

# 武夷山中段建宁地区淡色花岗岩形成时代、 地球化学特征及地质意义

卢运可, 辛宇佳\*, 李建华, 王金铭

自然资源部古地磁与古构造重建重点实验室, 北京 100081;  
中国地质科学院地质力学研究所, 北京 100081

**摘要:** 淡色花岗岩是了解造山过程中地壳物质部分熔融行为的重要岩石探针, 对于揭示造山演化过程中变质和岩浆作用之间的联系具有十分重要的意义。本文对武夷山中段建宁地区淡色花岗岩开展了系统的岩石学、锆石 U-Pb 年代学及地球化学研究。结果表明, 建宁淡色花岗岩形成于~440 Ma, 并记录了晚期 410~405 Ma 深熔事件。淡色花岗岩属强过铝质岩石, 且富含 800~700 Ma 年龄继承锆石, 表明其源岩为新元古代麻源群变质沉积岩。建宁淡色花岗岩具高 SiO<sub>2</sub>、K<sub>2</sub>O, 贫 MgO、FeO<sub>t</sub>、CaO、Na<sub>2</sub>O, 富集 LREE 和 LILEs, 亏损 HREE 和 HFSEs, 高 Rb/Sr 比值等特征, 暗示其源岩可能发生了黑云母参与的含水或脱水熔融反应。综合本文结果和华南早古生代沉积、变质、岩浆等多方面地质记录可知, 建宁地区淡色花岗岩形成于同造山地壳加厚背景下, 而晚期 410~405 Ma 的深熔事件可能与后造山伸展减薄有关。

**关键词:** 武夷山; 早志留世—早泥盆世; 淡色花岗岩; 地壳加厚; 伸展减薄; MC-LA-ICPMS 锆石 U-Pb

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## Geochronological and Geochemical Constraints of Leucogranites in Jianning Area, Central Wuyishan, and Their Geological Implications

LU Yunke, XIN Yujia\*, LI Jianhua, WANG Jinming

Key Laboratory of Paleomagnetism and Tectonic Reconstruction, Ministry of Natural Resources, Beijing 100081;  
Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081;

**Abstract:** Our study shows the combined petrological, geochemical, and geochronological analysis of the Jianning leucogranites in Central Wuyishan. MC-LA-ICPMS zircon U-Pb dating data show the formation of Jianning leucogranites at ~440 Ma with a late-stage anatetic event occurring at 410–405 Ma. These leucogranites are strongly peraluminous and contain inherited zircons with ages clustering at 800–700 Ma, suggesting that the Neoproterozoic meta-sedimentary rocks of the Mayuan Group are their source rocks. They exhibit high SiO<sub>2</sub> and K<sub>2</sub>O, low MgO, FeO<sub>t</sub>, CaO, and Na<sub>2</sub>O, enrichment in LREE and LILEs, depletion in HREE and HFSEs, and high Rb/Sr ratios, suggesting their generation by biotite fluid-fluxed or dehydration melting reactions. Integrating our results and other Early Paleozoic orogenic sedimentary, metamorphic, and magmatic records of South China, we inferred that the Jianning leucogranites were formed during the syn-orogenic crustal thickening phase, and the 410~405 Ma anatetic event may be related to the post-orogenic crustal thinning.

**Key words:** Wuyishan; Early Silurian to Early Devonian; leucogranite; crustal thickening; extensional thinning; MC-LA-ICPMS zircon U-Pb dating

华南由扬子和华夏两个地块组成, 二者具有不同的前寒武纪基底: 扬子地块包含太古宙结晶基底(>3.2~2.9 Ga TTG 片麻岩; Qiu et al., 2000; Zheng et

al., 2006; Liu X M et al., 2008; Guo et al., 2014; Li et al., 2014a), 而华夏地块基底主要为古元古代和新元古代变质火山-沉积岩系(Yu et al., 2007, 2009,

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第一作者简介: 卢运可, 男, 1997 年生。硕士研究生。地质工程专业。E-mail: luyunke2021@163.com。

\*通信作者: 辛宇佳, 男, 1988 年生。博士, 副研究员。主要从事岩石地球化学研究。E-mail: xinyujiacags@cags.ac.cn; xyjasd123@163.com。

2010; Liu Y S et al., 2008; Li et al., 2011)。扬子和华夏地块于新元古代碰撞拼合形成统一的华南大陆(图 1; Shu et al., 1996; Li et al., 2009; 舒良树, 2012; Zhang et al., 2015; Xia et al., 2018; Yan et al., 2019; Yao et al., 2019; Shu et al., 2021)。

显生宙以来, 华南大陆主要遭受了三期造山事件的叠加改造, 分别为早古生代、印支期以及侏罗—白垩纪造山事件(Lin et al., 2008; Faure et al., 2009, 2014; Charvet et al., 2010; Wang Y J et al., 2013; Li et al., 2014b, 2018, 2023; Shu et al., 2015)。其中, 早古生代造山事件是影响最为深远的一期构造-岩浆事件, 其导致华南大陆地壳显著缩短加厚, 并诱发广泛的地壳深熔和岩浆作用, 形成了壮观的NE-SW 走向造山带, 范围覆盖了扬子地块东南和华夏地块西部(图 1; Cluzel et al., 1991; Ren, 1991; Charvet et al., 2010)。该期造山作用主要表现为: 中—上泥盆统角度不整合于前志留系之上、志留系沉积缺失、奥陶—志留纪中-高级(绿片岩相到角闪岩相, 局部可达麻粒岩相)变质和地壳深熔作用、志留—泥盆纪岩浆活动等(Faure et al., 2009; Charvet et al., 2010; Li et al., 2010; 舒良树, 2012; Charvet, 2013; Yao et al., 2014a, b; Shu et al., 2015; Huang et al., 2019)。

华南早古生代造山带一个显著特征是发育大规模面状展布的花岗质岩浆岩, 面积超过 20 000 km<sup>2</sup>(舒良树等, 2008; Wang Y J et al., 2013)。围绕这些花岗质岩浆岩, 学者开展了大量研究, 它们的结晶时代介于 460 Ma 和 380 Ma 之间, 集中在~445~425 Ma, 多为强过铝质 S 型花岗岩(舒良树等, 2008; Wang Y J et al., 2011, 2013; Chu et al., 2012; Xu et al., 2015), 少数为准铝质 I 型(台山、张家坊和宏夏桥岩体; Huang et al., 2013; Guan et al., 2014; Yu et al., 2016)、S-I 过渡类型(下湾和墩头花岗岩; Xia et al., 2014)或 A 型花岗岩(营上、会同和鹅婆花岗岩; Feng et al., 2014; Xin et al., 2020)。全岩地球化学和 Sr-Nd-Hf 同位素结果表明, 这些花岗质岩石大多起源于古老变质沉积岩和/或变火成岩的部分熔融, 并不同程度地混入了新生地壳衍生的熔体(Wang et al., 2011; Huang et al., 2013; Feng et al., 2014; Xia et al., 2014; Shu et al., 2015; Zhang et al., 2017)。

除花岗岩外, 该期造山事件还诱发广泛的地壳深熔, 形成早古生代混合岩。这些混合岩主要分布于武夷山、武功山和云开大山等地区, 并在空间上与花岗岩体密切伴生(图 1)。混合岩中常发育有淡色花岗质岩脉或岩株, 这些淡色花岗岩是了解造山过程中地壳物质部分熔融行为的重要岩石探针, 对于

