

# 西南天山晚古生代后碰撞岩浆作用：以阔克萨彦岭地区巴雷公花岗岩为例<sup>\*</sup>

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**Abstract** Southern Tianshan is one of the regions with most complex structural evolution history in the Tianshan Orogenic belt. Compared with other regions in the northern Xinjiang, studies on problems of continental dynamics of the post-collision procedure and the magma genesis are relatively weak. Baleigong pluton, which is located in the southwestern section of the Southern Tianshan, is carefully studied in this study. Based on geochemistry and geochronology, the petrogenesis, characteristics of the magma source, as well as the geodynamic are discussed, in order to provide some constraints for the further studies on the evolutionary patterns of the ocean-crust system in the region such as closure of the oceanic crust and timing of the collisional orogeny. The Baleigong pluton located in the Southwestern Kokshal area, the western segment of the Southwestern Tianshan; and emplaced into the south of the Baleigong ophiolitic m range. Lithologically, the pluton consists mainly of biotite moyites. Geochemically, the rocks are high-K calc-alkaline to shoshonitic series, and rich in alkali ( $K_2O + Na_2O$  for 8.25% ~ 8.72%) and K ( $K_2O/Na_2O$  for 1.34 ~ 1.56), with the A/CNK values between 0.94 and 1.05, which fall into the range of metaluminous to slightly peraluminous rocks. The rocks are also characterized by enrichment of LREE and LILE (Cs, Rb, Th and Ba) and depletion of Sr, P, Nb and Ti, with moderate negative Eu anomaly ( $\delta Eu$  for 0.49 ~ 0.59), showing the transitional features between high-K calc-alkaline and A-type granites. The elemental ratios of the Baleigong pluton, such as Nd/Th (1.64 ~ 3.19), Th/U (5.95 ~ 7.11), Nb/Ta (7.26 ~ 9.17), combined with the high  $K_2O/Na_2O$  and low Sr/Ba ratios, indicate the partial melting of middle to lower crust with intermediate magmatic rocks as protoliths, with plagioclase amphibolite as the restite. In situ zircon U-Pb LA-ICP-MS dating on the magmatic genetic zircons yielded an age of the  $273 \pm 2$  Ma, representing the emplacement age of the pluton. Combined with the previous studies, it is concluded that the Late Paleozoic post-collisional granitic magmatism in the South Tianshan took place in the period between 282 and 259 Ma and obviously later than that of other areas in the Northern Xinjiang. Together, these studies also indicate that the post-collisional granitic magmas evolved from high-K calc-alkaline series (282 ~ 266 Ma) to alkaline series (266 ~ 259 Ma) successively, which suggest the process of orogenic collapse and continuously extensional thinning of the continental crust during the post-collisional stage. The Baleigong high-K granite was probably formed during the first stage of the collapse after the collisional orogeny or during the transitional stage between collision and post-collision, by partial melting of the middle to lower crust materials. The post-collisional magmatism in the South Tianshan indicates that before the Middle Permian, the Paleozoic South Tianshan Ocean has been closed and the South Tianshan was in a post-collisional setting, which probably represents the last closure of southern part of the Paleo-Asia oceanic crust, as well as the ending of the accretionary orogeny in the southern section of the Central Asia. These conclusions provide some new constraints to the further study on the timing and petrogenesis of the post-collisional magmatism in the Central Asia.

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**Key words** Zircon LA-ICP-MS U-Pb dating, High-K granite, Post-collision, Baleigong pluton, Kokshal area, Southwest Tianshan

