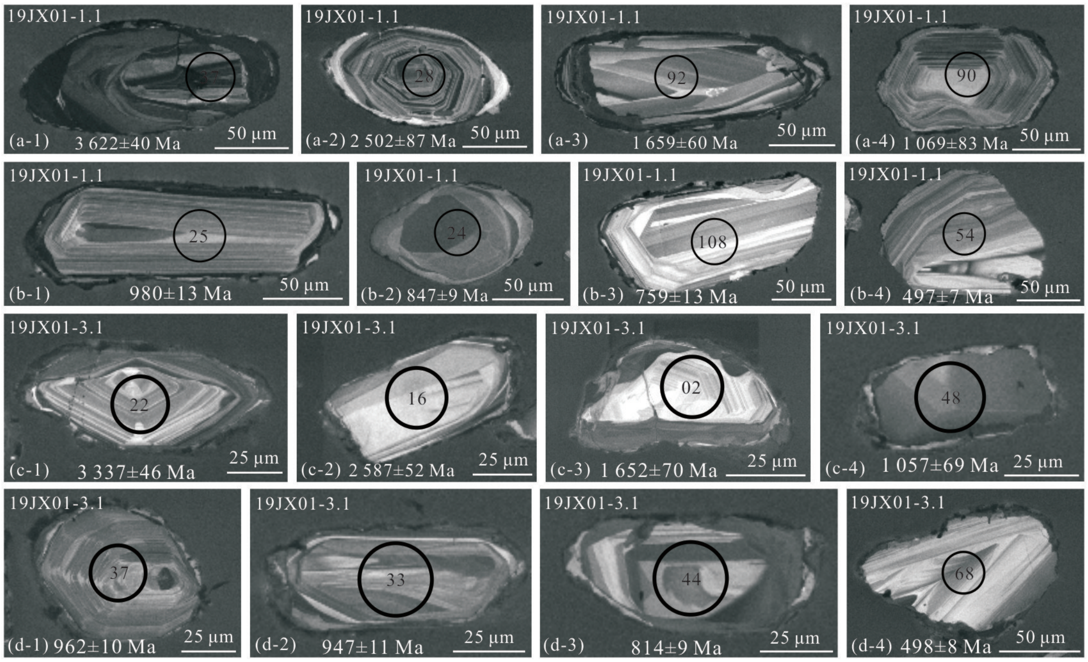


图3　武功山杂岩高滩组含榴云母石英片岩中碎屑锆石的阴极发光图像与U-Pb年龄

Fig.3　Cathodoluminescence image and U-Pb age of detrital zircon from the garnet-bearing mica quartz schist of the Gaotan Formation in the Wugongshan complex

(图4).碎屑锆石年龄最大为3 622 Ma,最小峰值年龄为506 Ma,结合其锆石内部结构特征,大致确定了其原岩沉积时代小于506 Ma.

此外,对含榴云母石英片岩样品19JX01-3.1中的72颗锆石进行U-Pb年代学研究(附表2).大多数锆石的U含量在$106.52\times10^{-6}$～$2\ 020.04\times10^{-6}$之间,Th含量在$17.57\times10^{-6}$～$1\ 568.84\times10^{-6}$之间,Th/U值大于0.1.在锆石U-Pb谐和图中,大部分碎屑锆石数据落在谐和线上(图4),说明这些年龄可近似代表锆石结晶年龄.72颗锆石的$^{207}Pb/^{206}Pb$年龄分布在3 337～498 Ma之间.主要年龄峰值为938 Ma,次要年龄峰值为535 Ma、1 070 Ma、1 668 Ma、2 480 Ma.碎屑锆石最大年龄峰值为3 337 Ma,最小年龄峰值为535 Ma,大致确定其原岩沉积时代小于535 Ma.

