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## 江南造山带东段新元古代九岭复式岩体 锆石 U-Pb 年代学及构造意义

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**摘要:**江南造山带东段的九岭岩体为华南分布面积最大的新元古代花岗质侵入体。据其岩石组合、结构构造及野外侵入关系, 可将其解体为由早到晚 3 个侵入序次的复式岩体, 依次为黑云母花岗闪长岩、英云闪长岩及黑云母二长花岗岩。其中, 黑云母花岗闪长岩分布面积最广, 黑云母二长花岗岩次之, 英云闪长岩分布面积最小, 围岩为新元古代双桥山群浅变质岩系。LA-ICP-MS 锆石 U-Pb 定年结果表明, 黑云母花岗闪长岩、英云闪长岩、黑云母二长花岗岩分别形成于 821.6~824.0 Ma、819.5~823.6 Ma、820.4~824.5 Ma, 指示它们基本同时侵位, 但三者均具有自 SE 向 NW 时代变新的趋势。九岭岩体与围岩(双桥山群)的侵入接触面具有南陡北缓、角岩化带南窄北宽且围岩捕虏体及捕获锆石也呈南少北多的特征, 表明九岭岩体 SE 侧岩体剥蚀深度强于 NW 侧, 可能暗示了新元古代华夏板块向扬子板块碰撞拼贴过程中, 研究区 SE 侧岩浆起源深度较深, 剥蚀程度较高, 且形成时代较早, 并逐渐向 NW 侧迁移(岩浆起源深度变浅、时代变新)。

**关键词:** 锆石 U-Pb 定年; S 型花岗岩; 新元古代; 九岭岩体; 江南造山带

中图分类号: P588.12<sup>\*1</sup>

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## Zircon U-Pb ages of the Neoproterozoic Jiuling complex granitoid in the eastern segment of the Jiangnan orogen and its tectonic significance

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**Abstract:** Located in eastern Jiangnan orogen, the Jiuling pluton is the largest Neoproterozoic granitoid intrusion in South China. According to mineral assemblage, structure and intrusive contact relationships, Jiuling pluton can be divided into complex massif with 3 intrusion orders, followed by biotite-granodiorite, tonalite and biotite-monzogranite from early to late respectively. Among

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them, granodiorite are distributed most widely, followed by biotite–monzogranite, while tonalite is only distributed in a minimum area. They intruded into the surrounding epimetamorphic rocks of Neoproterozoic period. The LA–ICP–MS zircon U–Pb dating results show that the biotite–granodiorite, tonalite and biotite–monzogranite were formed in 821.6–821.6 Ma, 819.5–823.6 Ma and 820.4–824.5 Ma, respectively, which indicates that they belong to the product of contemporary magmatic activity. On the whole, however, the granitoids tend to be younger from the southeast side to the northwest side. Besides, the dip angle of contact interface between Jiuling pluton and surrounding rocks (Shuangqiaoshan Group) is steep in the south and smooth in the north, hornfelsic belt is narrow in the south and wide in the north, and the xenoliths from the surrounding rock (Shuangqiaoshan Group) and the captured zircons also tend to decrease in size from south to north. These characteristics show that the rocks on the southeast side was eroded deeper than those on the northwest side, probably implying that, during the collision between Cathaysia plate and Yangtze plate in Neoproterozoic, the original depth of the granitic magma on the southeast side was deeper, the denudation was more intense, and the magma was formed earlier than the magma on the northwest side and gradually migrated northwestward, i.e., the origin depth of magma became shallow and the formation time became younger.

**Key words:** zircon U–Pb dating; S–type granite; Neoproterozoic; Jiuling Pluton; Jiangnan orogen

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## 1 引 言

不同类型花岗岩组合的形成过程蕴含了大量陆壳生长及演化的关键地球动力学信息,对其进行研究是了解陆壳生长和演化机制的重要途径。华南板块主要由华夏地块和扬子地块组成,二者分别位于华南板块的南东端和北西端(图1b),两者之间的拼贴带即为“江南造山带”。目前通常认为的江南造山带为一条近NE走向的前寒武纪地质单元,西起桂北,经黔西南、黔东南、湘西、赣西北、赣东北、皖南、浙西至浙北,长约1500 km、宽约200 km,主要由中新元古代浅变沉积质岩系、新元古代花岗岩和少量镁铁质岩组成。另外,自南西至北东,在江南造山带中分布包括本洞、三防、九岭、休宁、许村、歙县等二十几个岩体,大致呈NEE向,其中的九岭岩体位于江南造山带东段,为华南板块中出露面积最大的新元古代花岗质侵入岩(>2500 km<sup>2</sup>)(Li et al., 2003a)(图1a)。该岩体既是探究陆壳生长及演化机制的重要研究对象,也是研究江南造山带新元古代花岗质岩石成因及构造演化的极佳选择。

近年来,江南造山带和华南地块受到普遍关注。主要研究集中在以下3个方面:(1)华夏地块新元古代时在Rodinia超大陆中的位置。如部分研究

者认为华夏地块当时位于澳大利亚的SE侧和劳伦古陆的SW侧(Li et al., 1995, 2002, 2008a, b; Ye et al., 2007),但也有学者认为其当时(Rodinia裂解至Gondwana聚合期间)可能与印度和东南极毗邻(Yang et al., 2004; Wang et al., 2006; Yu et al., 2008; Zhou et al., 2009)。(2)关于扬子和华夏地块的最终拼合时限。部分学者提出二者的最终拼合时间在1000~900 Ma(Li et al., 1995, 2002, 2007, 2008c, 2009; Greentree et al., 2006; Ye et al., 2007),且在此期间形成的江南造山带属于格林威尔期造山事件的一部分(Li et al., 2002, 2008b),而另一部分学者基于区域前寒武纪地层层序和岩浆事件记录,提出江南造山带的碰撞造山作用一直持续到830 Ma,甚至800 Ma,其与格林威尔期的主体造山事件无关(Zhao and Cawood, 1999, 2012; Zhou et al., 2002b; Wang et al., 2006, 2007b, 2010, 2012b, 2012c; Zhao et al., 2011; 舒良树, 2012; Yao et al., 2013; 徐先兵等, 2015)。(3)扬子地块周缘新元古代花岗岩的成因及其构造属性,并可进一步分为3种不同观点:①认为新元古代花岗岩是地幔柱活动伴随伸展作用导致地壳重熔的产物(Li et al., 1999, 2003a, b, 2006, 2008b, 2010; 葛文春等, 2001; 李献华等, 2001; Wang et al., 2007a)。②认为新元古代岩浆活

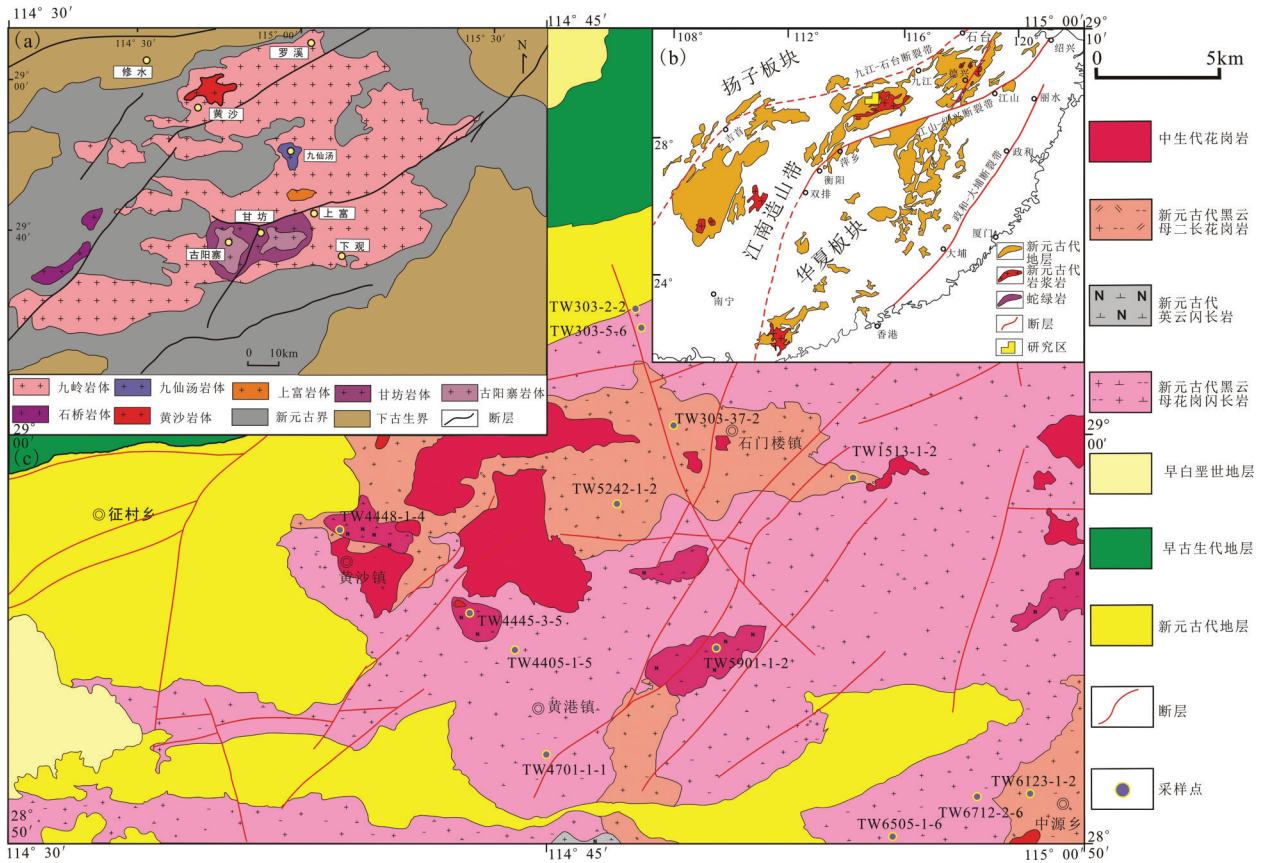


图1 九岭岩体地质简图(a)、华南前寒武纪岩石分布地质简图(b,修改自 Yao et al., 2014)及赣西北修水—武宁地区地质简图(c,据1:5万罗溪幅、黄沙桥幅、石门楼幅地质图改绘)

Fig.1 Simplified geological map of Jiuling pluton (a), simplified geological map of South China (b, modified from Yao et al., 2014), simplified geological map of Xiushui–Wuning area in northwest Jiangxi Province (c, modified from 1:50,000 Luoxi Sheet, Huangshaqiao Sheet, Shimenlou Sheet geological map)

动是由于洋壳俯冲消减于扬子板块下引起的岛弧岩浆活动(Zhou et al., 2002a, b; Zhou et al., 2004), 而其中的新元古代花岗岩为洋壳俯冲消减于扬子板块下引起的造山过程晚期后碰撞和造山后岩浆活动产物(Wang et al., 2006, 2014);③认为新元古代花岗岩是俯冲碰撞事件之后裂谷背景的产物,其形成过程与弧-陆碰撞造山带的垮塌有关(Wu et al., 2006; Zheng et al., 2007, 2008)。

综上所述,对华南新元古代出露面积最大的花岗岩—九岭岩体进行研究,可为窥探上述地质问题开辟一个较好的研究窗口。近年来,虽然前人利用LA-ICP-MS和SHRIMP对江南造山带中新元古代花岗岩进行了大量的锆石U-Pb定年工作(表1),但因其结果较为相近,在813~830 Ma之间(Li et al., 2003a; 钟玉芳等, 2005; 张菲菲等, 2011; Wang et al., 2014),因此前人多认为九岭新元古代岩体为一期

岩浆事件产物,且岩性主要为花岗闪长岩。然而,笔者等通过详细的1:5万区域地质调查工作,根据岩体的侵入接触关系,注意到九岭新元古代岩体内部侵入活动至少可分为3个侵入序次。由早到晚依次为黑云母花岗闪长岩、英云闪长岩和黑云母二长花岗岩。三者矿物组成和地球化学特征上存在明显差异,如黑云母花岗闪长岩主要由斜长石(~30%)、黑云母(~15%)和石英(~40%)组成,另含少量钾长石(~10%)(图2b),而英云闪长岩中的斜长石(~45%)、黑云母(~25%)均较黑云母花岗闪长岩的多,而石英含量较少(~25%)组成,几乎不含钾长石,且其中斜长石主要为中长石,普遍发育环带构造(图2c);黑云母二长花岗岩则表现为斜长石和钾长石含量相近,均为约30%左右,钾长石主要为条纹长石,斜长石裹于钾长石之中,且斜长石边部还发育富钠长石的反映变结构(图2e),黑云母和石英

表1 江南造山带新元古代花岗岩年代学资料  
Table 1 Geochronological data for Neoproterozoic granites in Jiangnan orogen

| 岩体        | 岩性    | 地区    | 时代/Ma     | 测年方法                               | 资料来源               |
|-----------|-------|-------|-----------|------------------------------------|--------------------|
| 张邦源       | 花岗闪长岩 | 湘东北   | 816±5     | SHRIMP                             | 马铁球等,2009          |
|           | 花岗闪长岩 | 赣北    | 936±15    | <sup>40</sup> Ar- <sup>39</sup> Ar | 胡世玲等,1984          |
| 九岭        | 花岗闪长岩 | 赣北    | 819±9     | SHRIMP                             | Li et al., 2003a   |
|           | 花岗闪长岩 | 赣北    | 828±8     | SHRIMP                             | 钟玉芳等,2005          |
|           | 花岗闪长岩 | 赣北    | 820±4     | LA-ICP-MS                          | Wang et al., 2014  |
| 九岭(东部)    | 二长花岗岩 | 赣北    | 813±4     | LA-ICP-MS                          | 张菲菲等,2011          |
| 九岭(南部)    | 二长花岗岩 | 赣北    | 823±3     | LA-ICP-MS                          | 张菲菲等,2011          |
|           | 二长花岗岩 | 赣北    | 805±3     | LA-ICP-MS                          | 张菲菲等,2011          |
| 西园坑       | 二长花岗岩 | 赣北    | 804±3     | LA-ICP-MS                          | Wang et al., 2014  |
| 西湾        | 花岗岩   | 赣东北   | 880±19    | SHRIMP                             | Li et al., 2008d   |
|           | 花岗闪长岩 | 皖南    | 823±8     | SHRIMP                             | Li et al., 2003a   |
| 许村        | 花岗闪长岩 | 皖南    | 827±7     | LA-ICP-MS                          | Wu et al., 2006    |
|           | 花岗闪长岩 | 皖南    | 823±7     | LA-ICP-MS                          | Wu et al., 2006    |
| 歙县        | 花岗闪长岩 | 皖南    | 826±5     | LA-ICP-MS                          | Wang et al., 2014  |
|           | 花岗闪长岩 | 皖南    | 852±6     | LA-ICP-MS                          | 薛怀民等,2010          |
|           | 花岗闪长岩 | 皖南    | 823±9     | LA-ICP-MS                          | Zheng et al., 2007 |
|           | 花岗闪长岩 | 皖南    | 824±6     | LA-ICP-MS                          | Wu et al., 2006    |
| 休宁        | 花岗闪长岩 | 皖南    | 837±14    | LA-ICP-MS                          | 薛怀民等,2010          |
|           | 花岗闪长岩 | 皖南    | 824±7     | LA-ICP-MS                          | Wu et al., 2006    |
|           | 花岗闪长岩 | 皖南    | 825±7     | LA-ICP-MS                          | Wu et al., 2006    |
| 石耳山(或莲花山) | 花岗闪长岩 | 皖南    | 824±7     | LA-ICP-MS                          | Wang et al., 2006  |
|           | 花岗岩   | 皖南    | 826±6     | LA-ICP-MS                          | 薛怀民等,2010          |
| 石耳山(或白际山) | 花岗岩   | 皖南    | 779±11    | SHRIMP                             | Li et al., 2003b   |
|           | 花岗斑岩  | 浙西    | 797±6     | LA-ICP-MS                          | Wang et al., 2012a |
| 齐溪田(或白际山) | 花岗斑岩  | 浙西    | 783±8     | LA-ICP-MS                          | 薛怀民等,2010          |
|           | 花岗岩   | 浙西    | 775±5     | LA-ICP-MS                          | Zheng et al., 2008 |
| 灵山        | 花岗岩   | 浙皖赣交界 | 823±18    | LA-ICP-MS                          | 薛怀民等,2010          |
|           | 花岗岩   | 浙皖赣交界 | 814±26    | LA-ICP-MS                          | 薛怀民等,2010          |
| 莲花山       | 花岗岩   | 浙皖赣交界 | 771±17    | SHRIMP                             | Zheng et al., 2008 |
|           | 花岗岩   | 浙皖赣交界 | 777±7     | LA-ICP-MS                          | Zheng et al., 2008 |
|           | 花岗岩   | 浙北    | 794±9     | SHRIMP                             | Li et al., 2008b   |
| 道林山       | 花岗岩   | 浙北    | 775±13    | SHRIMP                             | Wang et al., 2010  |
|           | 花岗岩   | 浙北    | 780±5     | LA-ICP-MS                          | Wang et al., 2010  |
|           | 花岗岩   | 浙北    | 790.2±5.5 | LA-ICP-MS                          | Yao et al., 2014   |
| 桃红        | 英云闪长岩 | 浙东北   | 913±15    | SHRIMP                             | Ye et al., 2007    |
| 西裘        | 花岗闪长岩 | 浙东北   | 905±14    | SHRIMP                             | Ye et al., 2007    |
| 寨滚        | 花岗闪长岩 | 桂北    | 835.8±2.5 | LA-ICP-MS                          | Wang et al., 2006  |
|           | 花岗闪长岩 | 桂北    | 834.6±8.4 | LA-ICP-MS                          | 王孝磊等,2006          |
| 本洞        | 花岗闪长岩 | 桂北    | 822.7±3.8 | LA-ICP-MS                          | Wang et al., 2006  |
|           | 花岗闪长岩 | 桂北    | 819±9     | SHRIMP                             | Li et al., 1999    |
| 峒马        | 花岗闪长岩 | 桂北    | 824±13    | LA-ICP-MS                          | Wang et al., 2006  |
|           | 花岗闪长岩 | 桂北    | 804.3±5.2 | LA-ICP-MS                          | Wang et al., 2006  |
| 蒙洞        | 花岗闪长岩 | 桂北    | 837±7     | LA-ICP-MS                          | Wang et al., 2014  |
|           | 花岗闪长岩 | 桂北    | 833±5     | LA-ICP-MS                          | Wang et al., 2014  |
| 龙有        | 花岗闪长岩 | 桂北    | 832±5     | LA-ICP-MS                          | Wang et al., 2014  |
| 平英        | 花岗岩   | 桂北    | 835±5     | LA-ICP-MS                          | Wang et al., 2014  |
| 大寨        | 花岗岩   | 桂北    | 834±8     | LA-ICP-MS                          | Wang et al., 2014  |
| 三防        | 花岗岩   | 桂北    | 826±10    | SHRIMP                             | Li et al., 1999    |
| 田朋        | 花岗岩   | 桂北    | 794.2±8.1 | LA-ICP-MS                          | Wang et al., 2006  |
| 元宝山       | 花岗岩   | 桂北    | 824±4     | SHRIMP                             | Li et al., 1999    |
|           | 花岗岩   | 桂北    | 838±5     | LA-ICP-MS                          | Wang et al., 2014  |
| 长三背       | 花岗闪长岩 | 湘东北   | 837±6     | LA-ICP-MS                          | Wang et al., 2014  |
| 大围山       | 花岗闪长岩 | 湘东北   | 805±4     | LA-ICP-MS                          | Wang et al., 2014  |
| 梵净山       | 白岗岩   | 黔东北   | 835±5     | SHRIMP                             | 高林志等,2011          |
|           | 花岗岩   | 黔东北   | 827.5±7.4 | SIMS                               | Zhao et al., 2011  |
| 摩天岭       | 花岗岩   | 黔东南   | 826.8±5.9 | SHRIMP                             | 高林志等,2010          |
|           | 花岗岩   | 黔东南   | 825.0±2.4 | TIMS                               | 曾雯等,2005           |