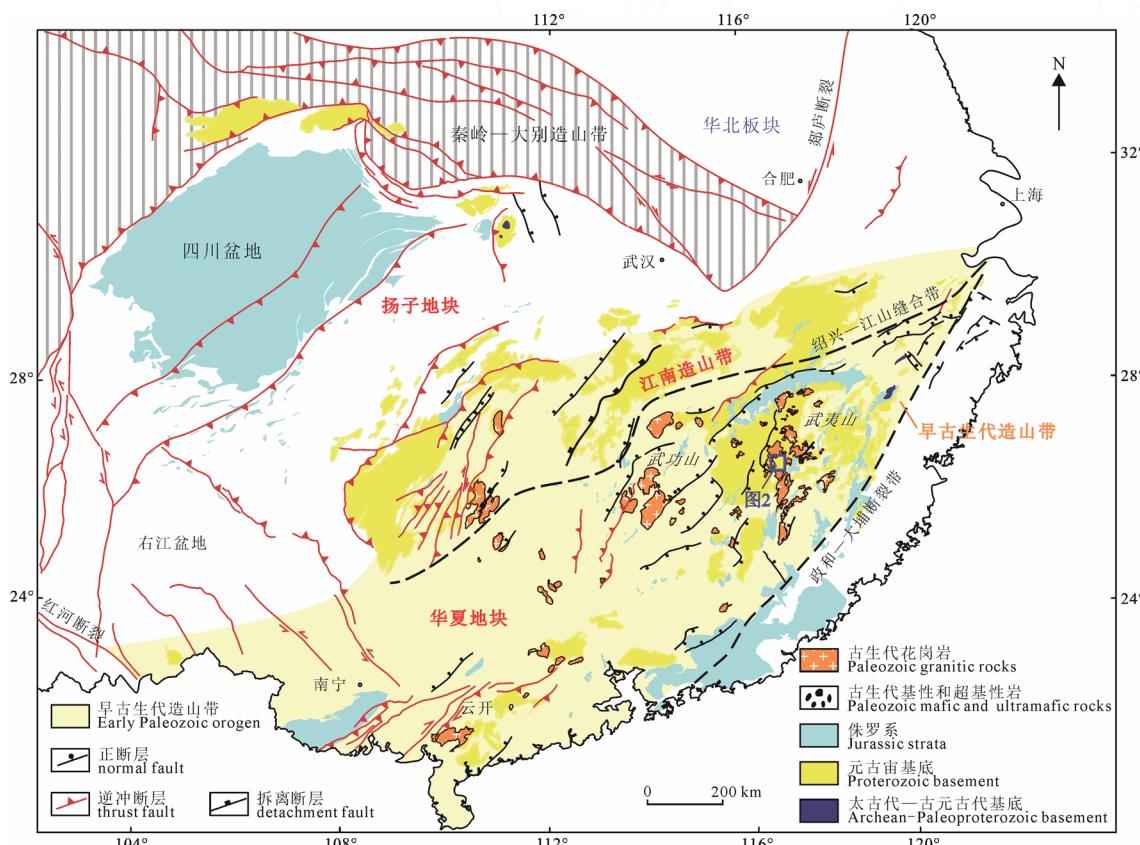


图 1 华南大陆及邻区大地构造简图(据 Li et al., 2017 改编)

Fig. 1 Simplified geological map of South China and its adjacent blocks (modified from Li et al., 2017)

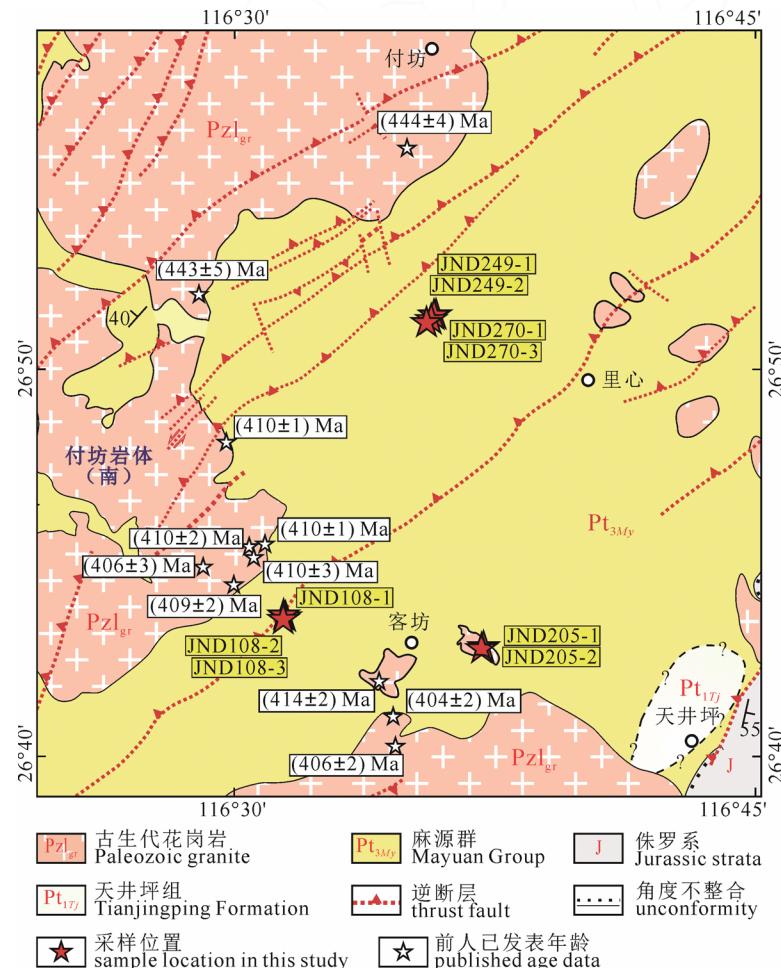
揭示造山演化过程中,变质和岩浆作用之间的联系具有十分重要的意义(曾令森等,2017)。尽管前人对华南早古生代花岗岩体开展了大量研究,但混合岩中淡色花岗岩的研究工作仍较少,其形成时代、地球化学特征和岩石学成因仍缺少限定。因此,本文选取武夷山中段的建宁地区作为研究区,对该地区混合岩中的淡色花岗质岩脉和岩株开展了系统的锆石U-Pb同位素定年和全岩地球化学研究,结果表明,淡色花岗岩形成于444~443 Ma,是同造山地壳加厚背景下新元古代变质沉积基底发生黑云母参与的部分熔融反应的产物。

## 1 区域地质概况

建宁地区位于武夷山中段,区内主要出露前寒武纪基底地层和古生代岩浆岩(图1,2)。前寒武纪基底地层主要包括古元古代天井坪岩组和新元古代麻源群。天井坪岩组分布于建宁西南天井坪村一带(图2),为一套变质-火山沉积岩系,主要由黑云(角闪)斜长变粒岩、云母片岩和斜长角闪岩透镜体等组成,

SHRIMP U-Pb定年结果表明其沉积时代为1 790~1 766 Ma(李献华等,1998; Wan et al., 2007)。麻源群地层是建宁地区分布最为广泛的基底地层(图2),其岩性主要为含矽线石、石榴子石的黑云(斜长)变粒岩夹云母片岩、石英岩和少量斜长角闪岩,原岩以泥砂质碎屑岩为主,夹基性、中酸性火山岩。碎屑锆石LA-ICP-MS U-Pb定年显示,这些变质沉积岩通常出现单一的~800~700 Ma年龄峰值,并含有少量古元古代—新太古代锆石,其沉积时代应<730 Ma(Wan et al., 2007; 徐先兵等,2010; Yao et al., 2017)。

受早古生代造山作用影响,这些前寒武纪基底地层普遍发生褶皱和韧性剪切,并伴随有中-高级变质作用和强烈的混合岩化(Charvet et al., 2010; Li et al., 2017),形成几何形态和流变学性质各不相同的混合岩,如条带状、网脉状和筏块状混合岩等(图3a-d)。岩相学和锆石U-Pb年代学研究表明,这些混合岩是基底变质岩在~0.5 GPa和~800~828 °C条件下,发生黑云母脱水熔融反应形成的(刘锐等,