### 3.2　锆石的稀土元素组成

本次研究对武功山高滩组19JX01-1.1、19JX01-3.1样品中锆石共进行了164个微区的稀土元素化学成分测试,其分析结果列入附表3、附表4中.从附表3和附表4中可以明显看出,这些碎屑锆石稀土元素含量变化较大,在$91.42\times10^{-6}$～$3\ 463.69\times10^{-6}$之间.在球粒陨石标准化稀土元素配分图中,绝大部分锆石测点具有典型岩浆结构锆石的特点(Hoskin and Ireland, 2000; Rubatto, 2002),即多数测点具有轻稀土元素明显亏损,而重稀土元素明显富集的特征(上翘).绝大部分具有重稀土元素富集的碎屑锆石Th/U比值均大于0.1,显示了岩浆结构的锆石Th/U比值特点(Belousova *et al.*, 2002).值得指出的是,少数测点重稀土元素分馏不明显,如测点19JX01-1.1-24重稀土元素趋于平坦模式,$Lu_N/Sm_N$比值为4.52(图4,附表3),结合其锆石内部结构特征,指示样品19JX01-1.1第24粒锆石为变质重结晶结构的碎屑锆石(Hoskin and Ireland, 2000; Rubatto, 2002).

## 4　讨论

### 4.1　沉积时代

**4.1.1　最大沉积年龄**　因缺少可用于测年的火山岩夹层,武功山杂岩中高滩组的沉积时代一直缺少可靠的同位素年代学约束,本次研究利用年轻的一组碎屑锆石来约束高滩组最大沉积时代.虽然高滩组含榴云母石英片岩发生了高绿片岩相变质,但其锆石内部结构表现出典型的岩浆锆石特征(如振荡环带)与少量重结晶特征(如变质增生边).因此,这些碎屑锆石测年结果能够真实地反映锆石的形成时代,并能用来约束岩石的最大沉积年龄.样品19JX01-1.1最年轻碎屑锆石年龄峰值为506 Ma