含量与花岗闪长岩相似,且部分地区还可见钾长石巨斑晶(粒径可达2~4 cm)(图2d)。

关于这3个侵入序次的花岗质岩石尚系统的岩石学和年代学工作。本文通过对这3类花岗岩开展详细的岩石学和LA-ICP-MS锆石U-Pb定年工作,将对进一步了解九岭新元古代岩浆活动的成因和演化过程,进而更深入地探索华夏和扬子板块的拼贴过程,提供更多细节的信息。

## 2 地质概况及岩石学特征

赣东北地区中新元古代地层称为双桥山群,为一套厚度巨大,主要由由泥砂质沉积岩夹少量火山碎屑岩为主组成的复理石建造。据其岩性特征,自下而上可划分为(鄣公山组)、横涌组、计林组、安乐林组和修水组,时代主要为新元古代(薛怀民等,2010),并被大面积分布的新元古代花岗岩类侵入,其中主要以九岭岩体为代表。九岭岩体分布于江西省北部,东起靖安、奉新,西达修水、铜鼓等地,北起武宁罗溪,南至高安、宜丰、万载一线,大致呈近东西向至北东东向分布,被多个中生代岩体侵入,如上富、甘坊、古阳寨、黄沙岩体等(图1a),这些中生代岩体时代集中在150~140 Ma(钟玉芳等,2005;黄兰椿等,2012)。

研究区位于江西省北部,区内明显可见九岭岩体侵入新元古界双桥山群(安乐林组和修水组)之中,主要由黑云母花岗闪长岩、英云闪长岩和黑云母二长花岗岩组成(图1c)。黑云母花岗闪长岩在研究区分布面积最广,呈不规则岩基形式产出,脉动侵入于双桥山群浅变质岩中,北接触面多呈外倾波状、枝叉状(图2a,图3d),南接触面较为平直,呈高角度脉动侵入接触(图3e)。岩体内接触带常发育15~35cm的细粒冷凝边,并有较多的围岩捕虏体;而外接触带常因热接触变质作用而形成宽度不一的角岩化带(图3d),且南部角岩化带较窄(250~550 m),北部较宽(~3000 m)<sup>①</sup>,并见20~50 cm的烘烤边现象(图3d,e)。另外,北部岩体中含有大量的双桥山群变沉积岩的残留顶盖和围岩捕虏体(图3d),但南部岩体中的围岩捕虏体较少(Duan et al., 2018)。岩体中斜长石含量为30%~35%,钾长石为10%~15%,石英含量为30%~40%,黑云母含量为10%~15%(图2b),可见靛蓝色的六方柱状堇青石,

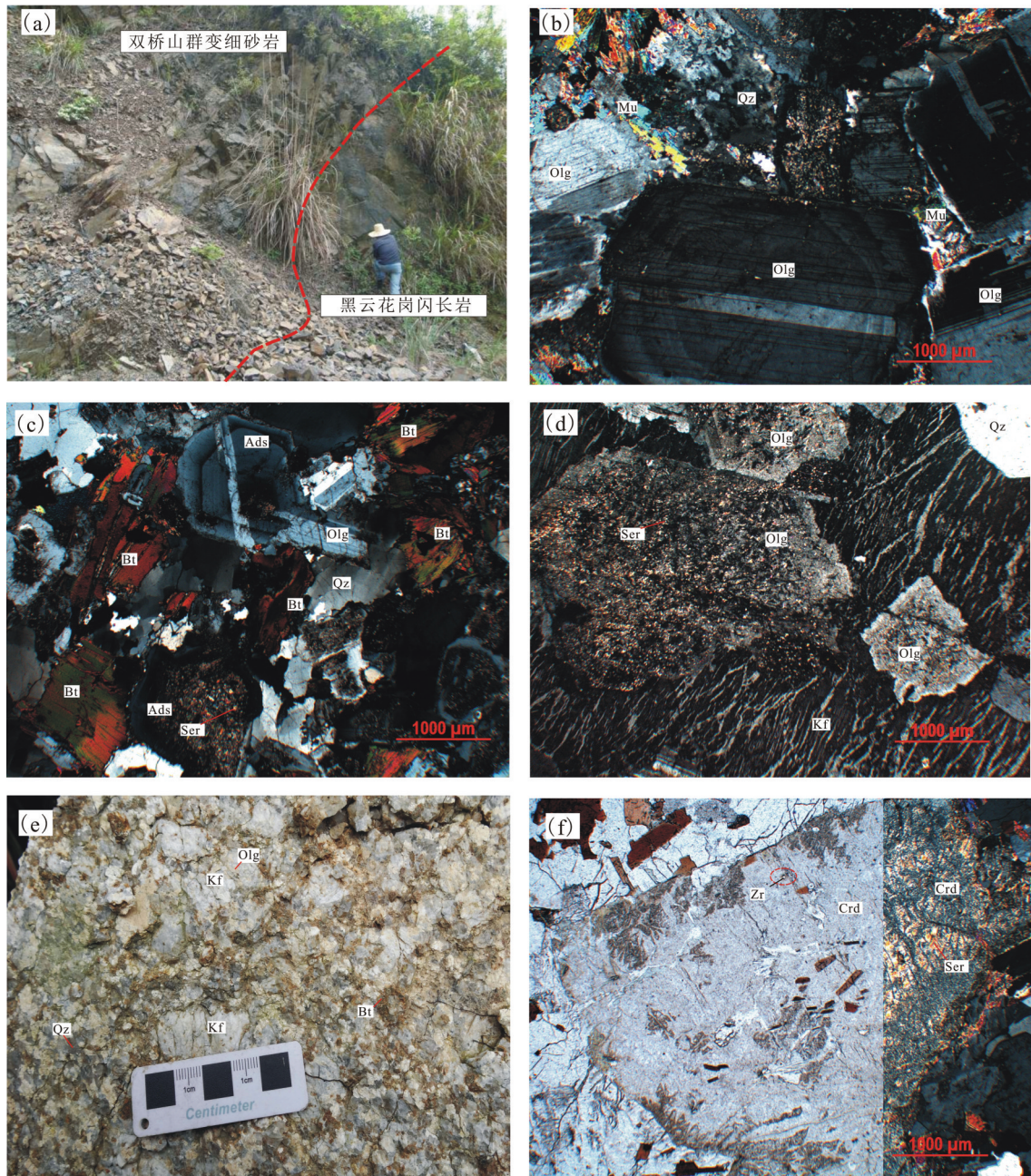


图2 研究区新元古代花岗岩类野外露头及岩石学特征

a—研究区新元古代黑云母花岗岩闪长岩侵入于双桥山群变细砂岩之中;b—黑云母花岗岩闪长岩镜下特征,正交偏光;c—英闪长岩镜下特征;d,e—钾长石巨斑晶黑云母二长花岗岩镜下特征(d,正交偏光)及野外特征(e);f—黑云母花岗岩闪长岩中堇青石显微特征,沿裂理绢云母化,且锆石包裹体周围发育柠檬黄多色晕,左为单偏光,右为正交偏光;Olg—更长石;Kf—钾长石;Ads—中长石;Qz—石英;Bt—黑云母;Crd—堇青石;Ser—绢云母;Mu—白云母;Zr—锆石

Fig.2 Petrological and field outcrops characteristics of Neoproterozoic granitoids in the study area

a—Neoproterozoic biotite granodiorite intruding into meta-sandstone of Shuangqiaoshan Group in the study area; b—Microscopic characteristics of biotite-granodiorite,perpendicular polarized light; c—Microscopic characteristics of tonalite; d, e—Microscopic characteristics of biotite-monzogranite with giant potassium feldspar phenocryst (d) and its outcrops characteristics in the field (e); f—Microscopic characteristics of the cordierite with sericitization along its rifts and showing the lemon yellow multi-color halo developed around the zircon inclusions from biotite granodiorite, the right side is perpendicular polarized light, the left side is plane polarized light. Olg—Oligoclase; Kf—K-feldspar; Ads—Adesine; Qz—Quartz; Bt—Biotite; Crd—Cordierite; Ser—Sericite; Mu—Muscovite; Zr—Zircon

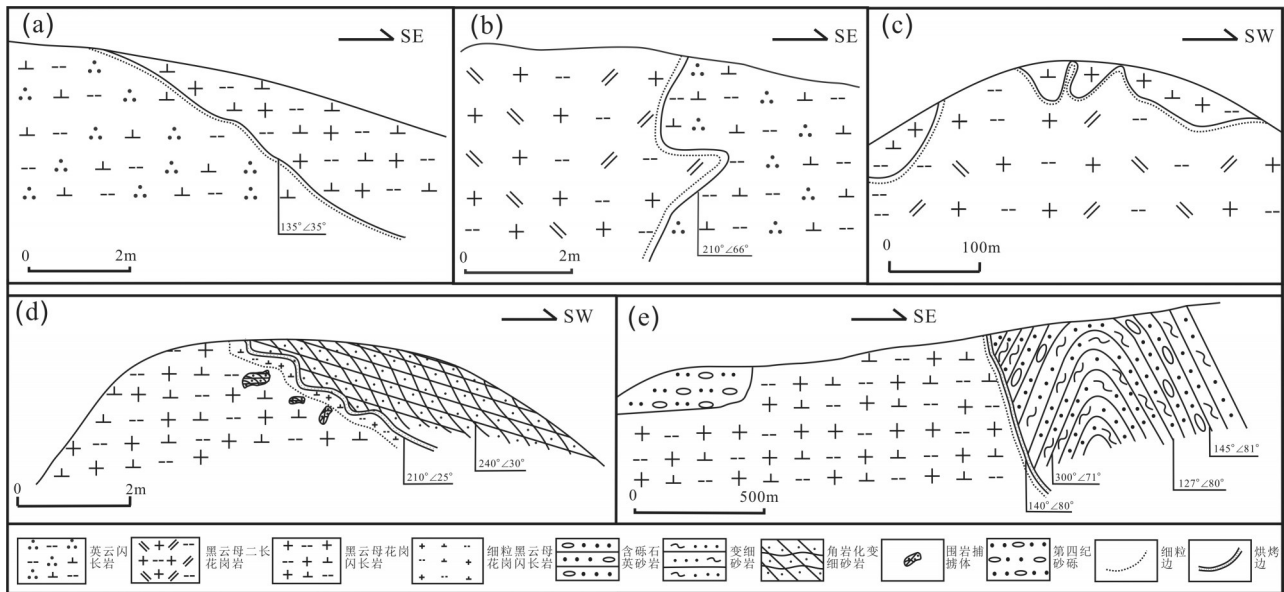


图3 研究区新元古代花岗岩接触关系地质简图

a—英云闪长岩侵入于黑云母花岗闪长岩之中;b—黑云母二长花岗岩侵入于英云闪长岩之中;c—黑云母二长花岗岩侵入于黑云母花岗闪长岩之中;d—研究区北部黑云母花岗闪长岩与双桥山群侵入接触关系;e—研究区南部黑云母花岗闪长岩与双桥山群侵入接触关系

Fig.3 Geological sketch map of contacting relationships of the Neoproterozoic granitoids in the study area

a—Tonalite intruding the biotite-granodiorite; b—Biotite-monzogranite intruding the tonalite; c—Biotite-monzogranite intruding biotite-granodiorite; d—The contacting relationship between the biotite-granodiorite and the Shuangqiaoshan Group in northern study area; e—The contacting relationship between the biotite-granodiorite and the Shuangqiaoshan Group in southern study area

但多已绢云母化,绢云母沿堇青石裂理交代,且锆石包裹体周围发育堇青石特征的柠檬黄多色晕(图2f)。岩石主要副矿物有钛铁矿、独居石、锐钛矿、石榴石、锆石、金红石、电气石等,其中的Al过饱和的石榴石、电气石为S型花岗岩的特征副矿物,反映了岩浆具S型花岗质岩浆特征。

研究区英云闪长岩出露面积最小,呈单独岩株分布,主要分布于测区中—南部。岩体涌动侵入于新元古代黑云母花岗闪长岩中(图3a)。在研究区西部何市附近,可见黑云母花岗闪长岩的残留顶盖覆于二长花岗岩之上(图3c),而在黄沙附近又见黑云母二长花岗岩侵入于英云闪长岩之中(图3b),这共同反映英云闪长岩侵入期次应晚于黑云母花岗闪长岩,而早于黑云母二长花岗岩。岩体斜长石含量为45%~55%,钾长石小于5%,石英含量为25%~35%,黑云母含量约15%,斜长石主要为中长石,环带发育(图2d)。副矿物含量低,但种类复杂,主要副矿物有钛铁矿、独居石、绿帘石、锐钛矿、石榴石、褐铁矿、赤褐铁矿、锆石、电气石、磷灰石等,这与黑云母花岗闪长岩中的副矿物组合类似,且其中的Al

过饱和的石榴石和电气石也指示了其母岩浆为S型花岗质岩浆。

黑云母二长花岗岩主要出露于研究区中部石门楼、黄沙一带,其他零星出露于南部黄港西南和中源地区,平面上呈椭圆状、不规则状或长条状近EW向岩基状展布,出露面积大于英云闪长岩而小于次黑云母花岗闪长岩。岩体脉动式侵入于新元古代双桥山群中,涌动式侵入于新元古代黑云母花岗闪长岩及新元古代英云闪长岩中(图3b、c),为研究区新元古代第3序次岩浆活动产物;岩体与双桥山群浅变质岩侵入接触面较平直,少数呈波状、枝叉状,产状外倾。北部黑云母二长花岗岩岩体中含有大量的双桥山群浅变质岩围岩捕虏体和黑云母花岗闪长岩的残留顶盖,顶盖宽几米至200 m不等。部分黑云母二长花岗岩(黄坳附近)中见钾长石巨斑晶(图2e),巨斑晶呈自形板状,长轴为2~5 cm,岩石中斜长石含量20%~30%,钾长石(主要为条纹长石)25%~35%,石英30%~40%,黑云母为10%~15%,部分黑云母蚀变为白云母。主要副矿物有钛铁矿、独居石、锐钛矿、石榴石、锆石、金红石、



图4 研究区九岭岩体锆石CL图像及测点位置和结果

Fig.4 CL images, site of analyzed point and dating data of zircons from Neoproterozoic granites in the study area