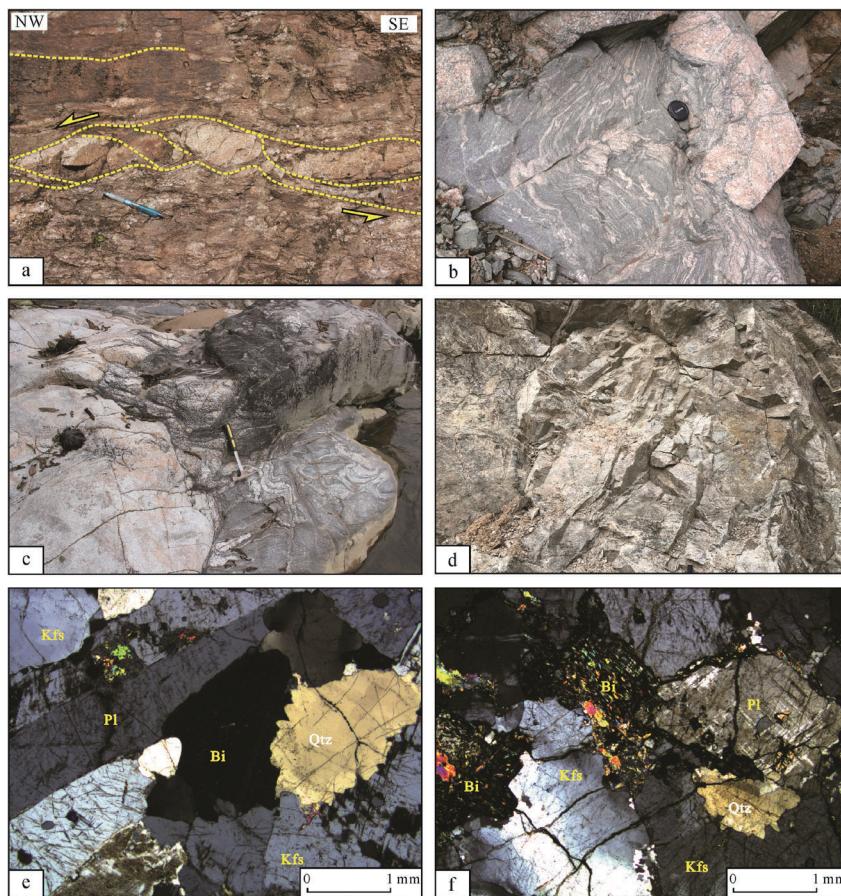


年龄数据来源:张芳荣等,2010; Xin et al., 2020。

Age data from: ZHANG et al., 2010; Xin et al., 2020.

图2 建宁地区地质简图及采样位置(据Xin et al., 2020改编)

Fig. 2 Sketch map of the Jianning area and sampling locations (modified from Xin et al., 2020)



a—条带状混合岩野外照片; b—网脉状混合岩野外照片; c—正长花岗岩野外照片; d—二长花岗岩野外照片; e—正长花岗岩正交偏光下显微照片; f—二长花岗岩正交偏光下显微照片; Pl—斜长石; Kfs—钾长石; Bi—黑云母; Qtz—石英。  
a—a field photograph of stromatic migmatite; b—a field photograph of net-structured migmatite; c—a photomicrograph of syenogranite (crossed nicols); d—a field photograph of monzonitic granite; e—a photomicrograph of syenogranite (crossed nicols); f—a photomicrograph of monzogranite (crossed nicols); Pl—plagioclase; Kfs—K-feldspar; Bi—biotite; Qtz—quartz.

图 3 建宁淡色花岗岩野外及镜下照片

Fig. 3 Representative field photographs and photomicrographs of leucogranite from the Jianning area

2008; Huang et al., 2020); 混合岩化作用发生时代大致为 503~433 Ma(Wan et al., 2007; 曾雯等, 2008; Li et al., 2011; Chen et al., 2018)。淡色花岗岩广泛分布于这些混合岩中, 在浅色体含量较少的条带状和网脉状混合岩中, 淡色花岗岩常以岩脉的形式产出(图 3a~c), 它们或平行于混合岩面理(图 3a), 或明显截切混合岩面理(图 3c)。在浅色体含量较多的筏块状混合岩中, 淡色花岗岩则以小型岩株的形式产出(图 3d)。

建宁地区古生代岩浆岩均侵入到上述前寒武纪基底地层中(图 2)。根据岩石矿物组合和产出形式的不同, 可将其分为花岗质岩基和基性侵入岩脉两部分。花岗质岩基包括 S 型花岗岩(~440 Ma)和 A 型花岗岩(414~404 Ma), S 型花岗岩与加厚地壳的部分熔融有关(张芳荣等, 2010), 而 A 型花岗岩是高温条件下, 下地壳麻粒岩相残余物发生部分熔融的产物(Xin et al., 2020)。基性侵入岩为马元辉绿岩脉(409~401 Ma), 是富集的岩石圈地幔发生部分熔融的产物(Xin et al., 2020)。S 型花岗岩形成于同造山地壳加厚的背景下(张芳荣等, 2010), 而 A 型花岗岩

和辉绿岩则形成于后造山地壳伸展坍塌背景下(Xin et al., 2020)。

## 2 岩石特征和样品采集

建宁地区淡色花岗岩岩性主要为正长花岗岩和二长花岗岩, 主要矿物由石英(25%~40%)、碱性长石(30%~60%)、斜长石(10%~40%)和少量黑云母(3%~5%)等组成(图 3e~f), 副矿物为锆石、磷灰石和磁铁矿等。斜长石为自形-半自形板状, 多发生高岭土化和绢云母化; 石英呈它形粒状, 部分石英与碱性长石形成滴状交生体; 碱性长石为半自形板状, 多为微斜长石和条纹长石; 黑云母呈片状分布于石英和长石颗粒间, 大都发生绿泥石化和白云母化(图 3e~f)。

本研究共采集 9 件淡色花岗岩样品, 其中锆石 U-Pb 同位素样品 4 件(JND108-1, JND205-1, JND249-1 及 JND270-1), 全岩地球化学样品 5 件(JND108-2、3, JND205-2, JND249-2 和 JND270-3), 具体采样位置见图 2 和表 1。

表 1 采样位置、岩石类型及矿物组合、同位素年龄结果汇总表  
Table 1 Summary of locations, rock types, mineral assemblages, and zircon U-Pb dating results of leucogranite samples in this study

样品号	岩石类型	经纬度		矿物组合	结晶年龄	分析测试方法
		经度	纬度			
JND108-1, 2, 3	正长花岗岩	E116°31'34.4"	N26°43'51.6"	石英(25%~40%)+斜长石 (10%~20%)+碱性长石 (35%~60%)+黑云母(3%~5%)	(444±2) Ma	锆石 LA-ICP-MS
JND205-1, 2	二长花岗岩	E116°37'02"	N26°43'01.8"	石英(30%~35%)+斜长石 (25%~30%)+碱性长石 (30%~40%)+黑云母(3%~5%)	(443±1) Ma	锆石 LA-ICP-MS
JND249-1, 2	二长花岗岩	E116°31'52"	N26°51'01.4"	石英(30%~35%)+斜长石 (30%~40%)+碱性长石 (30%~40%)+黑云母(3%~5%)	(443±1) Ma	锆石 LA-ICP-MS
JND270-1, 3	正长花岗岩	E116°35'20.9"	N26°51'39.5"	石英(35%~40%)+斜长石 (20%~25%)+碱性长石 (30%~50%)+黑云母(3%~5%)	(443±2) Ma	锆石 LA-ICP-MS

注: LA-ICP-MS: 激光烧蚀多接收器电感耦合等离子体质谱仪。

### 3 测试方法

首先, 将样品清洗晾干并粉碎至 80 目, 用水淘洗, 保留重砂部分, 经强磁分选剔除铁磁性物质, 再经电磁分选和酒精淘洗后, 获得锆石, 在显微镜下挑纯。样品的制靶及阴极发光(CL)照相均是在北京锆年领航科技有限公司完成。MC-LA-ICPMS 锆石 U-Pb 同位素测试工作是在中国地质科学院矿产资源研究所同位素实验室完成。激光剥蚀系统为 Newwave UP213, 多接收器电感耦合等离子体质谱仪为 Bruker M90。激光剥蚀过程中采用氦气作载气、氩气为补偿气来调节灵敏度, 激光束斑直径为 32  $\mu\text{m}$ , 剥蚀频率 10 Hz, 每个时间分辨分析数据包括大约 15~20 s 的空白信号和 45 s 的样品信号。锆石 U、Th、Pb 含量以 SRM610 作为外标的方法进行计算, U-Th-Pb 同位素比值采用 GJ-1 作外标进行校正。分析数据的离线处理(包括对样品和空信号的选择、仪器灵敏度漂移校正、元素含量及 U-Th-Pb 同位素比值和年龄计算)采用软件 ICPMSDataCal(Liu et al., 2010)完成。详细的仪器操作条件和数据处理方法可见侯可军等(2009)。