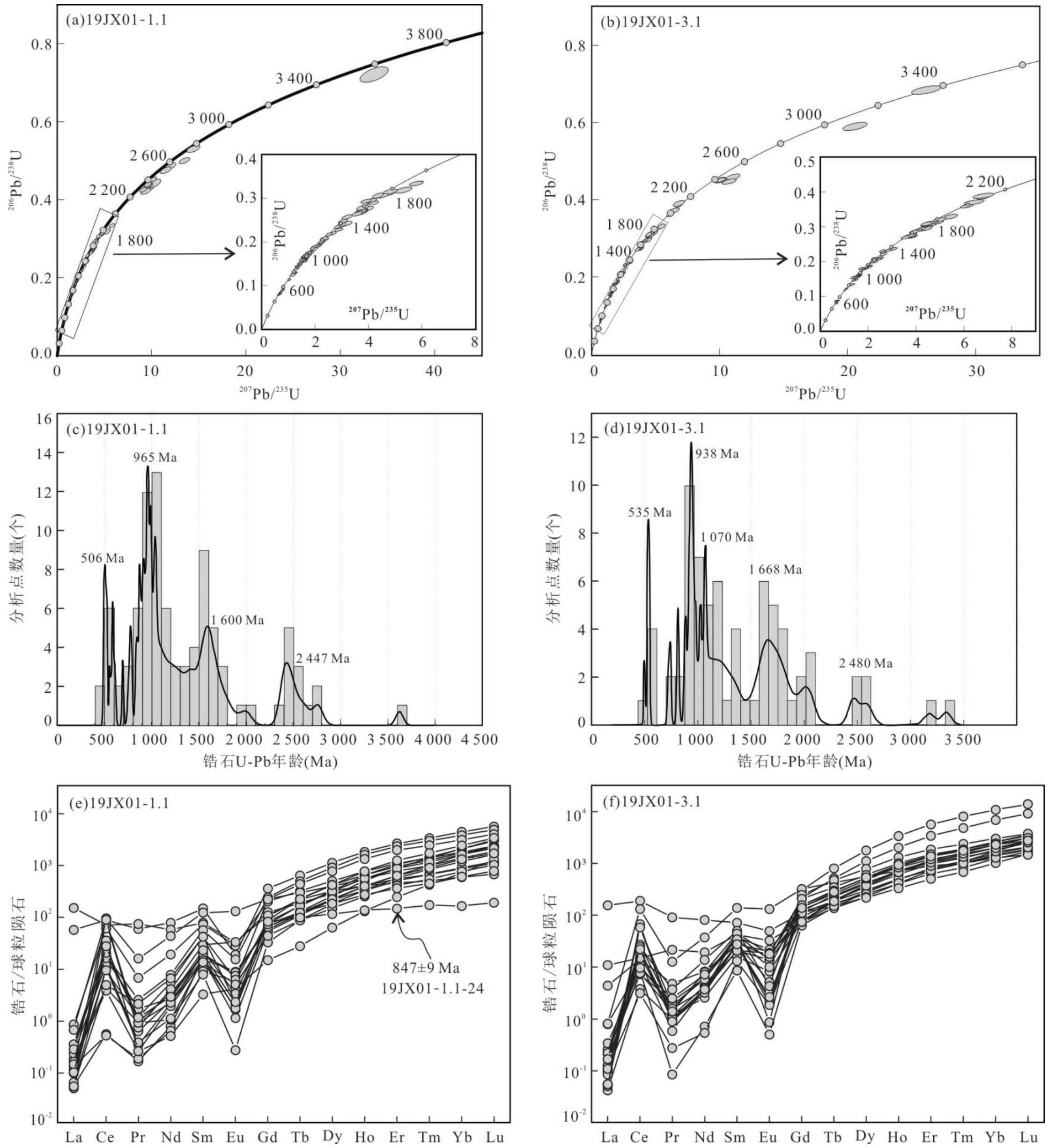


图4　武功山杂岩高滩组含榴云母石英片岩中碎屑锆石U-Pb年龄谐和图(a, b),锆石年龄频率直方图(c, d)与稀土元素配分模式(e, f)

Fig.4　U-Pb age concordia diagram (a, b), histogram with frequency distribution diagram (c, d) and REE patterns (e, f) of detrital zircons from the garnet-bearing mica quartz schist of the Gaotan Formation in the Wugongshan complex

球粒陨石稀土元素数据 Sun and McDonough (1989)

($n$=7),锆石谐和度为94%~98%,19JX01-3.1最年轻碎屑锆石年龄峰值为535 Ma($n$=5),锆石谐和度为93%~98%,取两组样品中年轻的锆石年龄数据(583~497 Ma)做加权平均年龄,获得的年龄为524±12 Ma.因此,武功山杂岩中高滩组含榴云母石英片岩的最早沉积年龄为524±12 Ma(图5).

**4.1.2　最小沉积年龄**　尽管碎屑锆石不能直接用于确定地层沉积时代上限,但华南板块早古生代加里东期构造运动产生的大规模持续性岩浆活动为约束地层最小沉积年龄提供了重要约束.在晚奥陶世-早泥盆世板内构造-岩浆作用阶段,华夏陆块(包括武功山在内)区域发生了强烈的褶皱-逆冲变形、绿片岩相变质作用和大规模的重熔作用,并伴有大量花岗岩侵位(Shu *et al.*, 2014),这些S型花岗岩体的年龄范围为460~390 Ma(Faure *et al.*, 2009; Charvet *et al.*, 2010; Wang *et al.*, 2011).在华夏陆块北缘的武功山地区,吴富江和张芳荣(2003)在武功山获得花岗岩岩体的岩浆锆石U-Pb

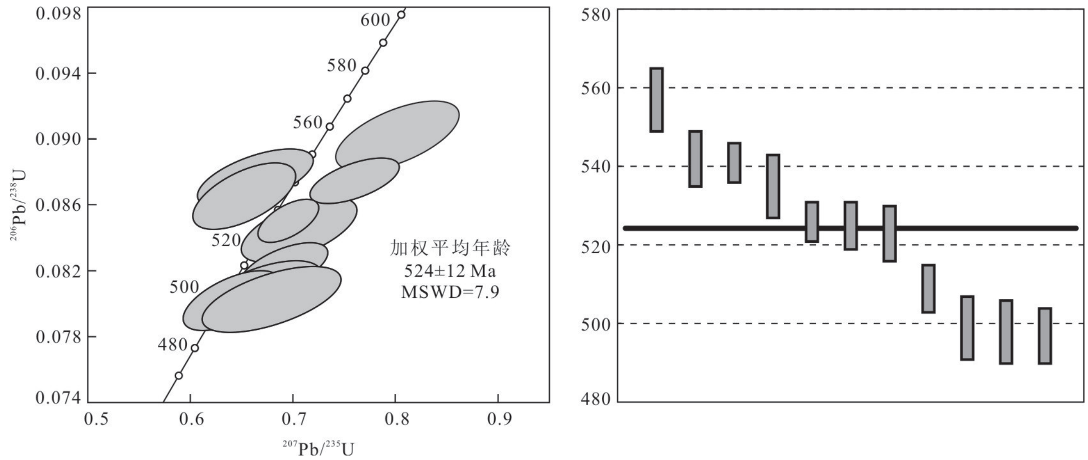


图5 武功山杂岩高滩组含榴云母石英片岩中最小一组碎屑锆石 $^{238}U$-$^{206}Pb$ 年龄谱和图与 $^{238}U$-$^{206}Pb$ 加权平均年龄