电气石等,同样反映了其岩浆为S型花岗质岩浆。

### 3 样品采集及分析测试方法

本次对研究区各岩体(黑云母花岗闪长岩、英云闪长岩及黑云母二长花岗岩)的13件样品进行了系统的LA-ICP-MS锆石U-Pb法同位素测年。采样位置见图1b。在河北省廊坊区调所实验室采用人工重砂方法分选锆石,CL图像分析及锆石制靶在JSM-6510型扫描电子显微镜和Gatan MiniCL型阴极荧光光谱仪上完成,CL图像见图4。锆石测年由中

Geolas Pro,具体实验室测试条件、标样U-Th-Pb同位素分析比值及分析流程见李凤春等(2016)。分析数据采用ICPMS DataCal(Liu et al., 2008; 2010a)程序计算获得同位素比值、年龄及误差,详细的仪器操作条件和数据处理方法同Liu et al. (2008; 2010a; 2010b)。锆石样品的U-Pb年龄谱和图绘制和年龄权重平均计算均采用Isoplot/Ex\_ver3(Ludwig, 2003)完成。

## 4 LA-ICP-MS锆石U-Pb定年结果

### 4.1 黑云母花岗闪长岩

本次共对测区6件黑云母花岗闪长岩样品进行了锆石U-Pb定年,测试分析结果如表2。本文对年

表2 九岭岩体LA-ICP-MS 锆石U-Pb分析数据  
Table 2 LA-ICP-MS zircon U-Pb dating data of Jiuling Pluton

| 分析<br>元素             | 含量/10 <sup>-6</sup> |     |     | Th/U | 同位素比值                                |        |                                     |        |                                     |        | 表面年龄/Ma                              |      |                                     |      |                                     |      |
|----------------------|---------------------|-----|-----|------|--------------------------------------|--------|-------------------------------------|--------|-------------------------------------|--------|--------------------------------------|------|-------------------------------------|------|-------------------------------------|------|
|                      | Pb*                 | Th  | U   |      | <sup>207</sup> Pb/ <sup>206</sup> Pb | 1σ     | <sup>207</sup> Pb/ <sup>235</sup> U | 1σ     | <sup>206</sup> Pb/ <sup>238</sup> U | 1σ     | <sup>207</sup> Pb/ <sup>206</sup> Pb | 1σ   | <sup>207</sup> Pb/ <sup>235</sup> U | 1σ   | <sup>206</sup> Pb/ <sup>238</sup> U | 1σ   |
| 点号                   |                     |     |     |      |                                      |        |                                     |        |                                     |        |                                      |      |                                     |      |                                     |      |
| 黑云母花岗闪长岩(TW4701-1-5) |                     |     |     |      |                                      |        |                                     |        |                                     |        |                                      |      |                                     |      |                                     |      |
| 1                    | 25.08               | 51  | 165 | 0.31 | 0.0683                               | 0.002  | 1.2882                              | 0.0383 | 0.1352                              | 0.002  | 876                                  | 91.7 | 841                                 | 17   | 818                                 | 11.5 |
| 2                    | 136                 | 118 | 365 | 0.32 | 0.1352                               | 0.0029 | 5.2422                              | 0.1258 | 0.2755                              | 0.0034 | 2169                                 | 37   | 1860                                | 20.5 | 1569                                | 17.4 |
| 3                    | 52.6                | 221 | 275 | 0.81 | 0.0664                               | 0.0021 | 1.2552                              | 0.0346 | 0.1365                              | 0.0018 | 820                                  | 66.7 | 826                                 | 15.6 | 825                                 | 10.2 |
| 4                    | 45.2                | 98  | 279 | 0.35 | 0.0695                               | 0.0016 | 1.3216                              | 0.0287 | 0.1364                              | 0.0014 | 915                                  | 41.7 | 855                                 | 12.6 | 824                                 | 8.1  |
| 5                    | 43.4                | 144 | 248 | 0.58 | 0.0664                               | 0.0017 | 1.2581                              | 0.0315 | 0.1358                              | 0.0016 | 820                                  | 51.8 | 827                                 | 14.1 | 821                                 | 9.2  |
| 6                    | 45.1                | 94  | 282 | 0.33 | 0.0668                               | 0.0016 | 1.2556                              | 0.0285 | 0.1349                              | 0.0015 | 831                                  | 48.9 | 826                                 | 12.8 | 816                                 | 8.6  |
| 7                    | 50.9                | 113 | 322 | 0.35 | 0.0659                               | 0.0016 | 1.2341                              | 0.0296 | 0.1344                              | 0.0017 | 806                                  | 50.8 | 816                                 | 13.4 | 813                                 | 9.9  |
| 8                    | 51.4                | 102 | 331 | 0.31 | 0.069                                | 0.0018 | 1.3184                              | 0.0339 | 0.1371                              | 0.0016 | 898                                  | 53.7 | 854                                 | 14.9 | 829                                 | 9.3  |
| 9                    | 46.6                | 77  | 301 | 0.26 | 0.0667                               | 0.0017 | 1.272                               | 0.0329 | 0.1368                              | 0.0017 | 828                                  | 53.7 | 833                                 | 14.7 | 827                                 | 9.6  |
| 10                   | 46.03               | 61  | 305 | 0.2  | 0.0663                               | 0.0015 | 1.2507                              | 0.0273 | 0.1354                              | 0.0015 | 817                                  | 46.3 | 824                                 | 12.3 | 819                                 | 8.3  |
| 11                   | 23.78               | 40  | 153 | 0.26 | 0.0696                               | 0.0022 | 1.3177                              | 0.0385 | 0.1372                              | 0.0019 | 917                                  | 69.4 | 854                                 | 16.9 | 829                                 | 10.7 |
| 12                   | 35                  | 110 | 197 | 0.56 | 0.0693                               | 0.0021 | 1.3255                              | 0.0422 | 0.137                               | 0.0021 | 909                                  | 64.8 | 857                                 | 18.4 | 828                                 | 11.6 |
| 13                   | 61.4                | 125 | 388 | 0.32 | 0.0658                               | 0.0015 | 1.2538                              | 0.0274 | 0.1371                              | 0.0015 | 798                                  | 52.8 | 825                                 | 12.3 | 828                                 | 8.7  |
| 14                   | 57.5                | 189 | 324 | 0.58 | 0.0706                               | 0.0018 | 1.3538                              | 0.0376 | 0.1366                              | 0.0016 | 946                                  | 51.9 | 869                                 | 16.2 | 825                                 | 8.8  |
| 15                   | 26.7                | 59  | 162 | 0.37 | 0.0707                               | 0.0021 | 1.3401                              | 0.0403 | 0.1364                              | 0.0018 | 950                                  | 61.1 | 863                                 | 17.5 | 824                                 | 10.2 |
| 黑云母花岗闪长岩(TW6505-1-6) |                     |     |     |      |                                      |        |                                     |        |                                     |        |                                      |      |                                     |      |                                     |      |
| 1                    | 35.7                | 103 | 216 | 0.48 | 0.0713                               | 0.002  | 1.3409                              | 0.0355 | 0.1366                              | 0.002  | 965                                  | 63.9 | 864                                 | 15.4 | 826                                 | 11.2 |
| 2                    | 46.26               | 63  | 325 | 0.2  | 0.0674                               | 0.0022 | 1.2733                              | 0.0386 | 0.1362                              | 0.0027 | 850                                  | 66.7 | 834                                 | 17.2 | 823                                 | 15.3 |
| 3                    | 39.71               | 65  | 278 | 0.23 | 0.0669                               | 0.0016 | 1.2643                              | 0.0312 | 0.1359                              | 0.0017 | 835                                  | 51.9 | 830                                 | 14   | 821                                 | 9.6  |
| 4                    | 111.3               | 621 | 531 | 1.17 | 0.0659                               | 0.0013 | 1.2514                              | 0.0231 | 0.1364                              | 0.0015 | 1200                                 | 41.5 | 824                                 | 10.4 | 824                                 | 8.3  |
| 5                    | 73.1                | 216 | 456 | 0.47 | 0.0667                               | 0.0016 | 1.2786                              | 0.0331 | 0.1366                              | 0.0018 | 828                                  | 43.5 | 836                                 | 14.7 | 825                                 | 10.3 |
| 6                    | 49.2                | 127 | 318 | 0.4  | 0.0675                               | 0.002  | 1.2731                              | 0.0477 | 0.1366                              | 0.0038 | 852                                  | 67.6 | 834                                 | 21.3 | 825                                 | 21.3 |
| 7                    | 63.74               | 60  | 466 | 0.13 | 0.0646                               | 0.0019 | 1.233                               | 0.0374 | 0.1365                              | 0.0024 | 761                                  | 61.1 | 816                                 | 17   | 825                                 | 13.7 |
| 8                    | 101.8               | 96  | 759 | 0.13 | 0.066                                | 0.0016 | 1.2542                              | 0.0321 | 0.1357                              | 0.0021 | 809                                  | 45.4 | 825                                 | 14.5 | 820                                 | 11.8 |
| 9                    | 53.8                | 145 | 337 | 0.43 | 0.0654                               | 0.0016 | 1.2456                              | 0.0297 | 0.1362                              | 0.0017 | 789                                  | 48   | 821                                 | 13.4 | 823                                 | 9.6  |
| 10                   | 38.1                | 71  | 257 | 0.27 | 0.0654                               | 0.0019 | 1.2571                              | 0.0427 | 0.1362                              | 0.0026 | 787                                  | 65.7 | 827                                 | 19.2 | 823                                 | 14.6 |
| 11                   | 52.1                | 118 | 345 | 0.34 | 0.0651                               | 0.0015 | 1.2399                              | 0.0279 | 0.1362                              | 0.0015 | 776                                  | 50   | 819                                 | 12.6 | 823                                 | 8.8  |
| 12                   | 47.47               | 45  | 345 | 0.13 | 0.0652                               | 0.0018 | 1.2489                              | 0.0352 | 0.1363                              | 0.0019 | 789                                  | 59.3 | 823                                 | 15.9 | 824                                 | 10.9 |
| 13                   | 56.3                | 112 | 387 | 0.29 | 0.0634                               | 0.0015 | 1.2084                              | 0.03   | 0.1358                              | 0.0018 | 720                                  | 19.4 | 804                                 | 13.8 | 821                                 | 10.4 |
| 14                   | 32.3                | 76  | 203 | 0.37 | 0.0654                               | 0.0019 | 1.2501                              | 0.035  | 0.1363                              | 0.0019 | 787                                  | 63   | 823                                 | 15.8 | 824                                 | 10.7 |
| 15                   | 49.61               | 48  | 356 | 0.13 | 0.0644                               | 0.0018 | 1.2287                              | 0.0325 | 0.1359                              | 0.0019 | 767                                  | 61.1 | 814                                 | 14.8 | 822                                 | 10.7 |
| 黑云母花岗闪长岩(TW6712-2-6) |                     |     |     |      |                                      |        |                                     |        |                                     |        |                                      |      |                                     |      |                                     |      |
| 1                    | 43.36               | 62  | 312 | 0.2  | 0.0645                               | 0.0016 | 1.227                               | 0.0336 | 0.1365                              | 0.0024 | 767                                  | 50.8 | 813                                 | 15.3 | 825                                 | 13.3 |
| 2                    | 44.35               | 72  | 315 | 0.23 | 0.0676                               | 0.0019 | 1.2768                              | 0.0353 | 0.1367                              | 0.0036 | 857                                  | 62   | 835                                 | 15.8 | 826                                 | 20.6 |
| 3                    | 50.2                | 123 | 338 | 0.37 | 0.0657                               | 0.0014 | 1.2382                              | 0.0274 | 0.136                               | 0.0019 | 796                                  | 46   | 818                                 | 12.4 | 822                                 | 10.6 |
| 4                    | 63.39               | 60  | 476 | 0.13 | 0.071                                | 0.0014 | 1.3435                              | 0.0313 | 0.136                               | 0.0024 | 967                                  | 40   | 865                                 | 13.6 | 822                                 | 13.5 |
| 5                    | 42.6                | 47  | 312 | 0.15 | 0.0671                               | 0.0019 | 1.2727                              | 0.0386 | 0.1367                              | 0.0024 | 843                                  | 57.4 | 834                                 | 17.2 | 826                                 | 13.8 |
| 6                    | 42.08               | 65  | 298 | 0.22 | 0.0687                               | 0.0017 | 1.3017                              | 0.0351 | 0.1366                              | 0.002  | 900                                  | 50   | 846                                 | 15.5 | 825                                 | 11.1 |
| 7                    | 43.25               | 61  | 308 | 0.2  | 0.0679                               | 0.0022 | 1.2797                              | 0.0433 | 0.136                               | 0.0025 | 866                                  | 66.7 | 837                                 | 19.3 | 822                                 | 14.4 |
| 8                    | 32.9                | 71  | 217 | 0.32 | 0.0704                               | 0.0026 | 1.3295                              | 0.0519 | 0.1367                              | 0.0028 | 939                                  | 75.2 | 859                                 | 22.6 | 826                                 | 15.6 |
| 9                    | 28.8                | 160 | 126 | 1.27 | 0.0724                               | 0.0024 | 1.353                               | 0.0438 | 0.1365                              | 0.0032 | 998                                  | 67.8 | 869                                 | 18.9 | 825                                 | 18.2 |
| 10                   | 51.5                | 45  | 305 | 0.15 | 0.0704                               | 0.0016 | 1.5663                              | 0.0366 | 0.1602                              | 0.002  | 943                                  | 46.3 | 957                                 | 14.5 | 958                                 | 10.9 |
| 11                   | 35.7                | 148 | 189 | 0.78 | 0.0679                               | 0.0019 | 1.2737                              | 0.0343 | 0.136                               | 0.0023 | 865                                  | 57.4 | 834                                 | 15.3 | 822                                 | 13   |
| 12                   | 33                  | 82  | 209 | 0.39 | 0.0694                               | 0.0016 | 1.3112                              | 0.0296 | 0.1365                              | 0.0015 | 909                                  | 52.8 | 851                                 | 13   | 825                                 | 8.5  |
| 13                   | 24.39               | 69  | 156 | 0.44 | 0.0663                               | 0.0021 | 1.2533                              | 0.0401 | 0.1363                              | 0.0023 | 817                                  | 65.6 | 825                                 | 18.1 | 824                                 | 12.9 |
| 14                   | 35.8                | 107 | 211 | 0.51 | 0.0647                               | 0.0023 | 1.2169                              | 0.0457 | 0.1363                              | 0.0022 | 765                                  | 75.9 | 808                                 | 20.9 | 824                                 | 12.4 |
| 15                   | 118.9               | 437 | 625 | 0.7  | 0.0738                               | 0.0017 | 1.411                               | 0.0424 | 0.1363                              | 0.0022 | 1037                                 | 45.2 | 894                                 | 17.9 | 824                                 | 12.7 |