全岩主、微量元素分析是在中国地质科学院国家地质实验测试中心进行的。主要氧化物包括烧失量(LOI)通过 X 射线荧光光谱仪(Rigaku-3080)测定, 误差<5%。微量元素, 如 Zr、Nb、V、Cr、Sr、Ba、Zn、Ni、Rb 和 Y, 使用 Rigaku-2100 型 X 射线荧光光谱仪分析, 误差<3%~5%。其他微量元素(包括稀土元素 REE)在 TJAPQ-ExCell 型 ICP-MS 上分析, 含量>10×10<sup>-6</sup> 和<10×10<sup>-6</sup> 的元素分析误差分别为<5% 和 5%~10%, 详细分析测试方法见何红蓼等(2002)。

### 4 测试结果

#### 4.1 锆石 U-Pb 定年结果

本文共对 4 个淡色花岗岩样品进行了 LA-ICP-MS 锆石 U-Pb 同位素定年。淡色花岗岩的锆石多为无色、透明-半透明、自形-半自形长柱状晶体(图 4a~d)。锆石颗粒较大, 长轴为 100~200  $\mu\text{m}$ , 长宽比约为~1.5:1~3:1。在 CL 图中, 大多数锆石显示出核-边结构特征: 核部明亮且形状不规则, 部分具有清晰的岩浆振荡环带, 可能为残留继承锆石核; 边部亮度较暗, 无环带或者发育弱的振荡环带, 可能为变质深熔成因锆石(图 4a~d)。锆石 U-Pb 同位素测试结果和 U-Pb 谱和图分别见附表 1 和图 5。

样品 JND108-1 采自建宁县以西小岭下村附近(图 2, 表 1)。本文共对该样品的 27 颗锆石进行了 43 个点的 U-Pb 同位素测试。其中, 27 个测试点位于锆石增生边上, 另外 16 个点位于锆石继承核上。锆石增生边上的 27 个测点具有较低的 Th 和较高的 U 含量, 分别为  $14 \times 10^{-6}$ ~ $131 \times 10^{-6}$  和  $1398 \times 10^{-6}$ ~ $4754 \times 10^{-6}$ , 对应 Th/U 比值较低, 介于 0.01~0.09 之间。这些测点年龄均谐和, 其中 24 个测点年龄稍大, 它们的  $^{206}\text{Pb}/^{238}\text{U}$  加权平均年龄为 (444±2) Ma ( $\text{MSWD}=0.58, n=24$ )(图 5a); 另外 3 个测点年龄较小,  $^{206}\text{Pb}/^{238}\text{U}$  加权平均年龄为 (406±3) Ma ( $\text{MSWD}=0.32, n=3$ )(图 5a)。位于锆石继承核的 16 个测点具有变化较大的 Th ( $83 \times 10^{-6}$ ~ $1318 \times 10^{-6}$ ) 和 U ( $86 \times 10^{-6}$ ~ $1886 \times 10^{-6}$ ) 含量, Th/U 比值较高, 介于 0.12~1.49 之间, 均大于 0.1(附表 1)。这些核部分析点的年龄较为谐和(谐和度均>90%), 且年龄变化较大, 介于 2 583~702 Ma 之间, 大多集中在 950~702 Ma 之间(12 个)。

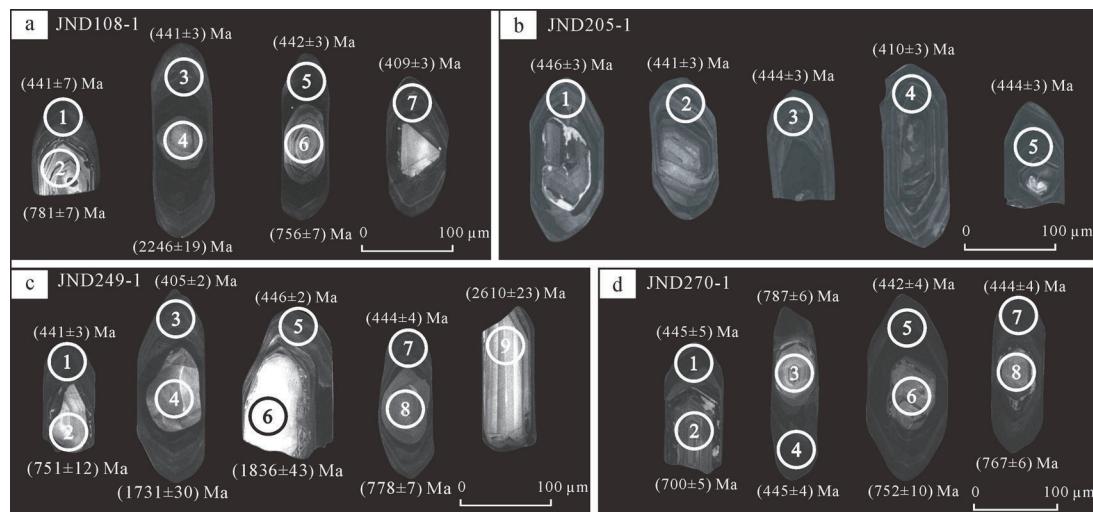


图 4 建宁淡色花岗岩代表性锆石阴极发光图像

Fig. 4 Cathodoluminescence images of representative zircons from the Jianning leucogranites

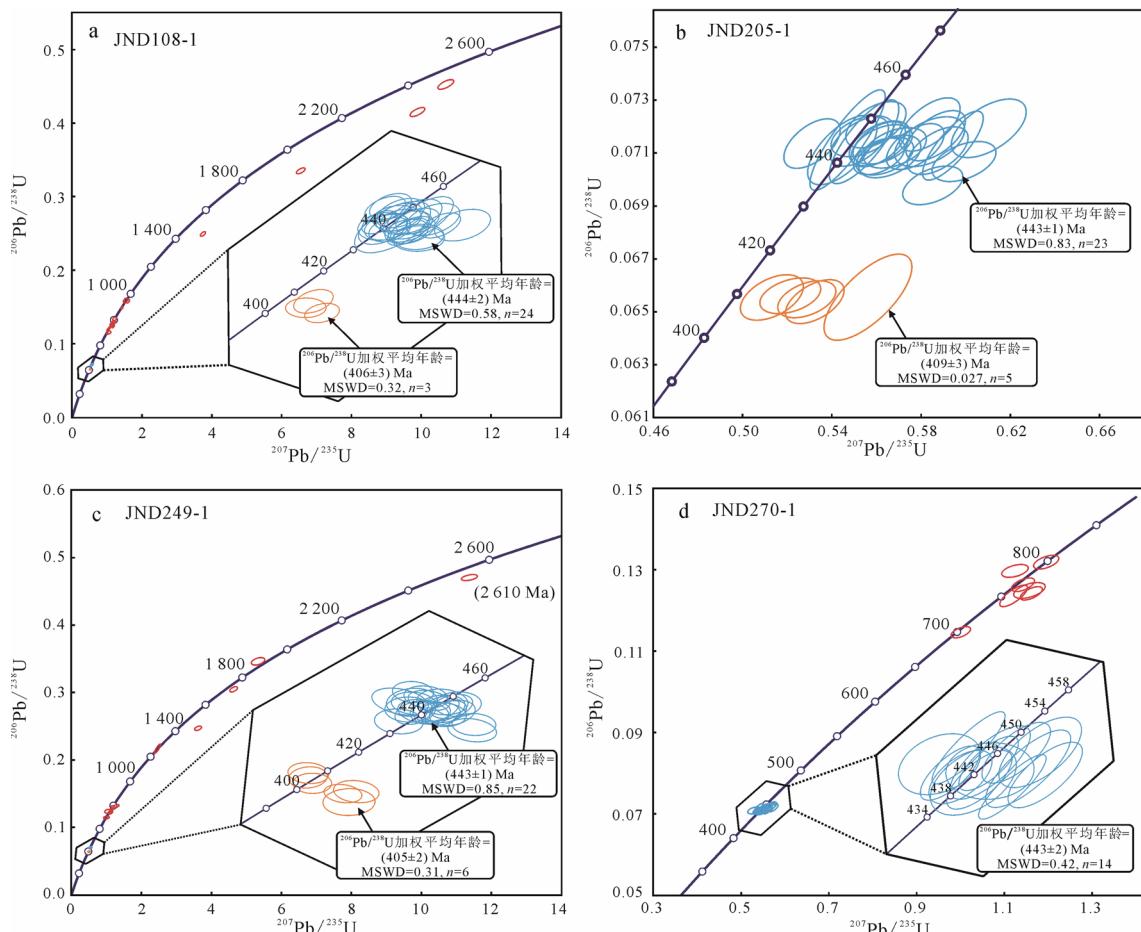


图 5 建宁淡色花岗岩锆石 U-Pb 谱和图

Fig. 5 Concordia diagrams of zircon U-Pb data for the leucogranite samples in the Jianning area