Fig.5 $^{238}U$-$^{206}Pb$ age concordia diagram and $^{238}U$-$^{206}Pb$ weighted average age map of the smallest group of detrital zircons from the garnet-bearing mica quartz schist of the Gaotan Formation in Wugongshan complex

年龄值为462±2.3 Ma，认为岩体形成于加里东期，属于同造山期花岗岩.楼法生等(2005)在武功山山庄地区获得了460±2 Ma的岩浆锆石U-Pb年龄，在张佳坊地区获得了428±1 Ma的岩浆锆石U-Pb年龄，表明岩体均属于早古生代晚期花岗岩.最近，王涛等(2018)从武功山杂岩老虎塘组(原定为震旦纪)的两个砂岩样品中获得了大量加里东期(主峰年龄为440～430 Ma)岩浆碎屑锆石，指示加里东期花岗岩是老虎塘组的主要物质源区.然而，这些470～430 Ma的加里东期岩浆年龄在本次研究数据中并没有出现.此外，前人对武功山杂岩详细的野外观测表明，武功山局部地区早古生代花岗岩侵入高滩组泥质砂质变质岩中(Faure *et al.*, 1996; Wang *et al.*, 2015)，表明高滩组含榴云母石英片岩的沉积时代应发生在早古生代花岗岩侵位之前.因此，综合以上分析可知，武功山杂岩中高滩组沉积时代为524～462 Ma.

### 4.2 物源分析

锆石是一种非常稳定的副矿物，广泛存在于碎屑沉积岩中.在众多研究中，碎屑锆石的U-Pb同位素体系可以有效地用于示踪其物质来源、成因、区域构造演化特征等信息(Yao *et al.*, 2011; Xue *et al.*, 2019).因此，本次研究选择了武功山地区早古生代高滩组中的2个含榴云母石英片岩样品进行碎屑锆石U-Pb年代学分析，旨在查明武功山地区高滩组的物质来源.高滩组含榴云母石英片岩碎屑锆石年龄谱与锆石内部结构揭示碎屑锆石主要来源于岩浆岩(图4和图5)，年龄大致分为2 765～2 384 Ma、2 058～1 422 Ma、1 100～900 Ma、850～700 Ma和600～497 Ma五个区间.对比马虎超等(2019)采自赣南兴国地区高滩组的碎屑锆石年龄图谱发现，两个地区高滩组具有相似的碎屑锆石年龄峰值，它们分别是～2 500 Ma、1 600～1 500 Ma、980～930 Ma与～800 Ma；二者不同之处在于武功山地区高滩组出现了500 Ma泛非期次峰年龄，而在赣南兴国地区则没有出现.

本次研究在武功山地区高滩组中获得了3颗年龄均大于3 000 Ma的中太古代岩浆锆石，其中年龄最大的一颗锆石年龄为3 622 Ma，这与前人在华夏陆块发现的中太古代碎屑锆石相一致.例如，于津海等(2007)在粤北地区发现3颗形成于约3 300 Ma和1颗约3 800 Ma的中太古代岩浆锆石，邹和平等(2014)在广西大明山地区发现一颗3 400 Ma的古老岩浆锆石，徐文坦等(2019)在赣南地区发现1颗3 500 Ma的古老碎屑锆石，马虎超等(2019)在赣南地区发现1颗3 000 Ma的古老碎屑锆石.武功山地区太古宙早期年龄信息的研究表明，华夏陆块可能存在太古宙地壳基底或接受过古老地体的物质供给，这对今后研究华南地区太古宙早期构造演化具有一定指示意义.