**摘 要** 西南天山阔克萨彦岭地区巴雷公钾长花岗岩出露于蛇绿混杂岩南侧。地球化学特征显示,该岩石富碱( $K_2O + Na_2O$  为  $8.25 \sim 8.72\% > 8\%$ ),富钾( $K_2O/Na_2O$  为  $1.34 \sim 1.56$ ),准铝质( $A/CNK$  为  $0.94 \sim 1.05$ ),为高钾钙碱性-钾玄岩系列;岩石富集大离子亲石元素和轻稀土,亏损 Sr、P 等大离子亲石元素及 Nb、Ti 等高场强元素,具有中等的负锆异常( $\delta Eu = 0.49 \sim 0.59$ ),为向 A 型花岗岩过渡的后碰撞高钾花岗岩特征;岩石的  $Nd/Th$  ( $1.64 \sim 3.19$ )、 $Th/U$  ( $5.95 \sim 7.11$ )、 $Nb/Ta$  ( $7.26 \sim 9.17$ ) 和高  $K_2O/Na_2O$  比值、低 Sr/Ba 比值特征表明,巴雷公花岗岩来源于中下地壳物质的部分熔融,残留相为斜长角闪岩。阴极发光图像显示,该岩石中锆石多呈完好的自形晶,具有岩浆锆石特有的韵律环带结构,LA-ICP-MS 微区原位 U-Pb 定年结果表明该花岗岩的结晶侵位年龄为  $273 \pm 2$  Ma。综合南天山已有研究成果,推测南天山造山带后碰撞花岗岩岩浆活动主要发生在  $282 \sim 259$  Ma 之间,具有从高钾钙碱系列( $282 \sim 266$  Ma)向碱性系列( $266 \sim 259$  Ma)演化的特征,暗示了一个后碰撞阶段的造山带垮塌、陆壳连续伸展减薄的过程。巴雷公高钾花岗岩应为南天山造山带碰撞造山峰期变质后垮塌过程中的第一个阶段或碰撞造山到后造山的一个转折阶段的中下地壳熔融的产物,指示南天山西段古洋盆在中二叠世以前已经闭合,西南天山已进入后碰撞演化阶段,代表了古亚洲洋南部的闭合和中亚南部增生造山作用的结束。这一认识为深入探讨中亚后碰撞岩浆作用的时限和机制提供了新的约束资料。

**关键词** 锆石 U-Pb 年代学; 后碰撞; 高钾花岗岩; 阔克萨彦岭; 南天山

**中图法分类号** P588.121; P597.3

中亚造山带独特的造山增生作用过程一直是国内外研究的热点,近年来在中亚地区发现了大量的晚古生代后碰撞岩浆作用的纪录(韩宝福等,1999,2006; Wu *et al.*, 2000; Jahn *et al.*, 2000; 王涛等,2005; Hong *et al.*, 2004; Kovalenko *et al.*, 2004; 姜常义等,2005; 徐学义等,2005; 夏祖春等,2005; 王京彬等,2006),这对于深入认识古亚洲洋消减闭合过程、中亚造山-成矿作用及大陆地壳增生等重大地学问题具有重要意义。新疆北部(塔里木盆地以北地区)及邻区处于中亚造山带的关键部位,近年来在准噶尔(韩宝福等,1999,2006)、东天山(孙桂华等,2005; 顾连兴等,2006; 李文铅等,2006)和阿尔泰山(王涛等,2005; 童英等,2006)等地区关于后碰撞花岗岩岩浆活动的成因和时限研究取得了一系列重要进展。

南天山是天山造山带地质构造最复杂的地区之一,与新疆北部其它地区相比,其后碰撞作用过程和岩浆成因等大陆动力学问题的研究程度相对薄弱。本文选择南天山西南端阿合奇县巴雷公花岗岩体为研究对象,在详细的地球化学及锆石 U-Pb 年代学研究基础上,探讨其岩石成因、源区及其动力学机制,为进一步探讨南天山古洋盆闭合和碰撞造山时限等洋-陆格局的演化问题提供新的约束资料。

## 1 地质背景及样品特征

天山造山带是位于哈萨克斯坦-准噶尔板块与卡拉库姆-塔里木板块之间的巨型构造带,被中天山北缘断裂和中天山南缘断裂自北而南划分为北天山、南天山和中天山三带(图 1a)。南天山造山带属于中天山南缘断裂带以南的天山地区,从我国新疆,沿中吉边境,经吉尔吉斯斯坦、塔吉克斯坦和乌兹别克斯坦,直到咸海,长达千余公里,夹于北部克孜尔库姆-哈萨克斯坦和南部卡拉库姆-塔里木板块之间(Volkova

and Budanov, 1999),保存有亚洲大陆形成演化的重要信息。

南天山造山带被后期的塔拉斯-费尔干拉走滑断裂分为东、西两段。中国南天山位于东段,主要由志留-泥盆系地层组成,前寒武系、寒武系-奥陶系仅有零星出露,古生界地层最为发育,沉积厚度巨大,火山岩稀少,海相沉积构成该区主体。