JND205-1 样品采自客坊乡以东(图 2, 表 1)。本文选取了该样品的 28 颗锆石, 进行了 28 个点的锆石 U-Pb 同位素分析。该样品的锆石具变化较大的 Th 含量( $158 \times 10^{-6}$ ~ $969 \times 10^{-6}$ )和较高的 U 含量( $662 \times 10^{-6}$ ~ $427 \times 10^{-6}$ ), 对应的 Th/U 比值为 0.18~3.79(附表 1)。这些测试点中, 23 个测点年龄较为集中且谐和, 它们的  $^{206}\text{Pb}/^{238}\text{U}$  加权平均年龄为

(443±1) Ma(MSWD=0.83, n=23)(图 5b)。另外 5 个测点的年龄偏小, 它们的  $^{206}\text{Pb}/^{238}\text{U}$  加权平均年龄为 (409±3) Ma(MSWD=0.027, n=5)(图 5b)。

JND249-1 样品采自建宁县岩上村以北(图 2, 表 1)。本文共选取该样品的 35 颗锆石, 进行了 41 个点的锆石 U-Pb 同位素测试。这些测试点中, 28 个测点位于锆石增生边上, 13 个测点位于锆石的继

承核上。位于增生边测点的年龄可以分为两组: 第一组年龄稍大, 数量较多(22个), 它们具有极低的Th含量( $14 \times 10^{-6}$ ~ $52 \times 10^{-6}$ )和较高的U含量( $1138 \times 10^{-6}$ ~ $1855 \times 10^{-6}$ ), 因而其Th/U比值很低, 为0.01~0.03。这些测点年龄均谐和, 其 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为( $443 \pm 1$ ) Ma(MSWD=0.85,  $n=22$ ) (图5c); 第二组测点年龄较小且数量较少(6个), 它们同样具有极低的Th含量( $34 \times 10^{-6}$ ~ $58 \times 10^{-6}$ )和较高的U含量( $1305 \times 10^{-6}$ ~ $1553 \times 10^{-6}$ ), Th/U比值极低

(0.02~0.04)。这些测点年龄同样谐和, 其 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为( $405 \pm 2$ ) Ma(MSWD=0.31,  $n=6$ ) (图5c)。核部13个测点的Th含量为 $46 \times 10^{-6}$ ~ $498 \times 10^{-6}$ , U含量为 $53 \times 10^{-6}$ ~ $486 \times 10^{-6}$ , 对应的Th/U比值为0.2~1.95(附表1)。这些核部分析点年龄均谐和, 且变化较大, 为2610~704 Ma(图5c, 附表1), 大多集中在803~704 Ma之间(8个)。同时, 继承核中出现了一颗新太古代年龄锆石, 为( $2610 \pm 23$ ) Ma(图5c, 附表1)。

表2 建宁淡色花岗岩全岩主量元素(wt%)和微量元素( $\times 10^{-6}$ )数据  
Table 2 Whole-rock major oxides (wt%) and trace elements ( $\times 10^{-6}$ ) of the Jianning leucogranites

样品号	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	Fe <sub>2</sub> O <sub>3</sub>	FeO <sub>t</sub>	MnO	MgO	CaO
JND108-2	75.78	0.12	13.17	0.40	0.44	0.80	0.06	0.35	0.11
JND108-3	71.07	0.13	14.84	0.36	0.78	1.10	0.05	0.42	0.16
JND205-2	71.91	0.30	14.46	0.75	0.85	1.53	0.04	0.59	0.75
JND249-2	72.96	0.16	14.11	0.54	0.57	1.06	0.05	0.41	1.32
JND270-3	74.00	0.06	13.22	0.79	1.96	2.67	0.02	0.10	0.24
样品号	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	灼失量	A/CNK	K <sub>2</sub> O+Na <sub>2</sub> O	K <sub>2</sub> O/Na <sub>2</sub> O	FeO <sub>t</sub> +MgO	Sc
JND108-2	1.06	6.20	0.07	1.53	1.52	7.26	5.85	1.15	3.50
JND108-3	0.48	9.98	0.11	1.06	1.25	10.46	20.79	1.52	3.74
JND205-2	3.01	5.50	0.05	0.80	1.56	8.51	1.83	2.12	5.63
JND249-2	3.21	4.95	0.06	0.93	1.08	8.16	1.54	1.47	3.29
JND270-3	2.45	5.73	0.02	0.44	1.24	8.18	2.34	2.77	1.25
样品号	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr
JND108-2	9.48	4.38	3.20	2.75	1.91	32.20	17.30	270.00	65.60
JND108-3	10.70	4.13	1.82	2.18	1.52	22.40	16.50	339.00	130.00
JND205-2	18.30	7.41	2.87	2.34	235.00	41.20	18.40	183.00	227.00
JND249-2	12.20	4.77	1.79	2.01	0.74	29.50	16.80	146.00	206.00
JND270-3	35.50	2.07	1.13	1.11	0.61	29.50	18.20	167.00	140.00
样品号	Y	Zr	Nb	Cs	Ba	Hf	Ta	Pb	Th
JND108-2	9.21	60.10	9.67	7.31	774.00	2.47	1.22	30.80	4.28
JND108-3	29.40	47.70	10.00	6.65	1400.00	1.87	1.21	46.90	7.12
JND205-2	9.19	112.00	14.30	6.29	1476.00	3.87	2.33	33.80	16.50
JND249-2	14.70	86.50	5.33	5.94	1100.00	3.37	0.71	27.00	18.60
JND270-3	4.45	93.30	0.92	5.46	1288.00	3.58	0.09	42.90	8.24
样品号	U	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb
JND108-2	2.61	15.60	23.80	3.24	12.80	1.45	0.51	1.90	0.30
JND108-3	3.57	24.60	36.20	5.05	20.50	2.36	0.93	3.78	0.70
JND205-2	3.44	52.90	104.00	11.40	42.00	5.31	1.00	5.02	0.55
JND249-2	2.92	61.40	119.00	13.40	50.60	7.05	0.98	5.91	0.67
JND270-3	0.98	25.60	44.30	5.24	20.90	1.88	0.40	2.32	0.26
样品号	Dy	Ho	Er	Tm	Yb	Lu	$\Sigma$ REE	LREE	HREE
JND108-2	1.72	0.37	1.02	0.16	1.02	0.16	64.05	57.40	6.65
JND108-3	4.48	1.02	2.94	0.49	2.79	0.44	106.28	89.64	16.64
JND205-2	2.45	0.36	1.04	0.12	0.74	0.13	227.02	216.61	10.41
JND249-2	3.28	0.55	1.62	0.25	1.62	0.28	266.61	252.43	14.18
JND270-3	1.26	0.18	0.43	<0.05	0.29	<0.05	103.16	98.32	4.74
样品号	(La/Yb) <sub>N</sub>	(Dy/Yb) <sub>N</sub>	Eu/Eu <sup>*</sup>	Rb/Sr					
JND108-2	10.33	1.10	0.94	4.12					
JND108-3	5.96	1.05	0.95	2.61					
JND205-2	48.31	2.16	0.59	0.81					
JND249-2	25.61	1.32	0.46	0.71					
JND270-3	59.65	2.83	0.59	1.19					

JND270-1 样品采自建宁县岩上村东北一个采石场中(图 2, 表 1)。本文共对该样品的 18 颗锆石进行了 21 个点的锆石 U-Pb 同位素分析。这些测试点中, 14 个点位于锆石增生边上, 其余 7 个点位于锆石继承核上。14 个锆石增生边测点的 Th 含量为  $24 \times 10^{-6} \sim 176 \times 10^{-6}$ , 相对较低, U 含量变化极大, 介于  $206 \times 10^{-6} \sim 090 \times 10^{-6}$  之间, 对应的 Th/U 比值为 0.02~0.61(仅 4 个分析点 Th/U 比值  $> 0.1$ , 其余均明显  $< 0.1$ )。这些测点年龄均谐和, 它们的  $^{206}\text{Pb}/^{238}\text{U}$  加权平均年龄为  $(443 \pm 2)$  Ma(MSWD=0.42,  $n=14$ )(图 5d)。7 个位于锆石继承核的测点年龄明显偏大, 它们的 Th 含量为  $120 \times 10^{-6} \sim 240 \times 10^{-6}$ , U 含量为  $124 \times 10^{-6} \sim 313 \times 10^{-6}$ , Th/U 比值为 0.64~1.29。这些测点年龄均谐和, 且集中在 799~700 Ma 之间(图 5d, 附表 1)。