新太古代-古元古代早期(2 765～2 384 Ma)的年龄区间与古大陆记录的全球地壳生长时间相一致(Zhai and Santosh, 2011; Geng *et al.*, 2012; Santosh *et al.*, 2015; 马虎超等, 2019)，相关研究资料表明，前人在华南板块内的其他区域也获得了大量该阶段碎屑锆石年龄.如扬子陆块

内岩浆锆石U-Pb年龄显示出～2 500 Ma的上交点年龄(涂城等,2021),而华夏陆块也有约2 440 Ma年龄峰值出现(Zhang and Zheng,2013),虽然没有相应的岩浆作用(2 765～2 384 Ma)报道,但类似的年龄普遍存在于以往的研究中(于津海等,2006;Duan *et al.*, 2011;邹和平等,2014;Yao *et al.*, 2015;Yang and Jiang, 2019).同时,根据19JX01-3.1阴极发光图像显示约2 587 Ma的锆石形态呈棱状-次棱状,磨圆度较差,表明其搬运距离不长.因此华夏陆块和扬子陆块新太古代-古元古代结晶基底在这一时期可能为武功山地区提供了物源.

古元古代晚期-中元古代早期(2 058～1 422 Ma)的岩石在华南板块中出露规模有限,前人的一些研究将此类似年龄划分为哥伦比亚超大陆的拼合(2 000～1 600 Ma)和裂解(1 500～1 300 Ma)(Hou *et al.*, 2008;Zhao *et al.*, 2009).虽然此年龄区域在本次研究形成较小峰值,但这个年龄区域在华南板块碎屑锆石的年龄谱中广泛出现,根据前人研究华夏陆块在古元古代已有岩浆锆石记录,比如武夷山地区1 890～1 770 Ma的一些小规模花岗岩和角闪质岩石露头,浙西南地区岩浆锆石U-Pb年龄显示出约1 850 Ma的年龄峰值(Li, 1997;Xiang *et al.*, 2008;Xia *et al.*, 2012).但华夏陆块中未发现约1 900～1 500 Ma的大规模岩浆构造活动的直接证据.结合该年龄段碎屑锆石的形态特征,锆石颗粒呈圆状-次圆状,且伴随不同程度的磨损(图3),指示其经历了较远距离的搬运.因此,本次研究推测这些碎屑可能来自于远离华夏陆块的外来地体.

中元古代末-新元古代早期(1 100～900 Ma)的年龄区域是研究区样品最主要的年龄分布区间,前人将此年龄区域对应为罗迪尼亚超大陆的碰撞造山事件(Zhao and Cawood, 2012;Yao *et al.*, 2014;马虎超等,2019).前人研究结果显示,华夏陆块存在大量该时期的变质岩.例如广东兴宁县径南地区出露有SHRIMP岩浆锆石U-Pb年龄为972±8 Ma的变质流纹岩(舒良树等,2008),覃小锋等(2006)在广东云开地区获得花岗质片麻岩的岩浆锆石U-Pb年龄为906±24 Ma,向磊和舒良树(2010)在赣南地区中的变余砂岩、杂砂岩中测得约980 Ma的岩浆锆石年龄峰值.与此同时,在江南造山带东段以及华夏陆块东北部也出露有1 000～900 Ma的俯冲带岩浆作用产物(Ye *et al.*, 2007;Li *et al.*, 2009).这些岩浆碎屑锆石年龄与本次研究的1 100～900 Ma年龄基本相一致.碎屑锆石年龄谱对比结果表明武功山地区1 100～900 Ma年龄区间峰值与华夏陆块年龄峰值高度一致,而且此年龄区域的锆石大多为自形至半自形,磨圆度较差,为次棱状,且基本都具有良好的岩浆振荡环带.表明它们来自于武功山周缘的岩浆岩,所以武功山地区1 100～900 Ma年龄段的物源主要来自于华夏陆块.

新元古代(890～700 Ma)的年龄峰值代表了罗迪尼亚超大陆的裂解及一系列的构造-岩浆活动(马虎超等,2019).前人研究成果显示,在新元古代扬子陆块内部和边缘有大量与该时期相吻合的S型后碰撞花岗岩,与裂谷相关的岩浆岩石组合(镁铁质花岗质岩墙、双峰火山岩和碱性玄武岩),以及同期裂谷型盆地等地质活动记录,而华夏陆块相关记录较少(Zhang and Zheng, 2013;Yao *et al.*, 2014).同时,前人在华夏和扬子陆块之间的南华裂谷内发现新元古代中期的岩浆活动记录以及大量833～705 Ma的岩浆锆石年龄数据(Wang *et al.*, 2010, 2012;杨树锋等,2019).另外,结合阴极发光图像,显示新元古代碎屑锆石大部分为自形至半自形,磨圆度较差,呈现棱状-次棱状,且具有典型的岩浆振荡环带,指示其来自于武功山周缘的地体,只经历短距离的搬运.再结合碎屑锆石年龄谱的对比结果,表明～800 Ma的年龄峰值与扬子陆块最突出峰值相一致.综上所述,笔者认为武功山地区新元古代～800 Ma的碎屑锆石物源来自于扬子陆块和南华裂谷.