续表2

| 分析<br>元素             | 含量/ $10^{-6}$ |     |     | Th/U | 同位素比值                             |           |                                  |           |                                  |           | 表面年龄/Ma                           |           |                                  |           |                                  |           |
|----------------------|---------------|-----|-----|------|-----------------------------------|-----------|----------------------------------|-----------|----------------------------------|-----------|-----------------------------------|-----------|----------------------------------|-----------|----------------------------------|-----------|
|                      | Pb*           | Th  | U   |      | $^{207}\text{Pb}/^{206}\text{Pb}$ | $1\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $1\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $1\sigma$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $1\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $1\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $1\sigma$ |
| 黑云母花岗闪长岩(TW4405-1-5) |               |     |     |      |                                   |           |                                  |           |                                  |           |                                   |           |                                  |           |                                  |           |
| 点号                   |               |     |     |      |                                   |           |                                  |           |                                  |           |                                   |           |                                  |           |                                  |           |
| 1                    | 23.57         | 60  | 146 | 0.41 | 0.0643                            | 0.0018    | 1.2164                           | 0.0385    | 0.1361                           | 0.002     | 750                               | 54.6      | 808                              | 17.6      | 822                              | 11.2      |
| 2                    | 28.1          | 110 | 149 | 0.73 | 0.07                              | 0.0022    | 1.314                            | 0.0419    | 0.136                            | 0.0018    | 929                               | 63.4      | 852                              | 18.4      | 822                              | 10.3      |
| 3                    | 29.49         | 62  | 188 | 0.33 | 0.0663                            | 0.0017    | 1.2553                           | 0.0329    | 0.1364                           | 0.0017    | 817                               | 58.3      | 826                              | 14.8      | 824                              | 9.8       |
| 4                    | 23            | 90  | 129 | 0.69 | 0.0666                            | 0.002     | 1.2606                           | 0.0426    | 0.1362                           | 0.0022    | 833                               | 64        | 828                              | 19.1      | 823                              | 12.4      |
| 5                    | 43.7          | 211 | 224 | 0.94 | 0.0662                            | 0.0018    | 1.2437                           | 0.0339    | 0.1359                           | 0.002     | 813                               | 55.6      | 821                              | 15.4      | 821                              | 11.6      |
| 6                    | 22.84         | 62  | 137 | 0.45 | 0.0684                            | 0.0019    | 1.2843                           | 0.0397    | 0.1354                           | 0.0019    | 880                               | 59.3      | 839                              | 17.6      | 819                              | 10.9      |
| 7                    | 41.1          | 106 | 247 | 0.43 | 0.0683                            | 0.0017    | 1.2912                           | 0.033     | 0.1361                           | 0.0016    | 880                               | 50.5      | 842                              | 14.6      | 822                              | 9.3       |
| 8                    | 41            | 106 | 246 | 0.43 | 0.0683                            | 0.0017    | 1.2939                           | 0.033     | 0.1363                           | 0.0016    | 880                               | 50        | 843                              | 14.6      | 824                              | 9.4       |
| 9                    | 32.33         | 78  | 209 | 0.37 | 0.0681                            | 0.0016    | 1.2856                           | 0.0336    | 0.1362                           | 0.0023    | 872                               | 49.2      | 839                              | 14.9      | 823                              | 12.8      |
| 10                   | 94.8          | 260 | 456 | 0.57 | 0.1002                            | 0.0073    | 1.9083                           | 0.135     | 0.1369                           | 0.004     | 1628                              | 139.8     | 1084                             | 47.2      | 827                              | 22.4      |
| 11                   | 25.1          | 86  | 143 | 0.6  | 0.0666                            | 0.0019    | 1.2533                           | 0.0356    | 0.1359                           | 0.002     | 828                               | 58.5      | 825                              | 16        | 821                              | 11.3      |
| 12                   | 21.91         | 23  | 154 | 0.15 | 0.0649                            | 0.002     | 1.2234                           | 0.0361    | 0.1357                           | 0.0019    | 769                               | 63        | 811                              | 16.5      | 820                              | 10.7      |
| 13                   | 102.2         | 502 | 510 | 0.98 | 0.069                             | 0.0014    | 1.3117                           | 0.0282    | 0.1361                           | 0.002     | 898                               | 40.7      | 851                              | 12.4      | 822                              | 11.4      |
| 14                   | 30.8          | 77  | 188 | 0.41 | 0.0645                            | 0.002     | 1.2328                           | 0.0364    | 0.137                            | 0.0019    | 759                               | 63        | 816                              | 16.6      | 828                              | 10.8      |
| 15                   | 39.4          | 179 | 196 | 0.91 | 0.0665                            | 0.0019    | 1.2619                           | 0.0345    | 0.1363                           | 0.0019    | 820                               | 59.3      | 829                              | 15.5      | 824                              | 10.7      |
| 黑云母花岗闪长岩(TW303-2-2)  |               |     |     |      |                                   |           |                                  |           |                                  |           |                                   |           |                                  |           |                                  |           |
| 1                    | 163.5         | 146 | 941 | 0.16 | 0.0639                            | 0.0014    | 1.2131                           | 0.0274    | 0.1362                           | 0.0017    | 739                               | 44.4      | 807                              | 12.6      | 823                              | 9.5       |
| 2                    | 73            | 146 | 397 | 0.37 | 0.0649                            | 0.0015    | 1.2285                           | 0.0292    | 0.1361                           | 0.0017    | 772                               | 47.1      | 814                              | 13.3      | 823                              | 9.4       |
| 3                    | 126.9         | 93  | 719 | 0.13 | 0.0687                            | 0.0012    | 1.3024                           | 0.0275    | 0.1358                           | 0.0018    | 900                               | 36        | 847                              | 12.1      | 821                              | 10        |
| 4                    | 103.2         | 413 | 460 | 0.9  | 0.0632                            | 0.0013    | 1.1961                           | 0.0262    | 0.1359                           | 0.0014    | 717                               | 47.2      | 799                              | 12.1      | 821                              | 7.8       |
| 5                    | 95            | 172 | 519 | 0.33 | 0.0632                            | 0.0011    | 1.1893                           | 0.0226    | 0.1361                           | 0.0017    | 715                               | 36.3      | 796                              | 10.5      | 822                              | 9.8       |
| 6                    | 93.3          | 97  | 498 | 0.19 | 0.0639                            | 0.0012    | 1.2996                           | 0.0283    | 0.1463                           | 0.0015    | 737                               | 38.9      | 846                              | 12.5      | 880                              | 8.7       |
| 7                    | 75.3          | 107 | 389 | 0.27 | 0.0639                            | 0.0012    | 1.3095                           | 0.0305    | 0.1471                           | 0.0015    | 739                               | 37        | 850                              | 13.4      | 884                              | 8.6       |
| 8                    | 105.6         | 244 | 562 | 0.44 | 0.0612                            | 0.0009    | 1.1607                           | 0.0234    | 0.1365                           | 0.0016    | 656                               | 29.6      | 782                              | 11        | 825                              | 8.9       |
| 9                    | 47.3          | 83  | 249 | 0.33 | 0.0621                            | 0.0016    | 1.2661                           | 0.0359    | 0.1465                           | 0.0018    | 676                               | 55.6      | 831                              | 16.1      | 881                              | 10.1      |
| 10                   | 72            | 105 | 397 | 0.26 | 0.0628                            | 0.0011    | 1.1888                           | 0.0261    | 0.1365                           | 0.0016    | 702                               | 40.9      | 795                              | 12.1      | 825                              | 9         |
| 11                   | 147           | 113 | 857 | 0.13 | 0.0593                            | 0.001     | 1.1203                           | 0.0237    | 0.1362                           | 0.0013    | 589                               | 35.2      | 763                              | 11.4      | 823                              | 7.2       |
| 12                   | 196.8         | 819 | 917 | 0.89 | 0.06                              | 0.0012    | 1.1336                           | 0.0293    | 0.1362                           | 0.0018    | 606                               | 47.2      | 769                              | 13.9      | 823                              | 10.2      |
| 13                   | 77.8          | 101 | 438 | 0.23 | 0.0563                            | 0.0014    | 1.0502                           | 0.0303    | 0.1354                           | 0.0018    | 465                               | 55.6      | 729                              | 15        | 818                              | 10.1      |
| 14                   | 92.2          | 188 | 481 | 0.39 | 0.058                             | 0.0016    | 1.0815                           | 0.0335    | 0.1353                           | 0.0017    | 532                               | 57.4      | 744                              | 16.3      | 818                              | 9.7       |
| 15                   | 65.7          | 136 | 337 | 0.4  | 0.0631                            | 0.0022    | 1.1659                           | 0.044     | 0.1351                           | 0.0019    | 722                               | 72.2      | 785                              | 20.6      | 817                              | 10.8      |
| 黑云母花岗闪长岩(TW303-5-6)  |               |     |     |      |                                   |           |                                  |           |                                  |           |                                   |           |                                  |           |                                  |           |
| 1                    | 97.4          | 107 | 379 | 0.91 | 0.0922                            | 0.0024    | 2.6214                           | 0.0892    | 0.1987                           | 0.004     | 1473                              | 43.5      | 1307                             | 25        | 1169                             | 21.4      |
| 2                    | 96.6          | 91  | 525 | 1.06 | 0.0692                            | 0.0014    | 1.3241                           | 0.0307    | 0.1365                           | 0.0018    | 906                               | 41.5      | 856                              | 13.4      | 825                              | 10.2      |
| 3                    | 201.2         | 303 | 531 | 0.66 | 0.1028                            | 0.0016    | 3.3424                           | 0.0676    | 0.2319                           | 0.0033    | 1678                              | 27.8      | 1485                             | 15.8      | 1341                             | 16.9      |
| 4                    | 102.8         | 66  | 597 | 1.57 | 0.0776                            | 0.0033    | 1.4473                           | 0.0881    | 0.1286                           | 0.0018    | 928                               | 52.8      | 838                              | 17.8      | 820                              | 12.5      |
| 5                    | 145.1         | 308 | 802 | 0.47 | 0.0699                            | 0.0013    | 1.2609                           | 0.028     | 0.1288                           | 0.0016    | 972                               | 39.4      | 869                              | 16.1      | 817                              | 13.3      |
| 6                    | 85.9          | 111 | 501 | 0.77 | 0.0691                            | 0.0012    | 1.244                            | 0.0242    | 0.129                            | 0.0014    | 843                               | 59.4      | 831                              | 11.5      | 819                              | 8.8       |
| 7                    | 61            | 123 | 336 | 0.49 | 0.0689                            | 0.0013    | 1.2388                           | 0.0271    | 0.1287                           | 0.0014    | 872                               | 43.7      | 839                              | 12.4      | 817                              | 7.7       |
| 8                    | 60.2          | 78  | 336 | 0.77 | 0.072                             | 0.0016    | 1.3716                           | 0.0372    | 0.1363                           | 0.0017    | 987                               | 46.3      | 877                              | 15.9      | 824                              | 9.7       |
| 9                    | 197.1         | 77  | 539 | 2.55 | 0.0997                            | 0.0014    | 3.6557                           | 0.1004    | 0.259                            | 0.0051    | 1618                              | 26.2      | 1562                             | 21.9      | 1485                             | 25.9      |
| 10                   | 124.8         | 305 | 637 | 0.41 | 0.0645                            | 0.0011    | 1.2267                           | 0.0237    | 0.1363                           | 0.0015    | 767                               | 35        | 813                              | 10.8      | 824                              | 8.4       |
| 11                   | 95.99         | 68  | 558 | 1.41 | 0.0663                            | 0.0012    | 1.2628                           | 0.0272    | 0.1361                           | 0.0016    | 817                               | 40        | 829                              | 12.2      | 823                              | 8.9       |
| 12                   | 77.55         | 69  | 439 | 1.13 | 0.0653                            | 0.0016    | 1.2482                           | 0.0327    | 0.1366                           | 0.0018    | 785                               | 45.4      | 823                              | 14.8      | 826                              | 10.1      |
| 13                   | 68.44         | 65  | 406 | 1.06 | 0.0641                            | 0.0016    | 1.2238                           | 0.0368    | 0.136                            | 0.0021    | 746                               | 52.9      | 812                              | 16.8      | 822                              | 11.9      |
| 14                   | 58.8          | 101 | 311 | 0.58 | 0.0691                            | 0.0019    | 1.3181                           | 0.0422    | 0.1356                           | 0.0018    | 902                               | 55.6      | 854                              | 18.5      | 820                              | 10.5      |
| 15                   | 69.1          | 159 | 355 | 0.45 | 0.0709                            | 0.0022    | 1.3527                           | 0.0474    | 0.1361                           | 0.0023    | 954                               | 58.3      | 869                              | 20.5      | 823                              | 13        |

续表2

| 分析<br>元素<br>点号    | 含量/ $10^{-6}$ |     |      | Th/U | 同位素比值                             |           |                                  |           |                                  |           | 表面年龄/Ma                           |           |                                  |           |                                  |           |
|-------------------|---------------|-----|------|------|-----------------------------------|-----------|----------------------------------|-----------|----------------------------------|-----------|-----------------------------------|-----------|----------------------------------|-----------|----------------------------------|-----------|
|                   | Pb*           | Th  | U    |      | $^{207}\text{Pb}/^{206}\text{Pb}$ | $1\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $1\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $1\sigma$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $1\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $1\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $1\sigma$ |
| 英云闪长岩(TW4448-1-4) |               |     |      |      |                                   |           |                                  |           |                                  |           |                                   |           |                                  |           |                                  |           |
| 1                 | 34.64         | 64  | 236  | 0.27 | 0.0639                            | 0.0019    | 1.2139                           | 0.0382    | 0.1361                           | 0.0022    | 739                               | 61.1      | 807                              | 17.5      | 823                              | 12.4      |
| 2                 | 67.4          | 149 | 433  | 0.34 | 0.0659                            | 0.0017    | 1.2543                           | 0.0334    | 0.1361                           | 0.0015    | 803                               | 54.8      | 825                              | 15.1      | 823                              | 8.6       |
| 3                 | 59.1          | 138 | 381  | 0.36 | 0.0633                            | 0.0016    | 1.2061                           | 0.0307    | 0.1368                           | 0.0019    | 717                               | 51.8      | 803                              | 14.2      | 827                              | 11        |
| 4                 | 47.7          | 150 | 284  | 0.53 | 0.0657                            | 0.0016    | 1.2448                           | 0.0303    | 0.1359                           | 0.0016    | 794                               | 56.5      | 821                              | 13.7      | 821                              | 9         |
| 5                 | 57.1          | 118 | 380  | 0.31 | 0.0638                            | 0.0014    | 1.2128                           | 0.0276    | 0.1362                           | 0.0015    | 744                               | 48.1      | 806                              | 12.7      | 823                              | 8.6       |
| 6                 | 78.7          | 214 | 493  | 0.43 | 0.0629                            | 0.0019    | 1.2012                           | 0.0349    | 0.1367                           | 0.0021    | 706                               | 63        | 801                              | 16.1      | 826                              | 11.8      |
| 7                 | 48.8          | 150 | 309  | 0.49 | 0.0653                            | 0.0017    | 1.2236                           | 0.0334    | 0.134                            | 0.0019    | 783                               | 55.6      | 811                              | 15.3      | 811                              | 10.6      |
| 8                 | 62.6          | 149 | 412  | 0.36 | 0.0637                            | 0.0016    | 1.2187                           | 0.032     | 0.1369                           | 0.0018    | 731                               | 52.6      | 809                              | 14.6      | 827                              | 10        |
| 9                 | 42.3          | 93  | 288  | 0.32 | 0.065                             | 0.0017    | 1.2371                           | 0.0342    | 0.1361                           | 0.0019    | 776                               | 53.7      | 818                              | 15.5      | 822                              | 10.7      |
| 10                | 56.9          | 234 | 321  | 0.73 | 0.0604                            | 0.0018    | 1.145                            | 0.0356    | 0.1362                           | 0.0021    | 617                               | 66.7      | 775                              | 16.9      | 823                              | 11.9      |
| 11                | 59.6          | 138 | 385  | 0.36 | 0.0617                            | 0.0015    | 1.1695                           | 0.0283    | 0.1366                           | 0.0017    | 661                               | 56.5      | 786                              | 13.3      | 825                              | 9.4       |
| 12                | 68.7          | 178 | 434  | 0.41 | 0.0595                            | 0.0015    | 1.1302                           | 0.0274    | 0.137                            | 0.0016    | 587                               | 53.7      | 768                              | 13.1      | 828                              | 8.9       |
| 13                | 76.5          | 92  | 526  | 0.18 | 0.0641                            | 0.0016    | 1.2256                           | 0.0389    | 0.1371                           | 0.0025    | 743                               | 47        | 812                              | 17.7      | 828                              | 14        |
| 14                | 55.4          | 173 | 335  | 0.51 | 0.0583                            | 0.0015    | 1.1011                           | 0.0318    | 0.1363                           | 0.002     | 539                               | 57.4      | 754                              | 15.4      | 824                              | 11.1      |
| 15                | 43.7          | 67  | 278  | 0.24 | 0.0641                            | 0.0082    | 1.1995                           | 0.1076    | 0.1369                           | 0.0063    | 746                               | 272.2     | 800                              | 49.7      | 827                              | 35.6      |
| 英云闪长岩(TW4445-3-5) |               |     |      |      |                                   |           |                                  |           |                                  |           |                                   |           |                                  |           |                                  |           |
| 1                 | 33.56         | 45  | 225  | 0.2  | 0.0645                            | 0.0017    | 1.206                            | 0.0307    | 0.135                            | 0.0018    | 767                               | 55.6      | 803                              | 14.1      | 816                              | 10        |
| 2                 | 54.4          | 105 | 328  | 0.32 | 0.0872                            | 0.0024    | 1.616                            | 0.0479    | 0.1354                           | 0.0026    | 1365                              | 53.2      | 976                              | 18.6      | 818                              | 14.6      |
| 3                 | 66.8          | 242 | 363  | 0.67 | 0.0669                            | 0.0014    | 1.2534                           | 0.0275    | 0.1346                           | 0.0015    | 835                               | 44.4      | 825                              | 12.4      | 814                              | 8.6       |
| 4                 | 84.6          | 56  | 410  | 0.14 | 0.0839                            | 0.0019    | 2.1935                           | 0.0851    | 0.1799                           | 0.0047    | 1300                              | 72.2      | 1179                             | 27.1      | 1066                             | 25.8      |
| 5                 | 44.8          | 112 | 263  | 0.43 | 0.0714                            | 0.0017    | 1.3465                           | 0.034     | 0.1353                           | 0.0015    | 969                               | 48.9      | 866                              | 14.7      | 818                              | 8.7       |
| 6                 | 70            | 185 | 404  | 0.46 | 0.0702                            | 0.0015    | 1.32                             | 0.0294    | 0.1346                           | 0.0016    | 1000                              | 38        | 854                              | 12.8      | 814                              | 8.9       |
| 7                 | 35.3          | 98  | 206  | 0.48 | 0.0672                            | 0.0019    | 1.2533                           | 0.0341    | 0.1348                           | 0.0018    | 856                               | 57.4      | 825                              | 15.4      | 815                              | 10.3      |
| 8                 | 57.8          | 100 | 363  | 0.28 | 0.0706                            | 0.0021    | 1.3545                           | 0.0632    | 0.1358                           | 0.0034    | 946                               | 61.3      | 869                              | 27.3      | 821                              | 19.5      |
| 9                 | 49.2          | 85  | 239  | 0.35 | 0.0782                            | 0.002     | 1.8509                           | 0.071     | 0.1696                           | 0.0054    | 1152                              | 83.5      | 1064                             | 25.3      | 1010                             | 29.9      |
| 10                | 37.4          | 105 | 195  | 0.54 | 0.0743                            | 0.0023    | 1.3997                           | 0.0399    | 0.136                            | 0.0018    | 1050                              | 61.9      | 889                              | 16.9      | 822                              | 10.1      |
| 11                | 15.94         | 50  | 84.9 | 0.58 | 0.0633                            | 0.0022    | 1.2056                           | 0.0397    | 0.1384                           | 0.002     | 720                               | 68        | 803                              | 18.3      | 835                              | 11.5      |
| 12                | 49.1          | 122 | 295  | 0.41 | 0.0662                            | 0.0014    | 1.2365                           | 0.0271    | 0.1346                           | 0.0017    | 813                               | 44.4      | 817                              | 12.3      | 814                              | 9.9       |
| 13                | 61.7          | 119 | 365  | 0.33 | 0.0654                            | 0.0012    | 1.256                            | 0.0247    | 0.1382                           | 0.0016    | 787                               | 40.7      | 826                              | 11.1      | 834                              | 9         |
| 14                | 54.9          | 122 | 322  | 0.38 | 0.0622                            | 0.0015    | 1.1686                           | 0.029     | 0.135                            | 0.0017    | 683                               | 51.1      | 786                              | 13.6      | 816                              | 9.8       |
| 15                | 30            | 100 | 164  | 0.61 | 0.0647                            | 0.0017    | 1.2177                           | 0.0362    | 0.1353                           | 0.002     | 765                               | 56        | 809                              | 16.6      | 818                              | 11.6      |
| 英云闪长岩(TW5901-1-2) |               |     |      |      |                                   |           |                                  |           |                                  |           |                                   |           |                                  |           |                                  |           |
| 1                 | 40.5          | 100 | 243  | 0.41 | 0.065                             | 0.0015    | 1.2237                           | 0.0281    | 0.1362                           | 0.0017    | 776                               | 48.1      | 811                              | 12.8      | 823                              | 9.5       |
| 2                 | 37.48         | 56  | 239  | 0.24 | 0.0646                            | 0.0017    | 1.2124                           | 0.0295    | 0.136                            | 0.0016    | 761                               | 55.6      | 806                              | 13.5      | 822                              | 9.4       |
| 3                 | 21.96         | 58  | 131  | 0.44 | 0.0655                            | 0.0018    | 1.2368                           | 0.0373    | 0.1359                           | 0.0018    | 791                               | 59.3      | 817                              | 17        | 822                              | 10.2      |
| 4                 | 27.16         | 68  | 161  | 0.42 | 0.0685                            | 0.0029    | 1.2922                           | 0.0602    | 0.1353                           | 0.0019    | 883                               | 87        | 842                              | 26.7      | 818                              | 11        |
| 5                 | 24.94         | 60  | 149  | 0.4  | 0.0677                            | 0.0018    | 1.279                            | 0.0355    | 0.1365                           | 0.0017    | 861                               | 58.3      | 836                              | 15.8      | 825                              | 9.4       |
| 6                 | 44.6          | 111 | 267  | 0.42 | 0.0685                            | 0.0015    | 1.2928                           | 0.0313    | 0.136                            | 0.0016    | 883                               | 47.1      | 843                              | 13.9      | 822                              | 9         |
| 7                 | 48            | 117 | 319  | 0.37 | 0.0669                            | 0.0019    | 1.1599                           | 0.0322    | 0.1252                           | 0.0018    | 835                               | 62        | 782                              | 15.1      | 761                              | 10.5      |
| 8                 | 29.6          | 69  | 176  | 0.39 | 0.0697                            | 0.0021    | 1.3081                           | 0.0341    | 0.1364                           | 0.002     | 920                               | 65.7      | 849                              | 15        | 824                              | 11.2      |
| 9                 | 34.1          | 82  | 205  | 0.4  | 0.0651                            | 0.0015    | 1.2245                           | 0.0292    | 0.1356                           | 0.0016    | 789                               | 48.1      | 812                              | 13.3      | 820                              | 9.3       |
| 10                | 38.2          | 94  | 226  | 0.41 | 0.0676                            | 0.0016    | 1.2741                           | 0.0307    | 0.1364                           | 0.0015    | 857                               | 50        | 834                              | 13.7      | 824                              | 8.7       |
| 11                | 34.1          | 87  | 199  | 0.44 | 0.0668                            | 0.0016    | 1.2575                           | 0.0297    | 0.136                            | 0.0014    | 831                               | 50        | 827                              | 13.4      | 822                              | 7.9       |
| 12                | 33.9          | 81  | 201  | 0.4  | 0.0642                            | 0.0014    | 1.2106                           | 0.0274    | 0.1362                           | 0.0016    | 750                               | 46.3      | 805                              | 12.6      | 823                              | 8.9       |
| 13                | 46.88         | 49  | 306  | 0.16 | 0.0668                            | 0.0013    | 1.2637                           | 0.0248    | 0.1366                           | 0.0015    | 831                               | 39.7      | 830                              | 11.1      | 825                              | 8.2       |
| 14                | 41            | 102 | 237  | 0.43 | 0.0641                            | 0.0015    | 1.2155                           | 0.0293    | 0.1367                           | 0.0015    | 746                               | 50        | 808                              | 13.4      | 826                              | 8.7       |
| 15                | 62.7          | 496 | 209  | 2.37 | 0.0677                            | 0.0024    | 1.282                            | 0.0453    | 0.1368                           | 0.0024    | 861                               | 74.1      | 838                              | 20.1      | 827                              | 13.5      |