## 4.2 全岩地球化学

本文对建宁地区淡色花岗岩的 5 个样品进行了全岩主、微量元素及稀土元素分析, 测试结果见表 2。

建宁地区淡色花岗岩具有较高的  $\text{SiO}_2$  含量( $71.07 \sim 75.78$  wt%) 和全碱含量( $\text{K}_2\text{O} + \text{Na}_2\text{O} = 7.26 \sim 10.46$  wt%), 在  $(\text{K}_2\text{O} + \text{Na}_2\text{O})-\text{SiO}_2$ (TAS) 图解中, 多数样品均落入亚碱性花岗岩区域内, 少数样品显示出碱性花岗岩特征(图 6a)。样品  $\text{K}_2\text{O}$  含量较高, 介于 4.95~9.98 wt% 之间, 具高钾钙碱性系列岩石特征(图 6a)。 $\text{Al}_2\text{O}_3$  含量较高( $13.17 \sim 14.84$  wt%),  $\text{A/CNK}$  值介于 1.08~1.56 之间, 属强过铝质岩石(图 6b)。所有样品具极低的  $\text{TiO}_2$ ( $0.06 \sim 0.30$  wt%)、 $\text{MgO}$ ( $0.10 \sim 0.59$  wt%)、 $\text{FeO}_t$ ( $0.80 \sim 2.67$  wt%)、 $\text{P}_2\text{O}_5$ ( $0.02 \sim 0.11$  wt%)、 $\text{CaO}$ ( $0.11 \sim 1.32$  wt%) 和  $\text{MnO}$ ( $0.02 \sim 0.06$  wt%) 含量。在 Hacker 图解中,  $\text{SiO}_2$  与  $\text{Al}_2\text{O}_3$  呈负相关关系, 而与其它主量元素之间的线性关系则不明显(图 7a~i)。

淡色花岗岩样品的稀土元素总量( $\Sigma\text{REE}$ )变化较为明显, 其  $\Sigma\text{REE} = 64.05 \times 10^{-6} \sim 266.61 \times 10^{-6}$ 。样品的 HREE 含量普遍较低( $4.74 \times 10^{-6} \sim 16.64 \times 10^{-6}$ ), LREE 含量变化较大( $57.40 \times 10^{-6} \sim 252.43 \times 10^{-6}$ ), 因而样品的  $(\text{La/Yb})_N$  比值较高且变化较大( $5.96 \sim 59.65$ ; 表 2), 轻、重稀土分馏明显。在球粒陨石标准化图解中(图 8a), 稀土配分曲线呈右倾型。各样品的  $\text{Eu/Eu}^*$  值为 0.46~0.95, 显示出不同程度的 Eu 负异常(图 8a)。在微量元素蛛网图中(图 8b), 样品均富集  $\text{Rb}$ 、 $\text{Ba}$ 、 $\text{Th}$  和  $\text{U}$ , 明显亏损  $\text{Nb}$ 、 $\text{Ta}$ 、 $\text{P}$  和  $\text{Ti}$ , 显示出壳源岩浆的微量元素特征。

## 5 讨论

### 5.1 建宁地区淡色花岗岩的形成时代

建宁地区淡色花岗岩样品中锆石具典型的核-

边结构, 锆石增生边通常亮度较暗, 无环带或者发育弱的振荡环带(图 4a~d), 并具有低 Th、高 U 和低 Th/U 比值(表 2)。这些特征表明, 这些增生边为深熔成因锆石(吴元保等, 2004)。本文在这些锆石增生边中获得了 444~443 Ma 和 409~405 Ma 两组年龄(图 5a~d)。其中, 444~443 Ma 年龄锆石数量较多(图 5a~d), 且与建宁地区混合岩中的花岗闪长质浅色体( $(447 \pm 2)$  Ma; 曾雯等, 2008)和 S 型花岗岩( $444 \sim 443$  Ma; 张芳荣等, 2010)结晶年龄在误差范围内一致, 因此, 本文将 444~443 Ma 解释为建宁地区淡色花岗岩的结晶时代。409~405 Ma 年龄锆石数量较少(图 5a~c), 其与建宁地区出露的 A 型花岗岩结晶年龄十分接近( $414 \sim 404$  Ma; Xin et al., 2020), 因此, 本文将 409~405 Ma 解释为晚期深熔事件时代, 暗示淡色花岗岩中可能混入了少量晚期深熔熔体。综合本文新获得的和前人已经发表的锆石 U-Pb 年龄数据可知, 建宁地区分别于 444~443 Ma 和 409~405 Ma, 发生了两期变质深熔事件。

### 5.2 建宁地区淡色花岗岩的成因

建宁地区淡色花岗岩普遍存在继承锆石核(图 4a, c, d), 这些继承核通常是在深熔作用过程中从源岩继承下来的, 因为基底变质岩在深熔过程中, 由于熔融温度相对较低, 碎屑锆石在熔体中不能完全溶解(Watson, 1996), 这些残留的锆石将为深熔成因锆石的生长提供成核作用, 因此淡色花岗岩中锆石通常具有核-边结构(图 4a~d), 而这些继承核的年龄信息能够很好地限定其源岩的时代。从本文获得的淡色花岗岩锆石继承核的年龄来看, 它们的年龄变化较大, 介于 2 610~700 Ma, 且大都集中在 800~700 Ma 之间, 并出现了少量古元古代和新太古代年龄的锆石(图 4a, c, d; 附表 1), 这种年龄分布规律与建宁地区出露的新元古代麻源群变质沉积岩的碎屑锆石年龄分布特征一致(Wan et al., 2007; Yao et al., 2017), 说明淡色花岗岩的源岩可能为新元古代麻源群变质沉积岩。除此之外, 建宁地区淡色花岗岩属强过铝质岩石( $\text{A/CNK} > 1.1$ ), 具高  $\text{SiO}_2$ 、 $\text{K}_2\text{O}$ , 贫  $\text{MgO}$ 、 $\text{FeO}_t$ , 富集 LREE 和 LILEs, 亏损 HREE 和 HFSEs 的特征(图 8a, b)。上述地球化学特征与变质沉积岩部分熔融产生的熔体特征相一致, 进一步证实淡色花岗岩的源岩为麻源群变质沉积岩。

前人的研究表明, 地壳中变质沉积岩发生部分熔融时, 主要发生下述反应: 水饱和条件下, 含水熔融反应: (1)  $\text{Qtz} + \text{Pl} + \text{H}_2\text{O} \rightarrow \text{Melts}$ , (2)  $\text{Qtz} + \text{Pl} + \text{Mus} + \text{H}_2\text{O} \rightarrow \text{Melts}$ , (3)  $\text{Qtz} + \text{Pl} + \text{Bt} + \text{H}_2\text{O} \rightarrow \text{Grt} + \text{Crd} + \text{Melts}$ ; 水不饱和条件下, 黑云母或白云母脱水熔融反应: (4)  $\text{Qtz} + \text{Pl} + \text{Mus} \rightarrow \text{Als} \pm \text{Grt} \pm \text{Kfs} + \text{Melts}$ ,

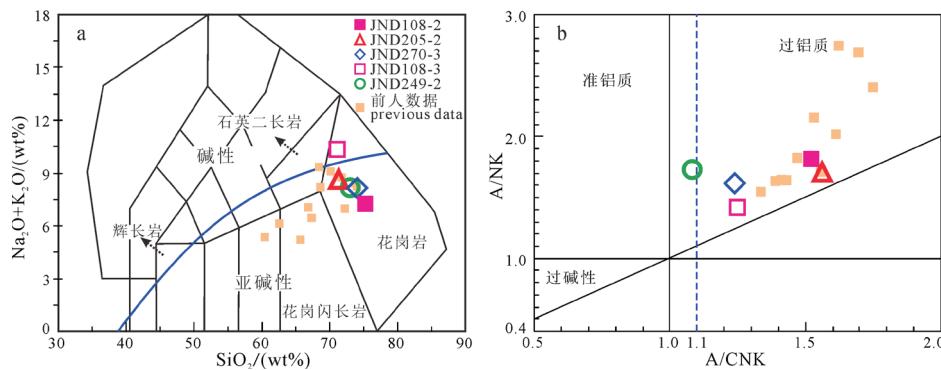


图 6 建宁淡色花岗岩的 TAS(a; 据 Middemost, 1994 修改)和 A/CNK-A/NK(b; 据 Maniar et al., 1989 修改)图解  
(数据引自曾雯等, 2008; 张芳荣等, 2010)