值得注意的是,新元古代末-早古生代年龄区间(600～450 Ma)对应于与冈瓦纳大陆组合相关的泛非造山事件(Torsvik and Cocks, 2013).但在华南板块内,至今为止还未发现与冈瓦纳大陆泛非造山事件相关地质体,目前普遍认为华南地区早古生代变质地层记录的600～500 Ma碎屑锆石可能来自于泛非造山带S型花岗质岩石(Yao *et al.*, 2014).最近,600～500 Ma花岗岩或600～500 Ma岩浆碎屑锆石年龄在越南中-北部地区早古生代花岗岩类中均被不断报道(Nguyen *et al.*, 2019;Jiang *et al.*, 2020),可能指示在印支板块与华南板块之间存在一定规模的泛非期地质体,它们可能是武功山地区新

元古代末-早古生代碎屑锆石潜在物源.

### 4.3 构造意义

**4.3.1 武功山杂岩前寒武纪基底的构造亲缘性** 前人研究证明,碎屑锆石的年龄谱系可用于追踪碎屑物源及其构造属性(Rino *et al.*, 2004; Condie *et al.*, 2009; Yao *et al.*, 2011).碎屑锆石年龄图显示,在武功山杂岩高滩组含榴云母石英片岩碎屑锆石中可识别出多期多阶段的年龄信息(图6).因此,为了更好地了解武功山杂岩基底的构造演化历史及其与其他主要大陆的亲缘关系,本文将武功山、华夏陆块、扬子陆块、印度板块、南极洲板块、南美洲板块、西澳大利亚板块的前寒武纪年龄分布进行了对比.

碎屑锆石年龄对比图显示,武功山地区高滩组含榴云母石英片岩中含有大量2 476 Ma峰值的锆石年龄信息(图6),这个年龄峰值与全球克拉通记录的太古宙末期-古元古代早期地壳生长与再造事件相对应.华夏陆块、扬子陆块、印度板块和南极洲板块同时代沉积岩中的碎屑锆石也表现出相同的峰值年龄,而西澳大利亚板块和南美洲板块有明显的2 700 Ma的岩浆记录(图6;Li *et al.*, 2014).另外,华夏陆块、扬子陆块、印度板块、南极洲板块含有大量1 000~900 Ma的年龄信息,这与武功山地区~956 Ma年龄峰值相一致,表明它们都与罗迪尼亚超大陆聚合造山事件有关.而西澳大利亚板块和南美洲板块寒武纪沉积岩的相关研究表明,它们具有1 300~1 100 Ma的年龄区间(图6),明显早于前者对罗迪尼亚超大陆聚合造山事件的响应,同时也暗示着罗迪尼亚超大陆聚合造山事件具有明显的穿时性.综上所述,华夏陆块(包括武功山地区)在早古生代可能与扬子陆块、印度板块、南极洲板块具有更强的亲缘性,而与西澳大利亚和南美洲板块亲缘性较差.

**4.3.2 对华南新元古代早期变质事件的制约** 研究表明,扬子陆块与华夏陆块经过俯冲-碰撞拼合形成了统一的古华南板块,并在扬子陆块东南缘形成了以新元古代变质基底为主的江南造山带(Shu *et al.*, 2014, 2021; Yao *et al.*, 2019).而关于江南造山带的碰撞拼合时间,长期以来具有较大的分歧(Hsü *et al.*, 1990; Shu *et al.*, 2014).目前主要存在多种不同的认识,Hsü *et al.*(1990)提出扬子陆块和华南板块之间存在一个开阔海洋,在晚古生代到中生代时期,发生了一期东南向的洋壳俯冲运动,导致江南造山带的最终闭合.也有学者提出江南造山带碰撞-拼合时代为1 000~900 Ma,并认为江南造山带是格林威尔造山带的有机组成部分(Li *et al.*, 2002; Greentree *et al.*, 2006; Ye *et al.*, 2007; Zhang *et al.*, 2012).