续表2

| 分析<br>元素             | 含量/10 <sup>-6</sup> |     |      | Th/U | 同位素比值                                |        |                                     |        |                                     |        | 表面年龄/Ma                              |      |                                     |      |                                     |      |
|----------------------|---------------------|-----|------|------|--------------------------------------|--------|-------------------------------------|--------|-------------------------------------|--------|--------------------------------------|------|-------------------------------------|------|-------------------------------------|------|
|                      | Pb*                 | Th  | U    |      | <sup>207</sup> Pb/ <sup>206</sup> Pb | 1σ     | <sup>207</sup> Pb/ <sup>235</sup> U | 1σ     | <sup>206</sup> Pb/ <sup>238</sup> U | 1σ     | <sup>207</sup> Pb/ <sup>206</sup> Pb | 1σ   | <sup>207</sup> Pb/ <sup>235</sup> U | 1σ   | <sup>206</sup> Pb/ <sup>238</sup> U | 1σ   |
| 黑云母二长花岗岩(TW5242-1-2) |                     |     |      |      |                                      |        |                                     |        |                                     |        |                                      |      |                                     |      |                                     |      |
| 1                    | 212.6               | 99  | 849  | 0.12 | 0.0658                               | 0.0015 | 1.2537                              | 0.0368 | 0.1365                              | 0.0022 | 798                                  | 52.8 | 825                                 | 16.6 | 825                                 | 12.5 |
| 2                    | 163.2               | 55  | 665  | 0.08 | 0.0657                               | 0.0016 | 1.2465                              | 0.0338 | 0.1363                              | 0.002  | 796                                  | 54.6 | 822                                 | 15.3 | 824                                 | 11.1 |
| 3                    | 66.2                | 150 | 212  | 0.71 | 0.0662                               | 0.0017 | 1.248                               | 0.0306 | 0.1362                              | 0.0016 | 813                                  | 49.1 | 822                                 | 13.8 | 823                                 | 8.9  |
| 4                    | 143.4               | 232 | 495  | 0.47 | 0.0656                               | 0.0014 | 1.2562                              | 0.0279 | 0.1376                              | 0.0018 | 794                                  | 44.4 | 826                                 | 12.6 | 831                                 | 10.3 |
| 5                    | 170                 | 476 | 491  | 0.97 | 0.0659                               | 0.0014 | 1.2438                              | 0.0266 | 0.1361                              | 0.0016 | 806                                  | 41.7 | 821                                 | 12.1 | 823                                 | 9.3  |
| 6                    | 162.2               | 433 | 495  | 0.88 | 0.0663                               | 0.0017 | 1.258                               | 0.0426 | 0.1358                              | 0.0026 | 817                                  | 55.6 | 827                                 | 19.1 | 821                                 | 14.6 |
| 7                    | 79.1                | 271 | 214  | 1.27 | 0.0646                               | 0.0021 | 1.2106                              | 0.0339 | 0.1361                              | 0.0021 | 761                                  | 66.7 | 805                                 | 15.6 | 822                                 | 11.9 |
| 8                    | 457.4               | 164 | 1905 | 0.09 | 0.064                                | 0.0013 | 1.2152                              | 0.0269 | 0.1363                              | 0.0019 | 743                                  | 44.4 | 808                                 | 12.3 | 824                                 | 11   |
| 9                    | 76.2                | 346 | 186  | 1.85 | 0.0658                               | 0.002  | 1.2474                              | 0.0426 | 0.1368                              | 0.0022 | 798                                  | 64.8 | 822                                 | 19.3 | 827                                 | 12.5 |
| 10                   | 143.5               | 398 | 451  | 0.88 | 0.0674                               | 0.0014 | 1.2774                              | 0.0267 | 0.1365                              | 0.0015 | 850                                  | 42.6 | 836                                 | 11.9 | 825                                 | 8.5  |
| 11                   | 102.2               | 290 | 292  | 0.99 | 0.0663                               | 0.0032 | 1.2666                              | 0.0564 | 0.138                               | 0.0025 | 815                                  | 106  | 831                                 | 25.3 | 834                                 | 13.9 |
| 12                   | 133.2               | 152 | 518  | 0.29 | 0.0673                               | 0.0011 | 1.2714                              | 0.0224 | 0.1363                              | 0.0016 | 856                                  | 33.3 | 833                                 | 10   | 824                                 | 8.9  |
| 13                   | 58.6                | 132 | 199  | 0.66 | 0.0674                               | 0.0017 | 1.2567                              | 0.0305 | 0.136                               | 0.0018 | 850                                  | 51.8 | 826                                 | 13.7 | 822                                 | 10.2 |
| 14                   | 97.3                | 145 | 370  | 0.39 | 0.0678                               | 0.0014 | 1.2772                              | 0.0278 | 0.1362                              | 0.002  | 865                                  | 42.6 | 836                                 | 12.4 | 823                                 | 11.4 |
| 15                   | 102.2               | 342 | 293  | 1.17 | 0.0697                               | 0.0016 | 1.3123                              | 0.0319 | 0.1363                              | 0.0019 | 920                                  | 47.4 | 851                                 | 14   | 824                                 | 10.9 |
| 黑云母二长花岗岩(TW303-37-2) |                     |     |      |      |                                      |        |                                     |        |                                     |        |                                      |      |                                     |      |                                     |      |
| 1                    | 216.1               | 186 | 1172 | 0.16 | 0.0688                               | 0.0013 | 1.2943                              | 0.027  | 0.136                               | 0.0018 | 892                                  | 37.8 | 843                                 | 12   | 822                                 | 10.4 |
| 2                    | 108.8               | 262 | 505  | 0.52 | 0.0708                               | 0.0018 | 1.336                               | 0.0378 | 0.1362                              | 0.0021 | 954                                  | 53.7 | 861                                 | 16.4 | 823                                 | 11.8 |
| 3                    | 109                 | 173 | 535  | 0.32 | 0.0726                               | 0.0023 | 1.3598                              | 0.0431 | 0.1353                              | 0.0021 | 1011                                 | 63   | 872                                 | 18.6 | 818                                 | 12   |
| 4                    | 117.2               | 413 | 495  | 0.83 | 0.0664                               | 0.0024 | 1.2389                              | 0.0428 | 0.1358                              | 0.0023 | 817                                  | 78.7 | 818                                 | 19.4 | 821                                 | 12.9 |
| 5                    | 319                 | 240 | 1942 | 0.12 | 0.063                                | 0.0015 | 1.0772                              | 0.0261 | 0.1228                              | 0.0018 | 709                                  | 54.6 | 742                                 | 12.8 | 747                                 | 10.5 |
| 6                    | 72.2                | 183 | 362  | 0.51 | 0.0678                               | 0.0024 | 1.163                               | 0.0409 | 0.1238                              | 0.0019 | 865                                  | 106  | 783                                 | 19.2 | 753                                 | 10.7 |
| 7                    | 120.3               | 233 | 594  | 0.39 | 0.0679                               | 0.0021 | 1.2796                              | 0.0393 | 0.1354                              | 0.0023 | 865                                  | 64   | 837                                 | 17.5 | 818                                 | 12.9 |
| 8                    | 159.2               | 114 | 875  | 0.13 | 0.066                                | 0.0021 | 1.247                               | 0.0395 | 0.1355                              | 0.0024 | 806                                  | 66.7 | 822                                 | 17.8 | 819                                 | 13.5 |
| 9                    | 153.3               | 234 | 811  | 0.29 | 0.0662                               | 0.0022 | 1.2506                              | 0.0428 | 0.1352                              | 0.0025 | 813                                  | 69.3 | 824                                 | 19.3 | 817                                 | 13.9 |
| 10                   | 141.8               | 526 | 615  | 0.86 | 0.0674                               | 0.0022 | 1.272                               | 0.0431 | 0.1354                              | 0.0026 | 850                                  | 66.7 | 833                                 | 19.3 | 819                                 | 14.5 |
| 11                   | 82.7                | 199 | 398  | 0.5  | 0.0704                               | 0.0026 | 1.3373                              | 0.0496 | 0.1364                              | 0.0026 | 943                                  | 75.9 | 862                                 | 21.6 | 824                                 | 14.5 |
| 12                   | 108.9               | 177 | 563  | 0.31 | 0.0691                               | 0.0022 | 1.3125                              | 0.043  | 0.1357                              | 0.0023 | 902                                  | 65.3 | 851                                 | 18.9 | 821                                 | 13.1 |
| 13                   | 103.6               | 229 | 498  | 0.46 | 0.0666                               | 0.0021 | 1.2654                              | 0.0413 | 0.1356                              | 0.0022 | 826                                  | 66.7 | 830                                 | 18.5 | 820                                 | 12.3 |
| 14                   | 112.2               | 317 | 520  | 0.61 | 0.065                                | 0.0021 | 1.2273                              | 0.039  | 0.1354                              | 0.0022 | 772                                  | 66.7 | 813                                 | 17.8 | 819                                 | 12.7 |
| 15                   | 148.1               | 109 | 736  | 0.15 | 0.0814                               | 0.0032 | 1.5153                              | 0.0594 | 0.136                               | 0.0041 | 1231                                 | 76.7 | 937                                 | 24   | 822                                 | 23.4 |
| 黑云母二长花岗岩(TW1513-1-2) |                     |     |      |      |                                      |        |                                     |        |                                     |        |                                      |      |                                     |      |                                     |      |
| 1                    | 124.4               | 99  | 749  | 0.13 | 0.0615                               | 0.001  | 1.165                               | 0.0314 | 0.1363                              | 0.0031 | 717                                  | 34.4 | 800                                 | 15   | 824                                 | 17.8 |
| 2                    | 107.2               | 131 | 594  | 0.22 | 0.0647                               | 0.001  | 1.2268                              | 0.023  | 0.1358                              | 0.0012 | 835                                  | 29.6 | 832                                 | 10.1 | 820                                 | 7    |
| 3                    | 65.6                | 156 | 328  | 0.48 | 0.0614                               | 0.0016 | 1.1581                              | 0.0326 | 0.1356                              | 0.002  | 777                                  | 55.6 | 811                                 | 14.8 | 817                                 | 10.7 |
| 4                    | 96.4                | 258 | 475  | 0.54 | 0.0615                               | 0.0014 | 1.1604                              | 0.0285 | 0.1356                              | 0.0014 | 769                                  | 49.2 | 814                                 | 13.3 | 822                                 | 8.1  |
| 5                    | 56                  | 160 | 275  | 0.58 | 0.0615                               | 0.0013 | 1.155                               | 0.0282 | 0.1359                              | 0.0025 | 783                                  | 41.7 | 813                                 | 13   | 817                                 | 9.8  |
| 6                    | 52.9                | 96  | 282  | 0.34 | 0.0585                               | 0.0014 | 1.1096                              | 0.0309 | 0.1364                              | 0.0019 | 643                                  | 78.7 | 784                                 | 21.1 | 829                                 | 17.2 |
| 7                    | 70.9                | 174 | 356  | 0.49 | 0.0601                               | 0.0012 | 1.1334                              | 0.028  | 0.1357                              | 0.0017 | 770                                  | 40   | 816                                 | 12   | 825                                 | 9.5  |
| 8                    | 43.4                | 97  | 219  | 0.44 | 0.06                                 | 0.0017 | 1.1301                              | 0.0365 | 0.1364                              | 0.0019 | 1200                                 | 59.3 | 825                                 | 16.6 | 829                                 | 10.7 |
| 9                    | 89.2                | 154 | 475  | 0.32 | 0.0601                               | 0.0012 | 1.1318                              | 0.0284 | 0.1361                              | 0.0014 | 798                                  | 41.8 | 823                                 | 12.1 | 825                                 | 8.1  |
| 10                   | 62.9                | 142 | 323  | 0.44 | 0.0599                               | 0.0013 | 1.118                               | 0.0312 | 0.1359                              | 0.0019 | 815                                  | 46.3 | 817                                 | 15   | 810                                 | 10.2 |
| 11                   | 77.9                | 214 | 396  | 0.54 | 0.0591                               | 0.0011 | 1.1093                              | 0.0318 | 0.136                               | 0.002  | 767                                  | 40.7 | 809                                 | 12.9 | 822                                 | 11.3 |
| 12                   | 49.6                | 137 | 237  | 0.58 | 0.0585                               | 0.0012 | 1.1039                              | 0.0387 | 0.1358                              | 0.0023 | 731                                  | 42.6 | 802                                 | 15.2 | 817                                 | 12.5 |
| 13                   | 101.9               | 351 | 487  | 0.72 | 0.0614                               | 0.0015 | 1.155                               | 0.0433 | 0.1356                              | 0.0016 | 817                                  | 48.9 | 830                                 | 16.4 | 825                                 | 9.1  |
| 14                   | 127.8               | 189 | 689  | 0.27 | 0.0594                               | 0.0009 | 1.1097                              | 0.0365 | 0.1355                              | 0.0014 | 767                                  | 32.6 | 814                                 | 11.6 | 825                                 | 7.9  |
| 15                   | 60.4                | 135 | 307  | 0.44 | 0.0586                               | 0.0013 | 1.0999                              | 0.0445 | 0.1362                              | 0.0015 | 722                                  | 50   | 801                                 | 15.6 | 823                                 | 7.8  |