本文研究区位于南天山西南缘冲断带的阔克萨彦岭地区(图 1b),由一系列冲断岩片组成,主要为志留纪-泥盆纪和石炭纪地层。志留-泥盆纪地层与中亚南天山东阿赖地区十分相似,主要由碎屑岩、灰岩和火山岩组成。碎屑岩发育有特征的含炭千枚岩化泥质岩,火山岩主要为基性火山熔岩和少量中性火山岩。1/20 万地质图(阿合奇和廓格尔特山口部分幅)将该志留-泥盆纪地层归属于乌帕塔尔坎群((S—D<sub>2</sub>)wp)。最近在该地区巴雷公镁铁-超镁铁质岩套中的辉绿岩中获得了  $450 \pm 2$  Ma 的锆石 U-Pb 年龄,说明在中奥陶世南天山洋已经为一个成熟的多岛洋盆(王超等,待刊)。

巴雷公花岗岩体位于阔克沙勒岭西南部(阿合奇县城西北约 120 km 处),托什罕河上游北岸的齐齐加纳克苏河两侧,呈岩株状产出。岩体北侧紧邻巴雷公镁铁-超镁铁质岩套,南侧为第三系西域组( $N_2x$ )灰色巨厚层块状砾岩夹灰色、灰黄色含砾砂岩。岩石呈肉红色,中-粗粒自形结构,块状构造。主要矿物为钾长石(约 60%)、斜长石(28%~30%)、石英(约 6%)、黑云母(6%±),副矿物为锆石、磷灰石、榍石和磁铁矿等。该岩体中没有明显的变形变质现象。

## 2 分析方法

全岩的主量和微量元素分析均在西北大学大陆动力学国家重点实验室完成。主量元素在日本理学 RIX2100 XRF 仪上测定,元素分析误差  $< 5\%$ ; 微量和稀土元素是在美国