Fig. 6 TAS diagram (a; modified from Middemost, 1994) and A/CNK vs. A/NK diagram (b; modified from Maniar et al., 1989) for the leucogranite from the Jianning area (data from ZENG et al., 2008; ZHANG et al., 2010)

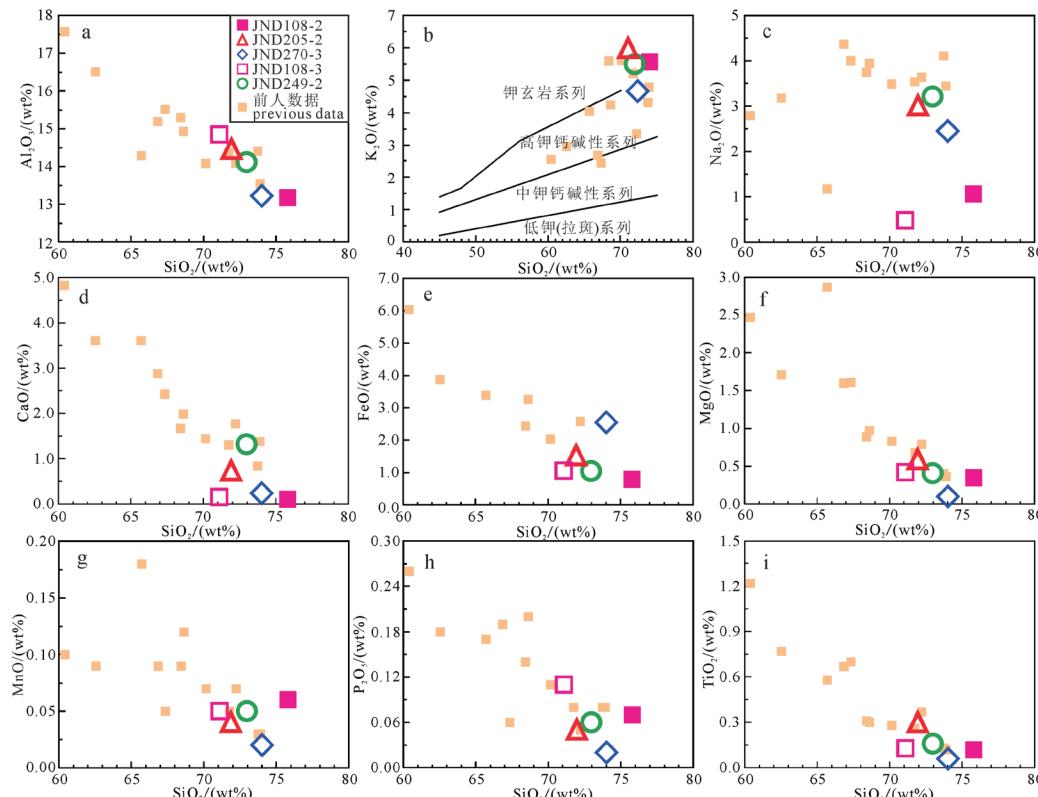


图 7 建宁淡色花岗岩主量元素 Harker 图解(数据引自曾雯等, 2008; 张芳荣等, 2010)

Fig. 7 Harker diagrams for the leucogranite from the Jianning area (data from ZENG et al., 2008; ZHANG et al., 2010)

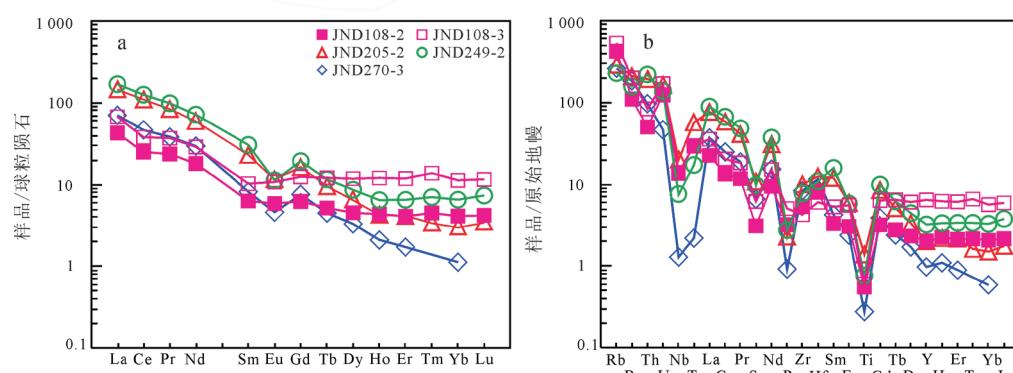


图 8 建宁淡色花岗岩稀土元素球粒陨石标准化配分模式图(a)及微量元素蛛网图(b)

(球粒陨石标准化值据 Taylor et al., 1985; 原始地幔标准化值据 Sun et al., 1989)

Fig. 8 Chondrite-normalized REE patterns (a) and primitive mantle-normalized multiple trace element diagrams (b) of the leucogranite from the Jianning area (chondrite and primitive mantle normalizing values are from Taylor et al., 1985 and Sun et al., 1989, respectively)

(5) Qtz+Pl+Bt+Als → Grt±Crd±Kfs+Melts, (6) Qtz+Pl+Bt → Opx+Grt+Kfs+Melts (Vielzeuf et al., 1988; Vielzeuf et al., 1994; Douce et al., 1995, 1996; Douce et al., 1998)。建宁地区淡色花岗岩的下述地球化学特征表明, 其源岩可能发生了黑云母参与的含水或脱水熔融反应: (1) 淡色花岗岩具高  $K_2O$ , 低  $CaO$  和  $Na_2O$ 、高  $Rb/Sr$  比值等特征, 暗示黑云母参与到了熔融反应当中(Zeng et al., 2005a, b; Gao et al., 2017; 曾令森等, 2017); (2) 淡色花岗岩 HREE 和 Y 含量较低(表 2), 而  $(La/Yb)_N$  比值较高(图 8a; 表 2), 暗示与其平衡的残余相中存在石榴子石, 而从上述几个深熔反应可知, 石榴子石通常出现在黑云母参与的深熔反应中; (3) 淡色花岗岩 LREE 变化较为明显, 且与 Th 呈很好的正相关关系(图 9), 这表明 LREE 变化与独居石溶解进入熔体相关(Bea, 1996), 在变质沉积岩中, 黑云母是独居石的主要载体(Douce et al., 1998; Burda et al., 2009; Brown, 2010), 暗示黑云母参与了部分熔融反应。在武夷山黎川、金溪和建阳等地区, 前人已经在混合岩中识别出了包裹有黑云母、斜长石、石英等矿物包体的石榴子石变斑晶(刘锐等, 2008; Huang et al., 2020), 进一步证实源岩发生了黑云母参与的含水或脱水熔融反应。综合上述, 建宁地区淡色花岗岩的源岩为新元古代麻源群变质沉积岩, 其形成与变质沉积岩发生黑云母参与的含水或脱水熔融反应有关。

### 5.3 大地构造意义

前人的研究已经证实, 受早古生代造山作用的影响, 武夷山地区前寒武纪基底岩石发生了显著的挤压缩短, 形成了叠瓦式逆冲推覆构造和紧闭褶皱, 并伴随有韧性剪切变形、高级变质和广泛的花岗质岩浆活动, 造山作用的峰期时代集中于 460~420 Ma(舒良树等, 2008; Faure et al., 2009; Charvet et al., 2010; Li et al., 2010; Wang D et al., 2013; Shu et al., 2014, 2015; Li et al., 2017; Lin et al., 2023)。本文在