续表2

| 分析<br>元素             | 含量/ $10^{-6}$ |     |     | Th/U | 同位素比值                             |           |                                  |           |                                  |           | 表面年龄/Ma                           |           |                                  |           |                                  |           |
|----------------------|---------------|-----|-----|------|-----------------------------------|-----------|----------------------------------|-----------|----------------------------------|-----------|-----------------------------------|-----------|----------------------------------|-----------|----------------------------------|-----------|
|                      | Pb*           | Th  | U   |      | $^{207}\text{Pb}/^{206}\text{Pb}$ | $1\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $1\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $1\sigma$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $1\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $1\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $1\sigma$ |
| 黑云母二长花岗岩(TW6123-1-2) |               |     |     |      |                                   |           |                                  |           |                                  |           |                                   |           |                                  |           |                                  |           |
| 1                    | 43.43         | 31  | 326 | 0.1  | 0.0703                            | 0.002     | 1.3166                           | 0.0477    | 0.1366                           | 0.0025    | 939                               | 60.3      | 853                              | 20.9      | 825                              | 14.1      |
| 2                    | 34.2          | 85  | 222 | 0.38 | 0.0666                            | 0.0028    | 1.2561                           | 0.0561    | 0.1362                           | 0.0027    | 828                               | 88.9      | 826                              | 25.3      | 823                              | 15.4      |
| 3                    | 90.2          | 67  | 547 | 0.12 | 0.0723                            | 0.0015    | 1.6409                           | 0.0387    | 0.1633                           | 0.0021    | 994                               | 41.8      | 986                              | 14.9      | 975                              | 11.5      |
| 4                    | 60.1          | 110 | 410 | 0.27 | 0.0675                            | 0.0014    | 1.2755                           | 0.0289    | 0.1365                           | 0.0021    | 854                               | 42.6      | 835                              | 12.9      | 825                              | 11.9      |
| 5                    | 68.22         | 66  | 505 | 0.13 | 0.0651                            | 0.0016    | 1.2234                           | 0.0277    | 0.1361                           | 0.002     | 789                               | 50        | 811                              | 12.7      | 823                              | 11.6      |
| 6                    | 53.9          | 74  | 380 | 0.2  | 0.0663                            | 0.0018    | 1.2535                           | 0.0351    | 0.1361                           | 0.002     | 817                               | 55.6      | 825                              | 15.8      | 822                              | 11.4      |
| 7                    | 46.07         | 47  | 341 | 0.14 | 0.0645                            | 0.0015    | 1.2147                           | 0.0286    | 0.1362                           | 0.002     | 767                               | 48.1      | 807                              | 13.1      | 823                              | 11.4      |
| 8                    | 46.52         | 43  | 339 | 0.13 | 0.0665                            | 0.0016    | 1.2677                           | 0.0379    | 0.1362                           | 0.0021    | 833                               | 50.8      | 831                              | 16.9      | 823                              | 11.7      |
| 9                    | 94            | 208 | 730 | 0.29 | 0.0646                            | 0.0014    | 1.0606                           | 0.025     | 0.1184                           | 0.002     | 761                               | 44.4      | 734                              | 12.3      | 721                              | 11.4      |
| 10                   | 58.2          | 92  | 256 | 0.36 | 0.0762                            | 0.0018    | 1.9261                           | 0.0452    | 0.1822                           | 0.0022    | 1102                              | 46.8      | 1090                             | 15.7      | 1079                             | 11.8      |
| 11                   | 77            | 125 | 619 | 0.2  | 0.0629                            | 0.0012    | 1.0298                           | 0.0199    | 0.1183                           | 0.0017    | 706                               | 42.6      | 719                              | 10        | 721                              | 9.9       |
| 12                   | 56.2          | 122 | 173 | 0.71 | 0.0838                            | 0.0017    | 2.8694                           | 0.0661    | 0.2463                           | 0.003     | 1288                              | 40.3      | 1374                             | 17.4      | 1419                             | 15.6      |
| 13                   | 46.4          | 82  | 308 | 0.27 | 0.0685                            | 0.0017    | 1.3107                           | 0.0488    | 0.1364                           | 0.0031    | 883                               | 84.3      | 850                              | 21.4      | 824                              | 17.4      |
| 14                   | 45            | 60  | 320 | 0.19 | 0.0609                            | 0.0014    | 1.1594                           | 0.0281    | 0.137                            | 0.0016    | 635                               | 48.1      | 782                              | 13.2      | 828                              | 9         |
| 15                   | 57.1          | 139 | 386 | 0.36 | 0.0606                            | 0.0015    | 1.1406                           | 0.03      | 0.1359                           | 0.0017    | 628                               | 53.7      | 773                              | 14.2      | 821                              | 9.7       |

注: Pb\*为放射性成因铅。

龄较老(>1.0 Ga)的锆石,采用 $^{207}\text{Pb}/^{206}\text{Pb}$ 年龄,而对年龄较小(<1.0 Ga)的锆石采用 $^{206}\text{Pb}/^{238}\text{U}$ 年龄(Griffin et al., 2004)。

样品 TW4701-1-5 采自岩体南西侧黄港附近,共对其中 15 颗锆石进行测试,CL 图像(图 4)显示锆石呈长柱状,长宽比为 2:1~3:1,粒径 150~200  $\mu\text{m}$ ,可见明显的震荡环带;所测锆石的 Th、U 含量分别介于  $51.1\times 10^{-6}$ ~ $221\times 10^{-6}$  和  $153\times 10^{-6}$ ~ $388\times 10^{-6}$ , Th/U 为 0.20~0.98,均大于 0.1,具明显岩浆锆石特征(Wu and Zheng, 2004),各测点年龄全部位于谐和线上或附近,其中测点-2 的 $^{207}\text{Pb}/^{206}\text{Pb}$ 年龄为(2169 $\pm$ 37) Ma,属古元古代捕获锆石;其余 14 颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为(823.1 $\pm$ 5.0) Ma (MSWD=0.10,图 5a),为研究区 SW 侧黑云母花岗闪长岩的成岩年龄。

样品 TW6505-1-6 采自岩体最南部,共对其中 15 颗锆石进行测试,CL 图像(图 4)显示锆石呈长柱状,长宽比为 2:1~3:1,粒径约 150~200  $\mu\text{m}$ ,可见明显的结晶成分环带;所测锆石的 Th、U 含量分别介于  $44.8\times 10^{-6}$ ~ $621\times 10^{-6}$  和  $203\times 10^{-6}$ ~ $759\times 10^{-6}$ , Th/U 比值为 0.13~1.17,均大于 0.1,具明显岩浆锆石特征(Wu and Zheng, 2004),各测点年龄全部位于谐和线上或附近,其 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为(823.2 $\pm$ 5.5)

Ma (MSWD=0.02(图 5b),应属南部黑云母花岗闪长岩的成岩年龄。

样品 TW6712-2-6 采自岩体南东部,共对其中 15 颗锆石进行测试,CL 图像(图 4)显示锆石呈长柱状,长宽比为 2:1~3:1,粒径 150~200  $\mu\text{m}$ ,可见明显的结晶成分环带;所测锆石的 Th、U 含量分别介于  $45\times 10^{-6}$ ~ $437\times 10^{-6}$  和  $126\times 10^{-6}$ ~ $625\times 10^{-6}$ , Th/U 比值为 0.23~0.96,均大于 0.1,具明显岩浆锆石特征(Wu and Zheng, 2004),各测点年龄全部位于谐和线上或附近,其中测点-10 的 $^{206}\text{Pb}/^{238}\text{Pb}$ 年龄为(958 $\pm$ 10.9) Ma,属新元古代早期的捕获锆石;其余 14 颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为(824.0 $\pm$ 6.7) Ma (MSWD=0.01,图 5c),为研究区 SE 侧黑云母花岗闪长岩的成岩年龄。

样品 TW4405-1-5 采自岩体中部,共对其中 15 颗锆石进行测试,CL 图像(图 4)显示锆石呈长柱状,长宽比为 2:1~3:1,粒径 150~200  $\mu\text{m}$ ,可见明显的结晶成分环带;所测锆石的 Th、U 含量分别介于  $22.5\times 10^{-6}$ ~ $502\times 10^{-6}$  和  $129\times 10^{-6}$ ~ $510\times 10^{-6}$ , Th/U 比值为 0.15~0.98,均大于 0.1,具明显岩浆锆石特征(Wu and Zheng, 2004),各测点年龄全部位于谐和线上或附近,其中测点-10 的 $^{206}\text{Pb}/^{238}\text{U}$ 年龄远离谐和线,可能是 Pb 丢失造成的;其余 14 颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平

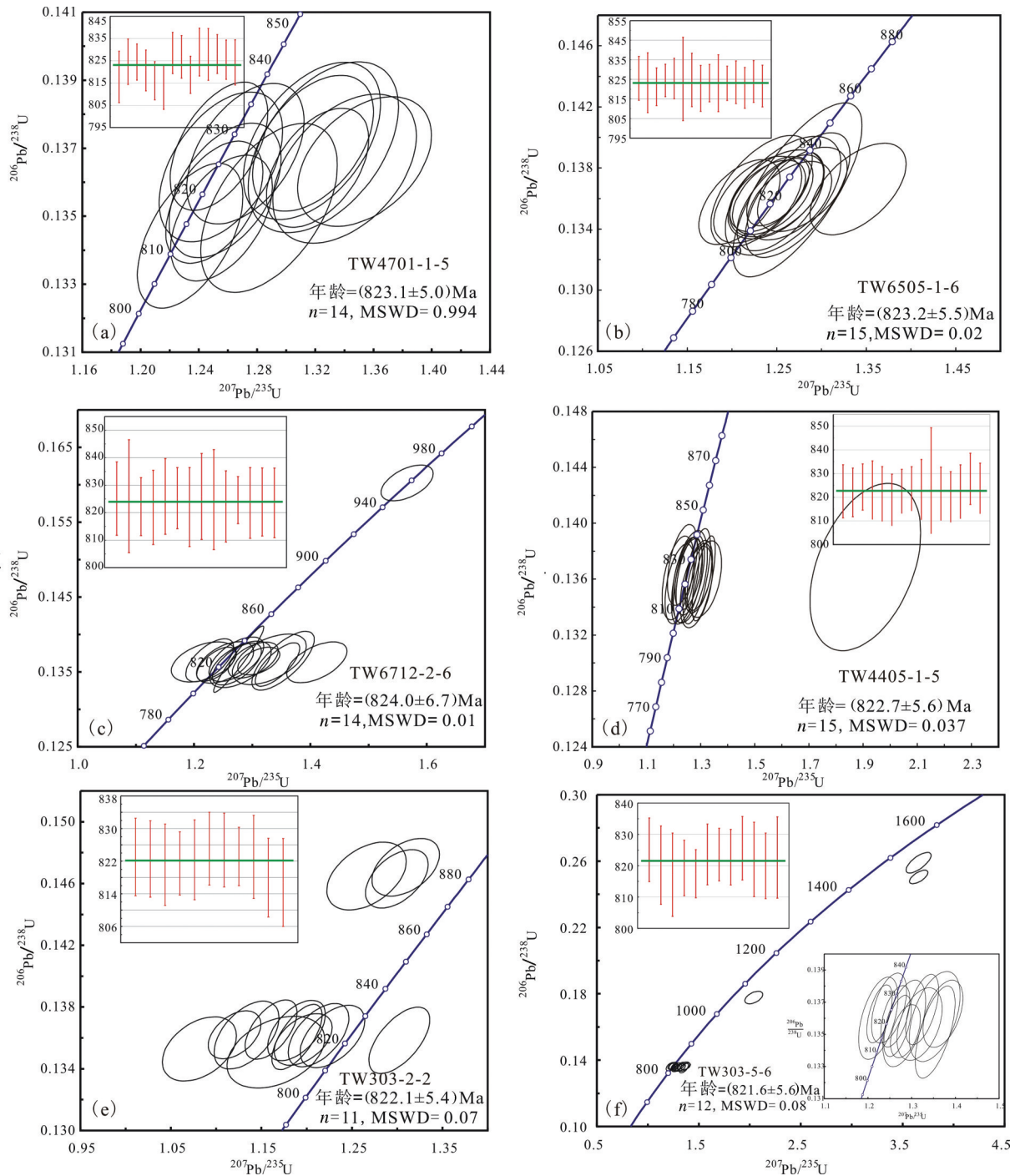


图5 研究区新元古代黑云母花岗闪长岩锆石U-Pb年龄谐和图  
Fig.5 U-Pb concordia diagram of the zircons from Neoproterozoic biotite granodiorite

均年龄为(822.7±5.6)Ma(MSWD=0.04,图5d),为中部黑云母花岗闪长岩的成岩年龄。

样品TW303-2-2采自岩体北部,共对其中15颗锆石进行测试,CL图像(图4)显示锆石呈长柱状,长宽比为2:1~3:1,粒径约150~200 μm,可见明显的结晶成分环带;所测锆石的Th、U含量分别介

于 $82.5 \times 10^{-6} \sim 819 \times 10^{-6}$ 和 $337 \times 10^{-6} \sim 941 \times 10^{-6}$ ,Th/U为0.13~0.90,均大于0.1,具明显岩浆锆石特征(Wu and Zheng, 2004),各测点年龄全部位于谐和线上或附近,其中测点-13的 $^{206}\text{Pb}/^{238}\text{U}$ 年龄远离谐和线,可能是Pb丢失造成的;测点-06、-07和-09的 $^{206}\text{Pb}/^{238}\text{Pb}$ 分别为880 Ma、884 Ma和881 Ma,为新

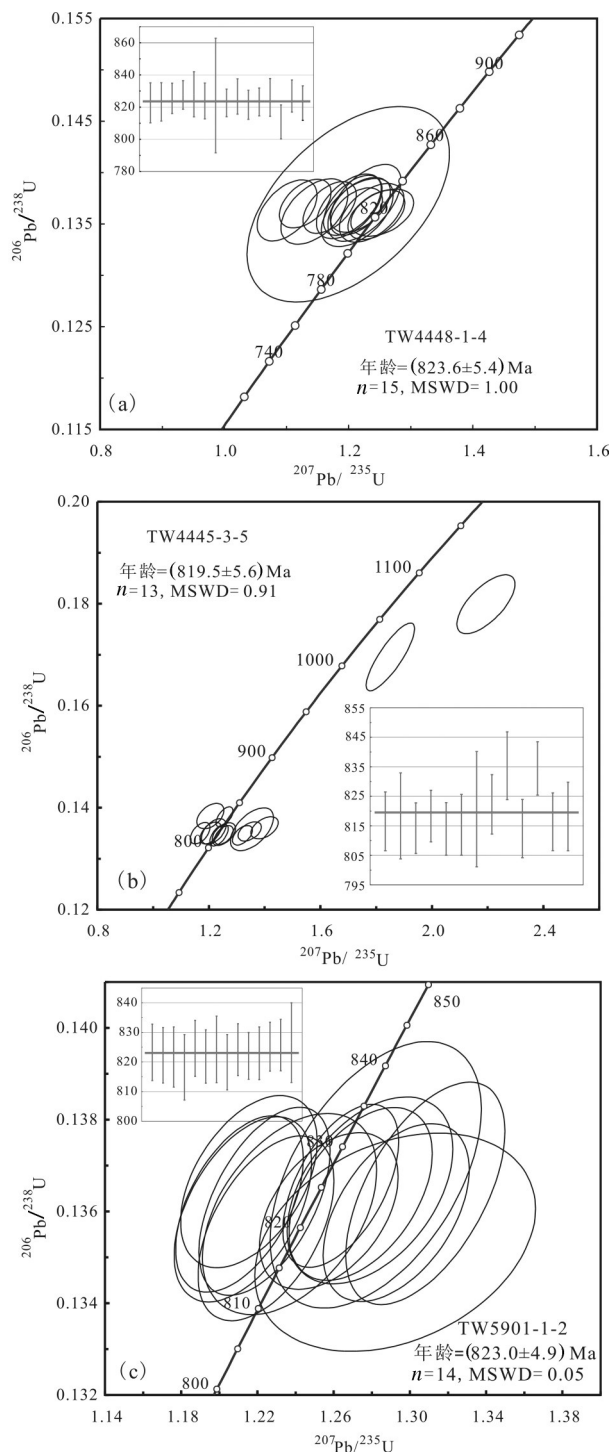


图6 研究区新元古代英云闪长岩锆石U-Pb年龄谐图  
Fig.6 U-Pb concordia diagram of the zircons from  
Neoproterozoic tonalite