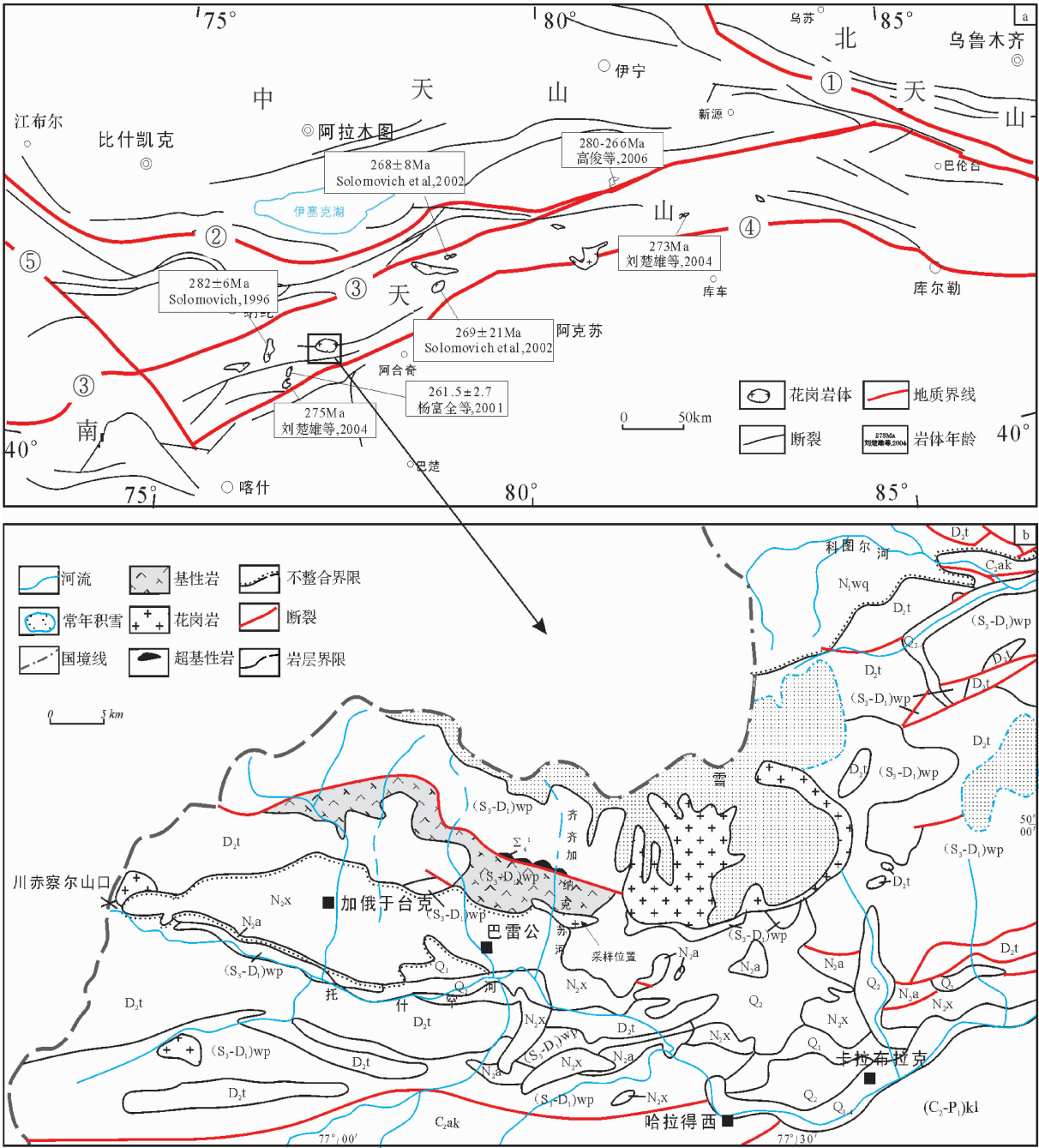


图1 南天山构造轮廓及后碰撞花岗岩分布图(a);巴雷公地质图(b)

①-中天山北缘断裂;②-塔拉斯-捷尔斯科伊(尼古拉耶夫线)-阿登布拉克断裂;③-中天山南缘断裂;④-塔里木盆地北缘断裂;⑤-塔拉斯-费尔干纳断裂

Fig. 1 a, Sketch geological map showing the location of the postcollisional granites in the South Tianshan orogenic belt; 1b, Geological map of the Baleigong

Perkin Elmer 公司 Elan 6100DRC 型电感耦合等离子质谱仪(ICP-MS)上进行的,样品测试经 AVG-1 和 BHVO-1 国际标样监控,分析精度一般优于 2%~5%。

锆石样品靶的制备,首先是将挑选好的无色透明无裂隙不含包裹体的锆石用环氧树脂固定,待环氧树脂充分固化后抛光至锆石露出核部,然后进行锆石的 CL 显微成像及 LA-

ICP-MS 分析。锆石的 CL 图象分析是利用中国科学院地质与地球物理研究所 Cameca 电子探针仪上加载的阴极荧光仪完成。锆石的 U-Pb 同位素组成利用大陆动力学国家重点实验室(西北大学)的四极杆 ICP-MS Elan6100DRC 进行测定。本研究在标准模式下进行。激光剥蚀系统为德国 MicroLas 公司生产的 GeoLas200M,分析采用激光束斑直径为 30μm,

激光脉冲为 10Hz, 能量为 32 ~ 36mJ。锆石年龄采用国际标准锆石 91500 作为外标。年龄计算及谐和图采用 Isoplot/Ex (ver2.94) 程序 (Luddwig, 1991) 完成。LA-ICP-MS 详细分析步骤和数据处理方法见袁洪林等(2003)。

### 3 测试结果

#### 3.1 地球化学特征

巴雷公花岗岩的主量、微量元素的测试结果见表 1。该

表 1 巴雷公花岗岩主量(wt%)、微量元素(×10<sup>-6</sup>)分析结果

Table 1 Major element(wt%) and trace element(×10<sup>-6</sup>) composition and some rations of granites from Baleigong