武夷山中段建宁地区的淡色花岗岩中识别出了 444~443 Ma 和 409~405 Ma 两期深熔事件, 可以为理解华南早古生代造山过程提供新的约束。

建宁地区淡色花岗岩的锆石 U-Pb 同位素年代学和地球化学研究表明, 淡色花岗岩形成于 444~443 Ma, 是新元古代变质沉积基底发生黑云母参与的部分熔融反应的产物。Huang et al.(2020)在建宁北部黎川地区的混合岩中识别出了包裹有黑云母、斜长石、石英等矿物包体的石榴子石变斑晶, 应用 Grt-Bt-Als-Qtz(GBAQ)地质压力计和 Grt-Bt 地质温度计, 估算出深熔反应发生的温压条件为 ~0.5 GPa 和 ~828 °C。这表明这些新元古代表壳岩石已经埋藏到了中-下地壳层位(>15 km), 暗示这些淡色花岗岩可能形成于同造山地壳加厚背景下。下述变质和变形证据也能够证实, 在 444~443 Ma, 华南早古生代造山带正处于地壳挤压缩短加厚阶段: (1) 与淡色花岗岩相伴生的混合岩浅色体普遍发生石香肠化和粘性褶皱, 局部可见无根褶皱, 显示出同变形熔体的特征(图 3a~b; 刘锐等, 2008); (2) 变质岩岩相学和同位素年代学研究表明, 武夷山地区角闪岩相或麻粒岩相变质岩的峰期变质时代为 460~440 Ma(图 10; Li et al., 2010; 于津海等, 2014; Huang et al., 2020; Xia et al., 2023), 与本文获得的淡色花岗岩的结晶时代相吻合; (3) 地壳挤压缩短相关的韧性剪切变形时代为 450~435 Ma(图 10; Xu et al., 2011; Shu et al., 2015; Li et al., 2016, 2017; Sun et al., 2018; Zhang et al., 2018), 与本文获得的淡色花岗岩的结晶时代相一致。缩短加厚的造山带地壳不仅能够提供放射性热使得地壳温度升高(K、U、Th 等放射性同位素衰变), 诱发深熔反应(Clark et al., 2011), 伴随的韧性或脆性变形还可以提供压力梯度, 促使深熔熔体向低压扩张部位发生迁移、汇聚形成淡色花岗质岩脉或岩株(Brown, 1994, 2010; Weinberg et al., 2013, 2015)。

除此之外, 本文还在淡色花岗岩中识别出了 409~405 Ma 深熔锆石。由于(1)在建宁地区已经识别出了早泥盆世(414~401 Ma)后造山伸展相关的双峰式高温岩石组合—A 型花岗岩和辉绿岩(图 10; Xin et al., 2020); (2) 华南大陆在泥盆纪已出现大面积被动陆缘沉积(图 10; Shu et al., 2014, 2015); (3) 华南大陆发育有泥盆纪走滑拉分盆地(阳朔盆地; Chen et al., 2001)和古生代(泥盆纪—石炭纪)地堑构造(陈竹新等, 2005; Jia et al., 2006), 所有这些沉积、构造、岩浆等地质证据均表明, 华南大陆在早泥盆世(<420 Ma)发生了强烈的后造山地壳伸展(Xin et al., 2020)。因此, 考虑到二者时间的一致性, 本文推测 409~405 Ma 深熔事件可能与后造山伸展减薄有关。

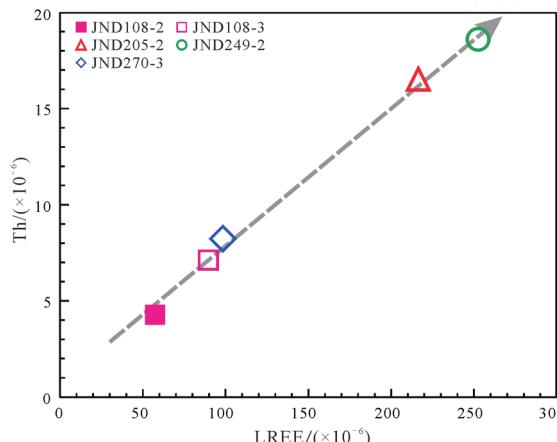


图 9 建宁淡色花岗岩 LREE-Th 图解

Fig. 9 LREE versus Th diagram of the leucogranite from Jianning area

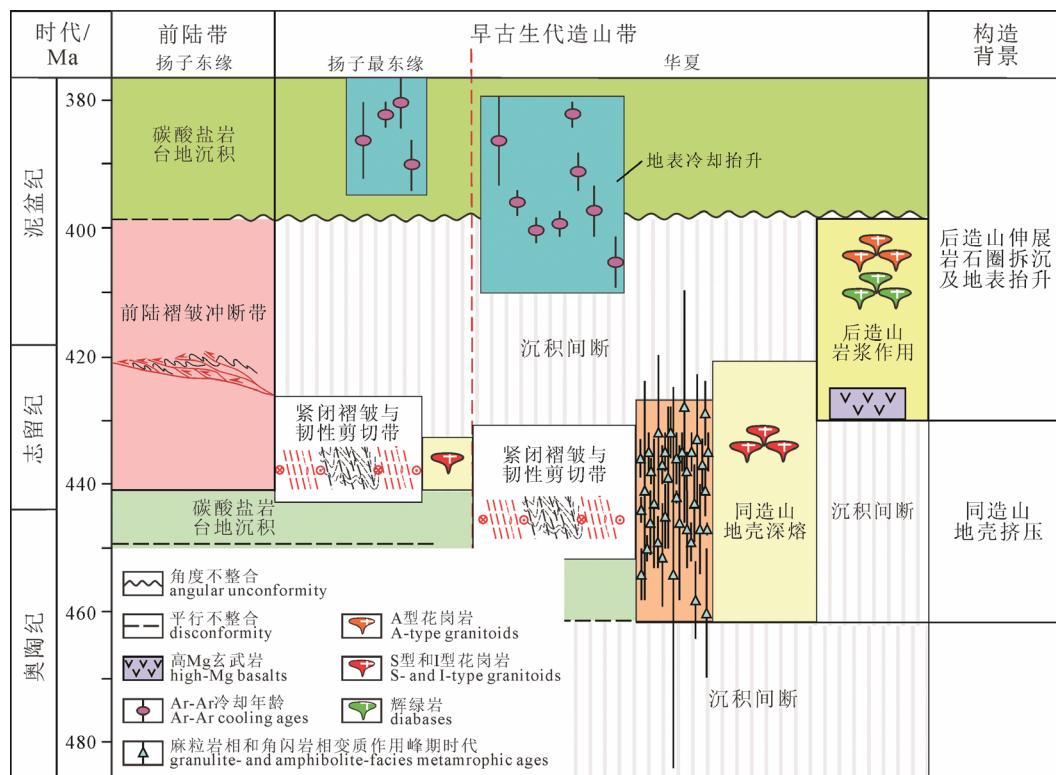


图 10 华南古生代沉积、变形、变质和岩浆作用汇编图(据 Li et al., 2022 改编)

Fig. 10 Compilation of Paleozoic sedimentation, deformation, metamorphism, and magmatism in South China (modified from Li et al., 2022)

## 6 结论

(1) 锆石 U-Pb 同位素定年结果表明, 建宁地区淡色花岗岩形成于 444~443 Ma, 并记录了 409~405 Ma 晚期深熔事件。

(2) 建宁地区淡色花岗岩属强过铝质花岗质岩石(A/CNK>1.1), 具高 SiO<sub>2</sub>、K<sub>2</sub>O, 贫 MgO、FeO<sub>t</sub>, 富集 LREE 和 LILEs, 亏损 HREE 和 HFSEs 等特征, 普遍含 800~700 Ma 年龄继承锆石, 表明其是新元古代麻源群变质沉积岩部分熔融的产物。

(3) 建宁地区淡色花岗岩具高 K<sub>2</sub>O、高 Rb/Sr 比值、低 CaO、Na<sub>2</sub>O、HREE 和 Y 等特征, 暗示源岩可能发生了黑云母参与的含水或脱水熔融反应。

(4) 建宁地区 444~443 Ma 淡色花岗岩形成于同造山地壳加厚背景下, 而晚期 409~405 Ma 深熔事件则可能与后造山伸展减薄有关。

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本文附有增强材料(附表 1), 请通过本文网络版阅读或下载。

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