元古代早期的捕获锆石,其余11颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(822.1 \pm 5.4)\text{Ma}$  ( $\text{MSWD}=0.07$ ,图5e),为北部黑云母花岗闪长岩的成岩年龄。

样品TW303-5-6采自岩体北部,共对其中15颗锆石进行测试,CL图像(图4)显示锆石呈长柱状,长宽比为2:1~3:1,粒径150~200  $\mu\text{m}$ ,可见明显的结晶成分环带;所测锆石的Th、U含量分别介于 $64.8 \times 10^{-6}$ ~ $308 \times 10^{-6}$ 和 $311 \times 10^{-6}$ ~ $802 \times 10^{-6}$ ,Th/U为0.11~0.57,均大于0.1,具明显岩浆锆石特征(Wu et al., 2004),各测点年龄全部位于谐和线上或附近,其中测点-01、-03、-09的 $^{207}\text{Pb}/^{206}\text{Pb}$ 年龄分别为1.5 Ga、1.7 Ga和1.6 Ga,应属中元古代的捕获锆石,其余12颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(821.6 \pm 5.6)\text{Ma}$  ( $\text{MSWD}=0.08$ ,图5f),为北部黑云母花岗闪长岩的成岩年龄。

#### 4.2 英云闪长岩

共对研究3件英云闪长岩样品进行了锆石U-Pb定年,测试分析结果如表2。

样品TW4448-1-4采自岩体西部,共对其中15颗锆石进行测试,CL图像(图4)显示锆石呈长柱状,长宽比为2:1~3:1,粒径150~200  $\mu\text{m}$ ,可见明显的结晶成分环带;所测锆石的Th、U含量分别为 $63.7 \times 10^{-6}$ ~ $234 \times 10^{-6}$ 和 $236 \times 10^{-6}$ ~ $526 \times 10^{-6}$ ,Th/U为0.18~0.73,均大于0.1,具岩浆锆石特征(Wu and Zheng, 2004)。各测点年龄全部位于谐和线上或附近,15颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(823.6 \pm 5.4)\text{Ma}$  ( $\text{MSWD}=0.15$ ,图6a),为西部英云闪长岩的成岩年龄。

样品TW4445-3-5采自岩体中西部,共对其中15颗锆石进行测试,CL图像(图4)显示锆石呈长柱状,长宽比为2:1~3:1,粒径150~200  $\mu\text{m}$ ,可见明显的结晶成分环带;所测锆石的Th、U含量分别为 $63.7 \times 10^{-6}$ ~ $234 \times 10^{-6}$ 和 $236 \times 10^{-6}$ ~ $526 \times 10^{-6}$ ,Th/U为0.14~0.67,均大于0.1,具岩浆锆石特征(Wu and Zheng, 2004)。各测点年龄全部位于谐和线上或附近,测点-04、-09的 $^{207}\text{Pb}/^{206}\text{Pb}$ 年龄分别为1.3 Ga、1.2 Ga,另外13颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(819.5 \pm 5.6)\text{Ma}$  ( $\text{MSWD}=0.15$ ,图6b),为中西部英云闪长岩的成岩年龄。

样品TW5901-1-2采自岩体中部,共对其中14颗锆石进行测试,CL图像(图4)显示锆石呈长柱状,长宽比为2:1~3:1,粒径150~200  $\mu\text{m}$ ,可见明显的结晶成分环带;所测锆石的Th、U含量分别为 $48.6 \times 10^{-6}$ ~ $496 \times 10^{-6}$ 和 $131 \times 10^{-6}$ ~ $319 \times 10^{-6}$ ,Th/U为

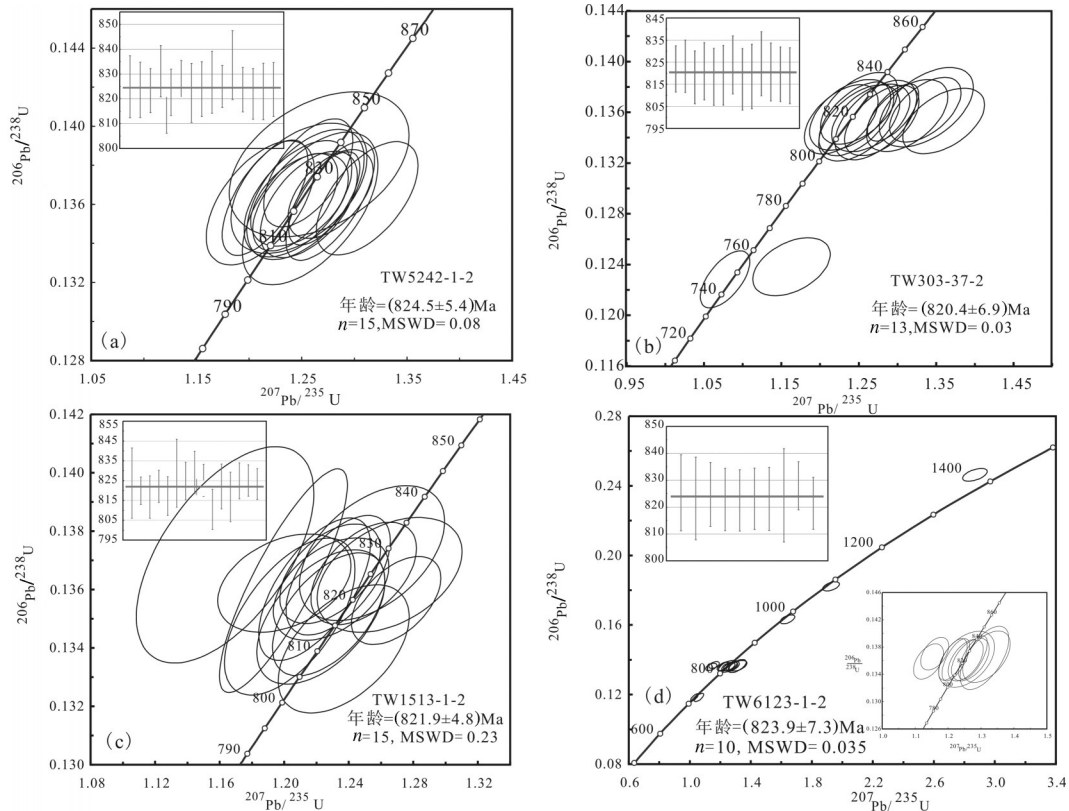


图7 研究区新元古代黑云母二长花岗岩锆石U-Pb年龄谐图

Fig.7 U-Pb concordia diagram of the zircons from Neoproterozoic biotite adamellite

0.15~0.44, 均大于0.1, 具岩浆锆石特征 (Wu and Zheng, 2004)。各测点年龄全部位于谐和线上或附近, 14颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(823.0 \pm 4.9)\text{Ma}$  (MSWD=0.15, 图6c), 属中部英云闪长岩的成岩年龄。

#### 4.3 黑云母二长花岗岩

共对研究区4件黑云母二长花岗岩样品进行了锆石U-Pb定年, 测试分析结果如表2。

样品TW5242-1-2采自岩体中部, 共对其中15颗锆石进行测试, CL图像(图4)显示锆石呈长柱状, 长宽比为2:1~3:1, 粒径150~200  $\mu\text{m}$ , 可见明显的结晶成分环带; 所测锆石的Th、U含量分别为 $54.5 \times 10^{-6} \sim 476 \times 10^{-6}$ 和 $212 \times 10^{-6} \sim 1905 \times 10^{-6}$ , Th/U为0.08~1.85, 大多数 $>0.1$ , 具岩浆锆石特征 (Wu and Zheng, 2004), 少量 $<0.1$ , 可能受到流体影响。各测点年龄全部位于谐和线上或附近, 15颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(824.5 \pm 5.4)\text{Ma}$  (MSWD=0.07, 图7a), 为中部黑云母二长花岗岩的成岩年龄。

样品TW303-37-2采自岩体北部, 共对其中15颗锆石进行测试, CL图像(图4)显示锆石呈长柱状, 长宽比为2:1~3:1, 粒径150~200  $\mu\text{m}$ , 可见明显的结晶成分环带; 所测锆石的Th、U含量分别为 $54.5 \times 10^{-6} \sim 476 \times 10^{-6}$ 和 $212 \times 10^{-6} \sim 1905 \times 10^{-6}$ , Th/U为0.13~0.86, 均大于0.1, 具岩浆锆石特征 (Wu and Zheng, 2004)。各测点年龄全部位于谐和线上或附近, 13颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(820.4 \pm 6.9)\text{Ma}$  (MSWD=0.03, 图7b), 属北部黑云母二长花岗岩体北部的成岩年龄。而测点-05、-06的 $^{206}\text{Pb}/^{238}\text{U}$ 年龄分别为747 Ma和753 Ma, 加权平均值为750 Ma, 可能是受后期流体改造, 使锆石U-Pb同位素体系发生重置所致。

样品TW1513-1-2采自岩体东部, 共对其中15颗锆石进行测试, CL图像(图4)显示锆石呈长柱状, 长宽比为2:1~3:1, 粒径150~200  $\mu\text{m}$ , 可见明显的结晶成分环带; 所测锆石的Th、U含量分别为 $95.6 \times 10^{-6} \sim 358 \times 10^{-6}$ 和 $219 \times 10^{-6} \sim 749 \times 10^{-6}$ , Th/U为0.13~0.72, 均大于0.1, 具岩浆锆石特征 (Wu and

Zheng, 2004)。各测点年龄全部位于谐和线上或附近, 15 颗锆石的  $^{206}\text{Pb}/^{238}\text{Pb}$  加权平均年龄为  $(821.9 \pm 4.8)\text{Ma}$  ( $\text{MSWD}=0.23$ , 图 7c), 为东部黑云母二长花岗岩的成岩年龄。

样品 TW6123-1-2 采自岩体南东部, 共对其中 15 颗锆石进行测试, CL 图像显示锆石呈长柱状, 长宽比为 2:1~3:1, 粒径 150~200 $\mu\text{m}$ , 可见明显的结晶成分环带; 所测锆石的 Th、U 含量分别介于  $31.3 \times 10^{-6}$ ~ $208 \times 10^{-6}$  和  $173 \times 10^{-6}$ ~ $730 \times 10^{-6}$  之间, Th/U 为 0.10~0.71, 均大于 0.1, 具岩浆锆石特征 (Wu and Zheng, 2004)。各测点年龄全部位于谐和线上或附近, 其中测点 -02、-04  $^{207}\text{Pb}/^{206}\text{Pb}$  年龄为 1.1 Ga、1.4 Ga, -05 的  $^{206}\text{Pb}/^{238}\text{U}$  年龄为 975 Ma, 均为捕获锆石年龄, 测点 -03 和 -15 的  $^{206}\text{Pb}/^{238}\text{U}$  年龄均为 721 Ma, 可能是受岩浆期后热液流体交代改造所致; 其余 10 颗锆石的  $^{206}\text{Pb}/^{238}\text{U}$  加权平均年龄为  $(823.9 \pm 7.3)\text{Ma}$  ( $\text{MSWD}=0.04$ , 图 7d), 应属南东部黑云母二长花岗岩的成岩年龄。

## 5 讨 论

### 5.1 九岭复式岩体的侵入期次及特征

前人对研究区内九岭新元古代花岗岩形成时代做了大量工作, 积累了一批年代学数据。胡世玲等 (1984) 测得九岭花岗闪长岩中的黑云母的  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  年龄为  $(936 \pm 15)\text{Ma}$ , 但从其原始数据上看, 随温度升高, 其表面年龄从 464 Ma 逐渐上升至 939 Ma, 而其所取的  $(936 \pm 15)\text{Ma}$  平均年龄, 则是实验最后高温阶段 (900~1200 $^{\circ}\text{C}$ ) 的年龄, 其年龄的实际意义还需要进一步考证。Li et al. (2003a) 测得九岭北部花岗闪长岩的 SHRIMP 锆石 U-Pb 年龄为  $(819 \pm 9)\text{Ma}$ 。钟玉芳等 (2005) 测得九岭花岗岩基主体 (样品岩性均为黑云母花岗闪长岩) SHRIMP 锆石 U-Pb 年龄为  $(828 \pm 8)\text{Ma}$ 。马铁球等 (2009) 测得湘东北张邦源岩体的 SHRIMP 锆石 U-Pb 年龄为  $(816 \pm 5)\text{Ma}$ 。张菲菲等 (2011) 测得九岭岩体 (样品岩性均为黑云母二长花岗岩) 东部主体时代为  $(813 \pm 4)\text{Ma}$ , 南部主体时代为  $(823 \pm 3)\text{Ma}$ , 而西南部西园坑二长花岗岩时代为  $(805 \pm 3)\text{Ma}$ 。Wang et al. (2014) 测得西园坑二长花岗岩和九岭花岗闪长岩的 LA-ICP-MS 锆石 U-Pb 年龄分别为  $(804 \pm 3)\text{Ma}$  和  $(820 \pm 4)\text{Ma}$ 。

另一方面, 从区域上看, 江南造山带新元古代花岗岩成岩时代主要集中在 820~830 Ma。如在江南造山带东段, Wang et al. (2014) 测得皖南许村花岗闪长岩的 LA-ICP-MS 锆石 U-Pb 年龄为  $(826 \pm 5)\text{Ma}$ ; Wang et al. (2006) 测得皖南休宁花岗闪长岩的 LA-ICP-MS 锆石 U-Pb 年龄为  $(824 \pm 7)\text{Ma}$ ; Zheng et al. (2007) 测得皖南歙县花岗闪长岩的 LA-ICP-MS 锆石 U-Pb 年龄为  $(823 \pm 9)\text{Ma}$ 。Wang et al. (2014) 测得湘东北长三背及大围山花岗闪长岩的 LA-ICP-MS 锆石 U-Pb 年龄分别为  $(837 \pm 6)\text{Ma}$  和  $(805 \pm 4)\text{Ma}$ 。Wang et al. (2014) 对江南造山带西段出露的桂北峒玛 ( $(837 \pm 7)\text{Ma}$ )、龙有 ( $(832 \pm 5)\text{Ma}$ )、蒙洞花岗闪长岩 ( $(833 \pm 5)\text{Ma}$ ) 及大寨 ( $(834 \pm 8)\text{Ma}$ )、平英 ( $(835 \pm 5)\text{Ma}$ ) 花岗岩进行了系统的定年工作。另外, 江南造山带西段新元古代其他花岗质岩体如本洞 ( $(822.7 \pm 3.8)\text{Ma}$ , Wang et al., 2006;  $(820 \pm 18)\text{Ma}$ , Li et al., 1999)、元宝山 ( $(838 \pm 5)\text{Ma}$ , Wang et al., 2014;  $(824 \pm 4)\text{Ma}$ , Li et al., 1999)、田朋花岗岩 ( $(794 \pm 8)\text{Ma}$ , Wang et al., 2006)、三防淡色花岗岩 ( $(826 \pm 13)\text{Ma}$ , Li et al., 1999) 的成岩时代亦集中在 820~830 Ma。

本文对九岭新元古代花岗质岩体进行了系统的 LA-ICP-MS 锆石 U-Pb 测年, 结果表明九岭新元古代花岗岩成岩时代均在 820~825 Ma, 据其内部 3 种不同类型花岗岩的侵入接触关系, 可进一步分为 3 个侵入序次:

第 1 序次为黑云母花岗闪长岩, 其成岩时代介于 821.6~824.0 Ma, 且总体上岩体南东侧成岩时代略早于北东侧。同时, 岩体北部捕获锆石明显高于南部, 且与围岩的接触带呈现出南陡北缓的特征, 加上北部岩体含有大量双桥山群围岩捕虏体的特征, 这可能共同暗示了南部岩体剥蚀深度显著高于北部, 导致北部保留大量的围岩信息。另外, 从其捕获锆石时代特征来看, 主要分为 3 期捕获锆石, 分别为: 古元古代早期 (2.2 Ga, 1 颗); 中元古代 (1.5~1.7 Ga, 3 颗); 新元古代早期 (880~958 Ma, 4 颗)。

第 2 序次为英云闪长岩, 其成岩时代在 819.5~823.6 Ma, 另外, 岩体靠近围岩一侧 (双桥山群) 捕获锆石明显高于远离围岩的一侧, 这可能反映了靠近围岩的一侧与围岩发生了显著的同化混染, 导致岩浆内含有大量围岩信息。另外, 其捕获锆石特征较为单