| 样品号                                         | 05QQ92 | 05QQ93 | 05QQ94 | 05QQ95 | 05QQ97 | 样品号                  | 05QQ92 | 05QQ93 | 05QQ94 | 05QQ95 | 05QQ97 |
|---------------------------------------------|--------|--------|--------|--------|--------|----------------------|--------|--------|--------|--------|--------|
| SiO <sub>2</sub>                            | 70.55  | 70.14  | 68.68  | 70.65  | 70.84  | Zr                   | 251.03 | 274.21 | 274.72 | 221.58 | 305.61 |
| TiO <sub>2</sub>                            | 0.38   | 0.39   | 0.36   | 0.36   | 0.46   | Nb                   | 18.04  | 18.63  | 18.59  | 17.26  | 16.47  |
| Al <sub>2</sub> O <sub>3</sub>              | 14.11  | 14.32  | 15.31  | 14.48  | 13.61  | Cs                   | 24.04  | 16.39  | 17.03  | 13.44  | 13.06  |
| Fe <sub>2</sub> O <sub>3</sub> <sup>T</sup> | 3.15   | 3.05   | 3.06   | 3.07   | 3.24   | Ba                   | 750.30 | 718.45 | 679.42 | 651.61 | 559.78 |
| MnO                                         | 0.04   | 0.04   | 0.06   | 0.05   | 0.05   | La                   | 55.52  | 57.17  | 51.90  | 54.08  | 41.43  |
| MgO                                         | 0.64   | 0.49   | 0.59   | 0.58   | 0.79   | Ce                   | 106.25 | 111.54 | 100.13 | 104.40 | 82.80  |
| CaO                                         | 1.65   | 1.48   | 1.87   | 1.87   | 2.07   | Pr                   | 12.10  | 12.75  | 11.59  | 11.67  | 9.58   |
| Na <sub>2</sub> O                           | 3.28   | 3.23   | 3.73   | 3.43   | 3.19   | Nd                   | 41.78  | 43.83  | 40.38  | 38.97  | 32.79  |
| K <sub>2</sub> O                            | 5.17   | 5.17   | 4.99   | 5.02   | 5.06   | Sm                   | 8.03   | 8.54   | 7.92   | 7.27   | 6.51   |
| P <sub>2</sub> O <sub>5</sub>               | 0.10   | 0.10   | 0.10   | 0.09   | 0.13   | Eu                   | 1.37   | 1.37   | 1.51   | 1.32   | 1.02   |
| 烧失量                                         | 0.71   | 1.63   | 1.13   | 0.56   | 0.89   | Gd                   | 7.62   | 8.06   | 7.57   | 6.88   | 6.17   |
| 总量                                          | 99.78  | 100.04 | 99.88  | 100.16 | 100.33 | Tb                   | 1.10   | 1.17   | 1.11   | 1.00   | 0.91   |
| Na <sub>2</sub> O + K <sub>2</sub> O        | 8.45   | 8.40   | 8.72   | 8.45   | 8.25   | Dy                   | 6.52   | 7.12   | 6.76   | 5.88   | 5.51   |
| K <sub>2</sub> O/Na <sub>2</sub> O          | 1.58   | 1.60   | 1.34   | 1.46   | 1.59   | Ho                   | 1.32   | 1.47   | 1.39   | 1.20   | 1.16   |
| Mg <sup>#</sup>                             | 0.29   | 0.24   | 0.28   | 0.27   | 0.33   | Er                   | 3.56   | 4.03   | 3.79   | 3.33   | 3.21   |
|                                             |        |        |        |        |        | Tm                   | 0.55   | 0.64   | 0.59   | 0.51   | 0.50   |
| Li                                          | 69.86  | 38.78  | 55.25  | 58.85  | 64.30  | Yb                   | 3.81   | 4.41   | 4.07   | 3.49   | 3.50   |
| Be                                          | 4.27   | 4.76   | 4.72   | 4.21   | 3.55   | Lu                   | 0.56   | 0.65   | 0.59   | 0.51   | 0.52   |
| Sc                                          | 5.54   | 5.56   | 5.45   | 4.85   | 4.91   | Hf                   | 7.85   | 8.72   | 8.20   | 6.49   | 7.83   |
| V                                           | 22.62  | 21.49  | 20.51  | 20.83  | 29.32  | Ta                   | 2.28   | 2.57   | 2.28   | 2.10   | 1.80   |
| Cr                                          | 8.32   | 7.05   | 5.66   | 7.63   | 5.39   | Pb                   | 63.90  | 58.61  | 56.46  | 64.86  | 42.20  |
| Co                                          | 126.19 | 123.50 | 114.52 | 126.13 | 128.97 | Th                   | 13.49  | 13.75  | 12.83  | 19.12  | 19.98  |
| Ni                                          | 4.96   | 5.09   | 5.29   | 7.80   | 3.79   | U                    | 2.10   | 1.99   | 1.81   | 2.72   | 3.36   |
| Cu                                          | 12.22  | 5.70   | 5.58   | 4.97   | 5.37   | Th/U                 | 6.42   | 6.92   | 7.11   | 7.02   | 5.95   |
| Zn                                          | 54.03  | 66.51  | 67.98  | 57.44  | 51.56  | Nb/Ta                | 7.91   | 7.26   | 8.14   | 8.21   | 9.17   |
| Ga                                          | 22.55  | 22.93  | 24.35  | 22.98  | 20.32  | K/Rb                 | 171.50 | 170.54 | 167.29 | 179.66 | 161.56 |
| Ge                                          | 1.64   | 1.66   | 1.62   | 1.64   | 1.58   | Nb/Ta                | 7.91   | 7.26   | 8.14   | 8.21   | 9.17   |
| Rb                                          | 250.15 | 251.56 | 247.51 | 231.86 | 259.89 | ΣREE                 | 250.07 | 262.75 | 239.29 | 240.51 | 195.63 |
| Sr                                          | 135.19 | 118.43 | 178.53 | 151.70 | 157.98 | (La/Yb) <sub>N</sub> | 10.46  | 9.29   | 9.14   | 11.12  | 8.48   |
| Y                                           | 32.10  | 35.27  | 34.30  | 31.14  | 33.84  | δEu                  | 0.54   | 0.50   | 0.59   | 0.57   | 0.49   |