通过对江南造山带及其周缘地区新元古代蛇绿岩、岛弧岩浆岩、S型花岗岩的锆石U-Pb测年、云母Ar-Ar测年、高压蓝片岩的发现(Shu and Charvet, 1996)以及蓝闪石的K-Ar测年、全岩地球化学等方面的深入研究,有的学者提出新元古代早期(860~800 Ma)古华南洋壳俯冲运动导致了江南活动大陆边缘的形成,随后扬子陆块和华夏陆块的聚合导致岛弧和扬子陆块发生碰撞,使得弧后边缘海或者弧后盆地的关闭,自此之后形成了中国统一的华南板块,华夏陆块与扬子陆块之间并无洋盆相隔(Shu and Charvet, 1996; 舒良树,2012;舒良树等,2020).值得指出的是,为何在扬子陆块与华夏陆块的碰撞拼合带只出现了新元古代绿片岩相变质作用,而没有发生高级变质作用?为何江南造山带缺少大规模的中-高级变质岩与高压变质岩?这是困惑研究江南造山带学者们的一个突出问题.

最近,Yan *et al.*(2015)报道了江南造山带西段岳阳-道县地区出露的新元古代-早古生代变质砂岩中的5个新元古代变质重结晶型碎屑锆石年龄为853~835 Ma,并将其解释为与扬子陆块与华夏陆块碰撞相关的变质作用的时代.类似地,Yao *et al.*(2017)对武夷山北缘的黎川-建宁地区出露的万源岩群含榴角闪黑云斜长片麻岩开展了锆石U-Pb测年,其中在7个变质边获得了谐和的$^{206}Pb/^{238}U$年龄,其加权平均年龄为860±8 Ma.Yao *et al.*(2017)基于华夏陆块早古生代地层仅仅遭受了低绿片岩相变质,推测万源群混合岩化含榴角闪黑云斜长片麻岩的变质时代为860 Ma;同时指出,在新元古代早期,华夏地块内部并不是统一的整体,不同块体间也存在A型俯冲-碰撞造山过程.

在本次研究的高滩组含榴云母石英片岩碎屑锆石中,笔者发现了一颗年龄为847±9 Ma的变质重结晶型碎屑锆石(测点19JX01-1.1-24),尽管仅发现了一颗重结晶结构的碎屑锆石,但仍具有重要的意义.测点19JX01-1.1-24碎屑锆石重稀土元素含量显著亏损,在稀土元素配分曲线上表现为平坦型,表明该变质锆石形成于与石榴子石