一,只有中元古代一期捕获锆石(1.2~1.3 Ga,2颗)。

第3序次为黑云母二长花岗岩,其成岩时代集中在820.4~824.5 Ma,但样品TW6123-1-2和TW303-37-2均存在时代分别为721 Ma和750 Ma的锆石。由于研究区新元古代黑云母二长花岗岩极度富硅,分异程度极高,且属于区内新元古代最后一次岩浆热事件,尤其是其中发育钾长石巨斑晶,并包裹黑云母、斜长石等矿物,暗示其为较晚期结晶的矿物。这表明黑云母二长花岗岩属于高分异花岗岩(待发表),且可能受到了岩浆期后热液作用的改造,而发生钾交代。这些U-Pb年龄显著偏低的锆石可能就是在岩浆高度分异演化后,受到了岩浆期后热液流体的交代,导致其中锆石U-Pb同位素体系发生重置的结果。另外,其中的捕获锆石年龄可分为两期,分别为中元古代中晚期(1.1~1.4 Ga)和新元古代早期(975 Ma)。

综上所述,研究区新元古代大规模花岗质岩浆活动始于825 Ma左右,形成大规模的花岗闪长岩,该期花岗闪长质岩浆活动未结束,第2序次的英云闪长质岩浆作用就已开始,涌动侵入于第1序次的花岗闪长岩中。前两个序次的岩浆未完全固结时,第3序次的黑云母二长花岗质岩浆侵入活动开始,均与前两期岩浆呈涌动接触。区域新元古代大规模花岗质岩浆活动应结束于820 Ma左右。

另一方面,研究区SE侧岩体与围岩(双桥山群)接触面较陡直,而北部接触面则较缓,多呈波浪状、枝杈状,且NW侧与围岩接触热变质产生的角岩化带远宽于SE侧<sup>①</sup>。这可能共同反映了NW侧岩浆上升速率较慢,与围岩接触热变质时间较长,致使角岩化带较宽,而SE侧岩浆上升速率较快,与围岩接触热变质时间较短,致使角岩化带较窄。而造成这种南北两侧具有不同岩浆上升速率的岩体共同出露于地表的原因,可能是由于南北两侧岩浆的起源深度和剥蚀程度不同所导致的。笔者对研究区新元古代花岗岩中黑云母进行了电子探针分析,利用黑云母全铝压力计测得黑云母花岗闪长岩、英云闪长岩和黑云母二长花岗岩的固结压力分别为356.6 MPa、343.9 MPa和307.5 MPa(笔者未发表数据),按上地壳(<15 km)正常压力梯度2.65 km/100 MPa(Anderson, 1989),其成岩深度分别约为9.5 km、9.1 km和8.1 km,属于上地壳范围,且起源深度依次变

浅。由此,研究区南部岩浆起源深度较大,且其剥蚀更为强烈,导致上升速率较快的底部岩体出露于地表;而北部岩体起源深度较浅,且剥蚀程度较低,导致上升速率较慢的上部岩体出露地表。另外,NW侧围岩捕虏体和碎屑锆石含量均显著高于SE侧,这也可能暗示了SE侧岩体剥蚀深度强于NW侧,导致NW侧还保留了大量的围岩物质,而南侧岩体中的围岩物质则被剥蚀掉了。

另外,本区SE侧岩体的成岩时代略早于NW侧,加上SE侧岩浆起源深度和岩体剥蚀程度均高于NW侧,这可能暗示了新元古代华夏板块(洋内弧)向扬子板块碰撞拼贴过程中,SE侧岩浆起源深度较深,且形成时代较早,并逐渐向NW侧迁移(岩浆起源深度变浅、时代变新)。

## 5.2 九岭岩体锆石组成特征及其对源区物质组成的指示意义

黑云母花岗闪长岩分布范围最广,黑云母二长花岗岩次之,而英云闪长岩分布面积最小,三者均为涌动侵入接触关系,故其成分差异可能是由源区物质组成存在差异所致。同时,研究区黑云母花岗闪长岩、英云闪长岩及黑云母二长花岗岩的物源分析结果(段政等,2017)也表明,黑云母花岗闪长岩源于砂质源区,黑云母二长花岗岩则主要源于泥质源区,而英云闪长岩的源区则位于泥岩与砂岩之间。另外,前人研究也表明九岭新元古代花岗岩具有S型花岗岩的特征,属沉积岩地壳部分熔融产物(Li et al., 2003a)。因此,研究区新元古代的3种花岗质岩石应为不同成分的源区经部分熔融作用形成。

另一方面,岩体北部捕获锆石明显多于南部,同时,北部岩体含有大量双桥山群围岩捕虏体,这共同暗示了南部岩体剥蚀深度高于北部,导致北部保留大量的围岩信息。同时,靠近围岩一侧(双桥山群)的岩体中捕获锆石也明显多于远离围岩的一侧,这反映岩体与围岩接触处,二者发生了显著的同化混染。

从捕获锆石时代特征上看,岩体中的捕获锆石大体可分为3期,分别为古元古代早期(2.2 Ga)、中元古代(1.1~1.7 Ga)和新元古代早期(880~975 Ma),这表明花岗岩源区物质组成复杂。古元古代和中元古代的捕获锆石在江南造山带东段基底地

层(双桥山群)碎屑锆石年龄谱中呈现较弱的峰(江南造山带东段基底地层碎屑锆石的年代主要集中在820~950 Ma,亦含有少量古元古代和中元古代锆石, Wang et al., 2014),这表明花岗岩源区与江南造山带东段基底地层源区可能较为相似,这些古一中元古代锆石可能源自扬子板块再循环古老地壳。另一方面,花岗岩中含有较多的新元古代早期捕获锆石,区域地质资料表明,浙西北地区双溪坞群底部玄武岩、中部安山岩和顶部的流纹岩(平水组、北坞组和章村组)分别形成于~970 Ma, 926 Ma和891 Ma (Li et al., 2009),形成于活动大陆边缘环境(Li et al., 2008b, 2009)。实际上,双溪坞地区弧火山岩(如双溪坞群中的海相玄武岩、安山岩、英安岩和流纹岩)及与俯冲相关的花岗质岩石(如桃红、西裘英云闪长岩-花岗闪长岩,均侵入平水组中、平水斜长花岗岩)、埃达克质岩石(如平水高Mg安山岩)和富Nb玄武岩,均形成于970~860 Ma (Li and Li, 2003; Li et al., 2009; Ye et al., 2007; Wang et al., 2013),并表现出弧地球化学属性及正的 $\epsilon_{\text{Hf}}(t)$ 和 $\epsilon_{\text{Nd}}(t)$ 特征(Li and Li, 2003; Ye et al., 2007; Chen et al., 2009a, 2009b; Li et al., 2009)。Xia et al. (2018)进一步指出,这些弧岩浆岩可能形成于洋内弧构造背景,而这一时段的锆石年龄与研究区新元古代中新元古代早期捕获锆石时代较为一致,可能暗示了部分花岗岩源区源自这些新生洋内弧岩浆岩。

综上所述,研究区新元古代花岗岩源区可能同时接受扬子板块古老地壳的剥蚀沉积物和洋内弧年轻岩浆岩碎屑。

### 5.3 九岭新元古代花岗岩的构造意义

近年来,关于扬子板块与华夏板块最终拼合时间及江南造山带中新元古代花岗岩的构造属性逐渐成为研究的热点。江南造山带中段和南西段的冷家溪群及可与之对比的广西四堡群、贵州梵净山群以及江西的双桥山群甚至以及下元古界中出现大量的850~880 Ma的碎屑锆石,却罕见1.0 Ga左右的锆石(Wang et al., 2007b, 2010, 2012c; Zhou et al., 2009; Zhao et al., 2011)。这就导致扬子和华夏板块汇聚历史的存在强烈争议,两板块的最终拼合时间有~880 Ma、~820 Ma和~800 Ma三种说法,而动力学机制也存在俯冲碰撞、地幔柱和板内裂谷等模式(Li et al., 1995, 2002, 2008, 2009; Ye et al., 2007;

Wang et al., 2006, 2008; Zheng et al., 2007; Zhao et al., 2011; Zhang et al., 2012b; Zhao and Cawood, 2012)。关于华夏与扬子的最终拼合时代,一些研究者提出在约850 Ma之前(1.2~0.9 Ga),且因二者碰撞拼贴形成的江南造山带与全球格林威尔期造山运动(1.0~1.3 Ga)一致,故将其与格林威尔期全球造山事件相联系。同时扬子板块中的850~750 Ma的岩浆岩被认为是在Rodinia超大陆裂解时,由于地幔柱活动引起的陆内裂谷岩浆活动产物(Li et al., 1999, 2002, 2003a, 2003b, 2008b, 2008c, 2008d; Wang et al., 2010)。

另一方面,很多学者基于层序地层学和岩浆事件记录,认为扬子和华夏板块的拼合时间可持续到830 Ma,甚至到800 Ma (Zhang et al., 2012b; Wang et al., 2007b; 2014),与全球格林威尔造山运动主体时代无关。同时,一系列研究表明分布于江南造山带东段赣东北樟树墩和浙北双溪坞地区发育新元古代最早(920~970 Ma)的弧后系统和洋内弧系统(Li et al., 2002, 2008a, 2009; Li and Li, 2003; Ye et al., 2007),并广泛分布大于835 Ma的基性岩(Li et al., 2002, 2008a, 2009; Ye et al., 2007; Zhou et al., 2009)。江南造山带中段和南西段有大量的835~750 Ma(大部分集中于830~800 Ma)的基性和花岗质岩石结晶年龄的报道,但缺乏>835 Ma基性岩的出露,这些835~750 Ma岩石产生于后碰撞、裂谷或地幔柱构造背景(钟玉芳等, 2005; Wang et al., 2006, 2011, 2012a, 2012b; Zhou et al., 2009; 马铁球等, 2009; 董树文等., 2010; 张菲菲等, 2011; Zhao et al., 2011; Zhang et al., 2012a, b; Dong et al., 2012; 鄢圣武等, 2017)。

笔者基于以下证据,笔者认为扬子和华夏板块碰撞时间应晚于825 Ma,且九岭新元古代花岗岩形成于后碰撞构造背景:

(1)九岭岩体侵入已发生明显变形的早新元古代双桥山群地层,后又被没有发生变形的南华纪莲沱组不整合覆盖。这两个地层不整合的时间能够制约两个板块碰撞结束的时间。Wang et al. (2014)对双桥山群的碎屑锆石的研究表明其沉积时间为860~825 Ma。九岭新元古代花岗岩的侵位年龄为819.5~824.5 Ma。因此扬子板块与华夏板块碰撞的时间不老于825 Ma,而不是约850 Ma之前(1.2~0.9 Ga)。

(2)江南古陆出露的新元古代花岗岩在空间上呈带状分布,这难以用地幔柱模型解释,另外,华南缺乏标志地幔柱活动的大陆溢流玄武岩及大量的放射状岩墙群,同时,湘北的高镁安山岩(益阳科马提质玄武岩),以前被认为是地幔柱相关的高温岩浆作用的证据(Zhou et al., 2004; Wang et al., 2007a),但近年来,也有学者指出其为俯冲带环境产物(Zheng et al., 2008; Zhao and Zhou, 2009; Zhou et al., 2009)。实际上,在新元古代扬子板块周缘并没有可靠的由地幔柱衍生的大陆溢流玄武岩(CFB)和洋岛玄武岩(OIB)的报道。需要指出的是,近年来,大量扬子板块周缘存在新元古代弧岩浆活动的信息却逐渐清晰,如皖南地区存在830 Ma左右的SSZ型蛇绿岩及850~825 Ma与弧火山作用相关的基性-超基性岩(丁炳华等, 2008; Zhang et al., 2012a, 2013);在赣北、湘东南和桂北地区(Li and Li, 2003; Zhou et al., 2004, 2009; Li et al., 2010a; Yao et al., 2014)及四堡群中均发育830 Ma(Chen et al., 2014)左右的高镁闪长岩;另外,在冷家溪群中也见有与弧岩浆活动有关的高镁安山岩和玄武岩(科马提岩)的报道(Wang et al., 2004; Zhang et al., 2012b);伏川地区蛇绿岩中辉长岩锆石U-Pb年龄为(848±12) Ma, 易剥橄榄岩锆石U-Pb年龄为(827±9) Ma(丁炳华等, 2008),而Zhang et al. (2012a)也获得伏川蛇绿岩中辉长岩的锆石U-Pb年龄为(824±3) Ma, 并表现为弧后环境的地球化学特征。赣东北张园地区和赣西北雷公坳地区发育同时代的枕状玄武岩和细碧岩(Zhang et al., 2012b),亦表现为弧后盆地的地球化学性质,这些特征表明沿着扬子板块南缘发育824~860 Ma弧后盆地,盆地闭合时间晚于830 Ma。这表明扬子板块南缘确实存在新元古代活动陆缘弧岩浆活动,并发育弧后盆地,且九岭花岗岩源区可能就属弧后盆地沉积,其同时接受了洋内弧新生岩浆岩和扬子板块古老沉积物的物源供应。同时,这也说明了850~805 Ma时,江南造山带新元古代花岗质岩浆岩的形成过程与俯冲作用及随后的后碰撞岩浆作用密切相关(Zhou et al., 2004, 2009; Wang et al., 2006, 2013, 2014)。

(3)江南造山带东段出露约860 Ma的高压蓝闪石片岩和约880 Ma西湾仰冲型淡色花岗岩(Shu et

al., 1994; Charvet et al., 1996; Li et al., 2008a),为扬子板块东南缘樟树墩弧与双溪坞弧的碰撞过程中,发育于樟树墩蛇绿岩逆冲岩席之下的弧后盆地沉积物的深熔作用产物(Cox et al., 1999),其较好地记录了扬子板块和华夏板块的碰撞拼贴过程。最近, Xia et al. (2018)提出,扬子板块和华夏板块之间存在一个新元古代沟-弧-盆系统,其形成于二者最后的拼合过程中(约825 Ma),这一时代明显较沿着劳伦古大陆、澳大利亚和东南极发育的全球格林威尔造山作用的年代年轻(1.0~1.3 Ga)。在新元古代中期(约825 Ma), Rodinia 超大陆已经拼合(Jayananda et al., 2000),内部并不发育陆-陆碰撞事件(Li et al., 2008c)。另外,地层学研究也表明,华南新元古代地层与格林威尔期造山作用无联系(Zhao et al., 2011)。同时,在扬子板块西缘和北缘,沿攀西-汉南褶皱带也发育同时代的岩浆事件(1000~750 Ma, Dong et al., 2012),亦是华南板块新元古代拼合的结果,这些均表明扬子和华夏板块最终拼合时间应晚于825 Ma。

结合区域上地层学、岩浆活动和变质作用的研究成果,笔者认为九岭岩体形成于弧-陆碰撞造山带的后碰撞阶段,扬子和华夏板块最终拼合时代不早于825 Ma。另外,江南造山带东段新元古代花岗岩常富黑云母、堇青石,属CPGs(含堇青石花岗岩)类(Wang et al., 2013),这与地幔上涌或玄武质底侵造成的贫水和高温环境有关(Barbarin, 1999)。这些花岗质岩石均形成于弧-陆碰撞构造背景,这种弧应属洋内弧(Xia et al., 2018)。因此,弧-陆碰撞带的隆起和剥蚀为同碰撞S型花岗岩提供了一个明显的沉积源区,导致研究区内花岗岩含较多的新元古代早期的捕获锆石。

研究表明,由于受到洋内弧和扬子板块的碰撞作用和同时代幔源岩浆底侵作用的影响,扬子板块东南缘新元古代花岗岩形成于后碰撞挤压背景(Charvet, 2013; Wang et al., 2014),另外,如前文所述,研究区SE侧岩体与围岩(双桥山群)接触面南陡北缓、角岩化带南窄北宽、围岩(双桥山群)捕虏体及捕获锆石南少北多,暗示了SE侧岩体剥蚀深度强于NW侧。同时,SE侧的岩体成岩时代亦总体上略早于NW侧,这可能说明江南造山带新元古代的洋内弧和扬子板块的碰撞过程是由SE向NW逐渐推

进的。由于碰撞导致的挤压作用逐渐向NW侧传递导致岩体与围岩的接触带南陡北缓,同时,由于幔源岩浆的底侵供热,导致弧后盆地内的九岭岩体源区物质部分熔融,产生九岭岩体母岩浆,且SE侧岩浆起源更深,剥蚀程度更高,形成时代更早,由此,这可能暗示了洋内弧和扬子板块东南缘的俯冲碰撞极性为NW向。

## 6 结 论

(1)九岭新元古代岩体主要由黑云母花岗闪长岩、英云闪长岩和黑云母二长花岗岩组成。其中黑云母花岗闪长岩分布面积最大,黑云母二长花岗岩次之,英云闪长岩分布面积最小。三者之间均为涌动侵入接触关系,脉动侵入于围岩双桥山群之中。

(2)九岭新元古代花岗岩为一复式岩基,并可分为3个侵入序次,第1序次为黑云母花岗闪长岩(821.6~824.0 Ma);第2序次为英云闪长岩(819.5~823.6 Ma);第3序次为黑云母二长花岗岩(820.4~824.5 Ma)。三者成岩时代极为接近,在误差范围内一致,为同一期岩浆活动产物,成岩时代总体上具SE→NE逐渐年轻的趋势。

(3)九岭SE侧岩体与围岩(双桥山群)接触面南陡北缓、角岩化带南窄北宽、围岩(双桥山群)捕虏体及捕获锆石南少北多,暗示了SE侧岩体剥蚀深度强于NW侧,新元古代的弧-碰撞过程是由SE向NW逐渐推进的。

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## 注释

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