Mg<sup>#</sup> = MgO/(MgO + FeO<sup>T</sup>), 其中 FeO<sup>T</sup> = Fe<sub>2</sub>O<sub>3</sub><sup>T</sup>/80. 由西北大学大陆动力学国家重点实验室分析测定.

花岗岩的常量元素岩石化学特征表明其为亚碱性, 属高钾钙碱性-钾玄岩系列(图 2), SiO<sub>2</sub> 含量介于 68.68% ~ 70.84% 之间; 低钛 (TiO<sub>2</sub> = 0.36% ~ 0.46%), 低钙 (CaO = 1.48% ~ 1.87%), 贫铁 (Fe<sub>2</sub>O<sub>3</sub><sup>T</sup> = 2.42% ~ 2.96%); 高铝 (Al<sub>2</sub>O<sub>3</sub> = 13.61% ~ 15.31%), 铝饱和指数 A/CNK = 0.94 ~ 1.05, 为弱过铝质系列(图 3); 富碱 (K<sub>2</sub>O + Na<sub>2</sub>O = 8.25% ~ 8.72% > 8%), 富钾 (K<sub>2</sub>O/Na<sub>2</sub>O = 1.34 ~ 1.56)。MgO (0.49% ~ 0.64%) 含量低, Mg<sup>#</sup> 较低 (0.24 ~ 0.33)。

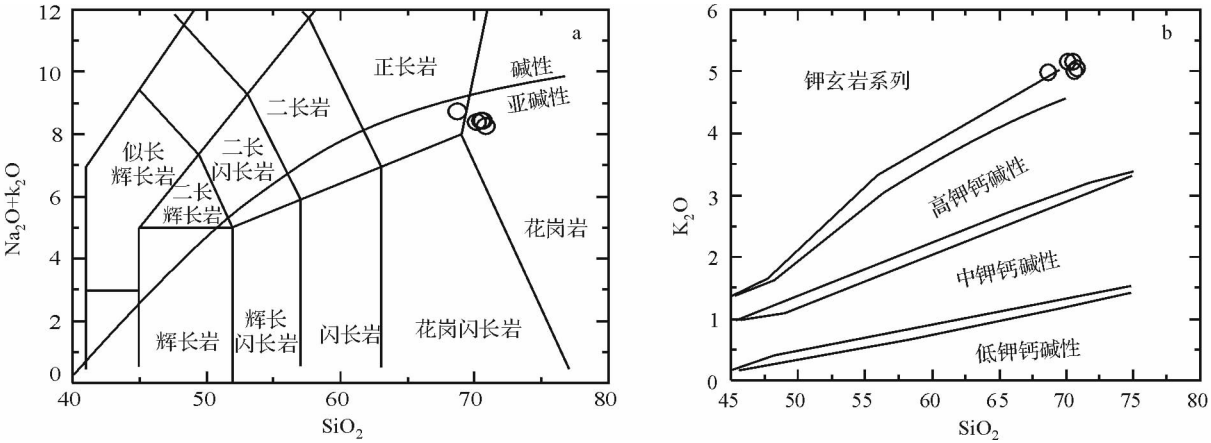


图2 花岗岩  $\text{SiO}_2$ -( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) (a) (据 Middlemost, 1994 和 Irvine and Baragar, 1971) 和  $\text{SiO}_2$ - $\text{K}_2\text{O}$  (b) (Richwood, 1989) 图解