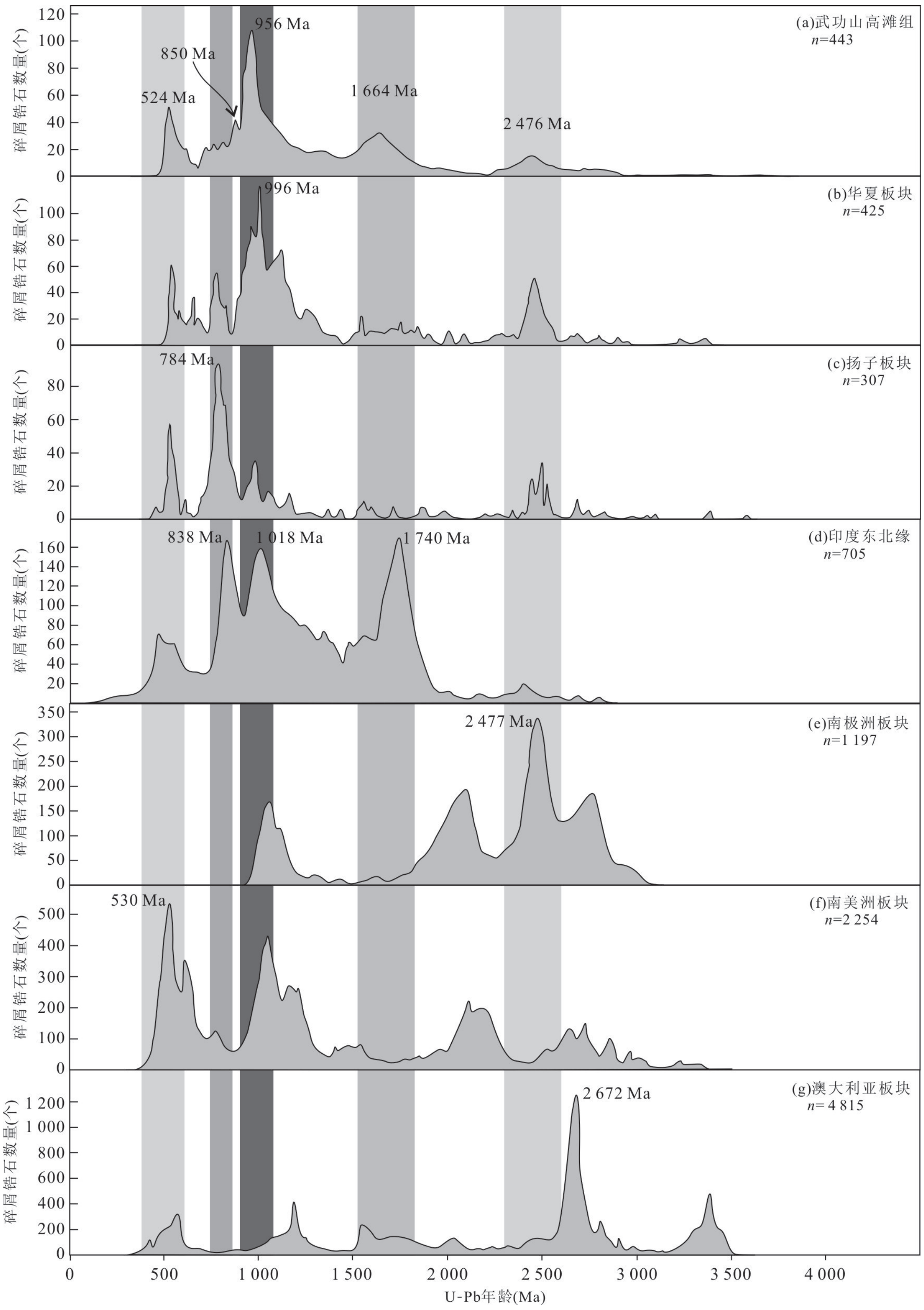


图6 武功山杂岩与世界区域前寒武系碎屑锆石U-Pb年龄频率直方对比图

Fig.6 Comparison of U-Pb age frequency histograms of Precambrian detrital zircons from Wugongshan complex and the world area

数据来源:a.本次研究及Wang *et al*.(2015);b.Yao *et al*. (2011);c. Yin (2003)、Wang *et al*. (2010)、Yao *et al*. (2015);d. Webb *et al*. (2011, 2013);e~g. Condie *et al*. (2009)

共生的变质岩中(Whitehouse *et al.*, 2003),结合其浑圆状晶形与内部结构(阴极发光图像表现为从边部至核部具有相对弱的阴极发光效应,为灰色-灰黑色,内部呈无明显环带结构),本次研究推测其形成于含石榴子石的高级变质岩(图3b-2).结合华南板块近年来新发现的新元古代年龄以及相关的S型花岗岩,本文推测包括江南造山带在内华南地区可能存在一套含石榴子石的中-高级变质岩系(Cawood *et al.*, 2013; Wang *et al.*, 2014; Yao *et al.*, 2017).

## 5 结论

本次研究对武功山杂岩中高滩组含榴云母石英片岩开展了锆石U-Pb定年和微量元素分析,结合已发表的相关数据,得出如下初步结论:

(1)高滩组中的含榴云母石英片岩最年轻一组碎屑锆石年龄为524±12 Ma,结合区域上高滩组被早古生代约462 Ma花岗岩侵入的地质关系,初步限定武功山地区高滩组的沉积时代为524~462 Ma.

(2)高滩组含榴云母石英片岩碎屑锆石U-Pb年龄变化于3 622~497 Ma之间,最主要的年龄峰值为956 Ma,4个次要的年龄峰值分别为2 456 Ma、1 644 Ma、850 Ma与524 Ma,高滩组与华夏陆块早古生代时期地层具有相似碎屑锆石年龄图谱与物源特征,指示早古生代武功山地区可能是华夏陆块的组成部分.

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附表见本刊官网(http://www.earth-science.net).

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