Fig. 2  $\text{SiO}_2$ -( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) (a) diagram (after Middlemost, 1994 and Irvine and Baragar, 1971) and  $\text{SiO}_2$ - $\text{K}_2\text{O}$  diagram (b) (after Richwood, 1989)

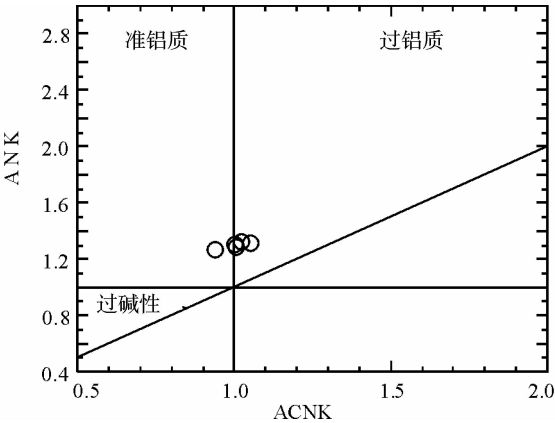


图3 巴雷公花岗岩 A/CNK-A/NK 图解

Fig. 3 A/CNK-A/NK diagram for granites from Baleigong

巴雷公花岗岩的稀土含量中等,  $\Sigma\text{REE}$  为  $195.63 \times 10^{-6} \sim 262.75 \times 10^{-6}$ , 轻重稀土分异明显 (图 4a),  $(\text{La}/\text{Yb})_N$  为  $8.48 \sim 11.12$ , 轻稀土较重稀土分异明显 ( $(\text{La}/\text{Sm})_N$  为  $4.11 \sim 4.8$ ,  $(\text{Gd}/\text{Yb})_N$  为  $1.48 \sim 1.66$ ), 具有中等的负铕异常 ( $\delta\text{Eu}[\text{Eu}_N/(\text{Sm}_N + \text{Gd}_N)^{1/2}]$  为  $0.49 \sim 0.59$ )。在原始地幔标准化蛛网图上 (图 4b), 巴雷公花岗岩表现出明显富集 Cs、Rb、Th、K 等大离子亲石元素 (LILE) 和 La, 强烈亏损 Sr、P、Ti 等元素, 具有低 Sr ( $118.43 \times 10^{-6} \sim 178.53 \times 10^{-6}$ )、高 Yb ( $3.49 \times 10^{-6} \sim 4.41 \times 10^{-6}$ ) 的特征。

3.2 锆石 U-Pb 年代学

巴雷公花岗岩中的锆石呈长柱状, 透明度较好, 粒度介于  $150\mu\text{m} \sim 250\mu\text{m}$  之间。阴极发光图像 (图 5) 显示, 多数锆石颗粒呈完好的自形晶, 具有岩浆锆石特有的韵律环带结构, 少数颗粒具有残核。本文研究利用  $30\mu\text{m}$  激光剥蚀束斑

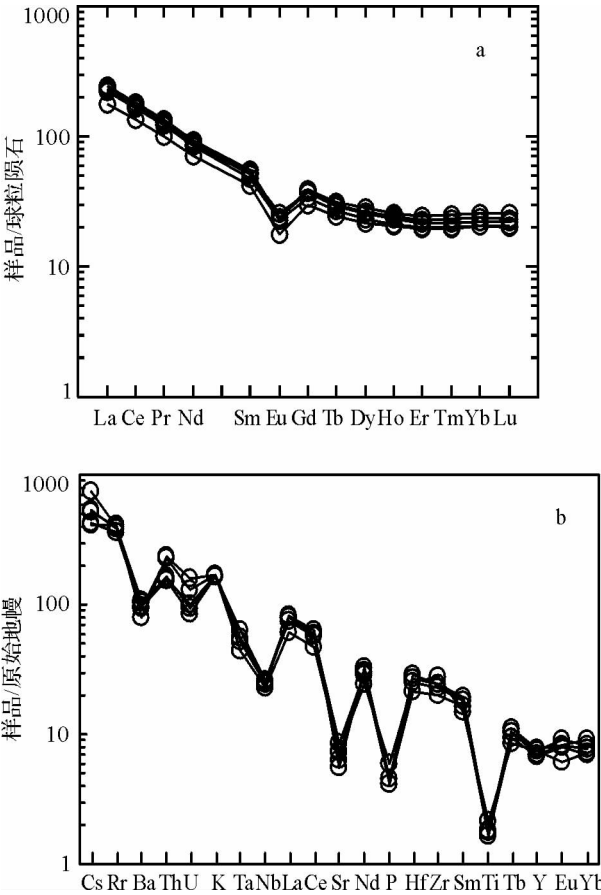


图4 巴雷公花岗岩稀土元素球粒陨石标准化图解 (a) 和微量元素原始地幔标准化图解 (b)

Fig. 4 Chondrite-normalized REE-patterns (a) and Primitive-mantle normalized spider diagram (b) for granites from Baleigong

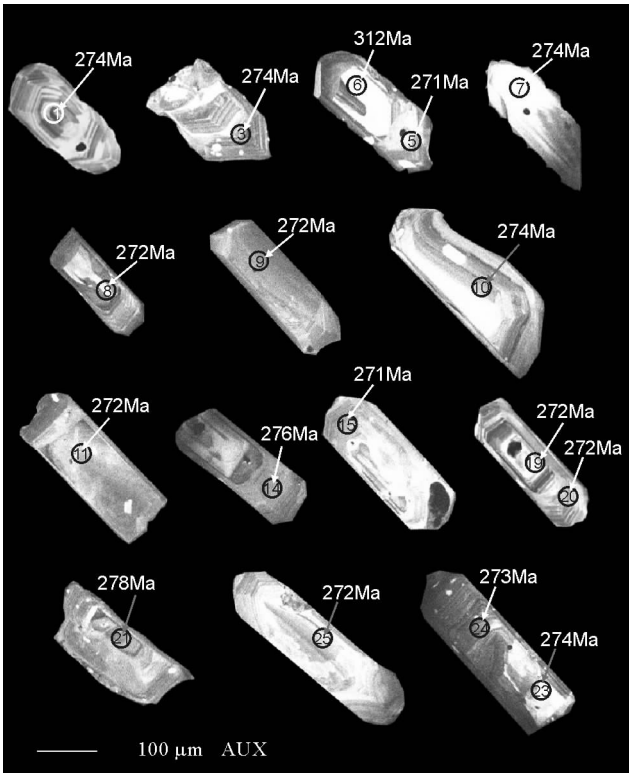


图5 锆石阴极发光图像(图中圆圈为测点位置,数字为测点年龄结果)

Fig.5 CL images of zircons for granites from Baleigong

表2 巴雷公花岗岩锆石的 LA-ICP-MS U-Pb 定年结果

Table 2 LA-ICP-MS U-Th-Pb isotopic data of zircons from Baleigong granites

| 测点 | 元素含量                 |                      |                      |      | 同位素比值                                |         |                                     |         |                                     |         | 年龄(Ma)                               |     |                                     |    |                                     |   |
|----|----------------------|----------------------|----------------------|------|--------------------------------------|---------|-------------------------------------|---------|-------------------------------------|---------|--------------------------------------|-----|-------------------------------------|----|-------------------------------------|---|
|    | Pb                   | <sup>232</sup> Th    | <sup>238</sup> U     | Th/U | <sup>207</sup> Pb/ <sup>206</sup> Pb |         | <sup>207</sup> Pb/ <sup>235</sup> U |         | <sup>206</sup> Pb/ <sup>238</sup> U |         | <sup>207</sup> Pb/ <sup>206</sup> Pb |     | <sup>207</sup> Pb/ <sup>235</sup> U |    | <sup>206</sup> Pb/ <sup>238</sup> U |   |
|    | (×10 <sup>-6</sup> ) | (×10 <sup>-6</sup> ) | (×10 <sup>-6</sup> ) |      | 1σ                                   |         | 1σ                                  |         | 1σ                                  |         | 1σ                                   |     | 1σ                                  |    | 1σ                                  |   |
| 01 | 18.43                | 196.03               | 316.68               | 0.62 | 0.05182                              | 0.00173 | 0.31049                             | 0.0098  | 0.04345                             | 0.00037 | 277                                  | 57  | 275                                 | 8  | 274                                 | 2 |
| 02 | 19.18                | 135.28               | 328.06               | 0.41 | 0.05376                              | 0.00112 | 0.34075                             | 0.00624 | 0.04596                             | 0.00027 | 361                                  | 31  | 298                                 | 5  | 290                                 | 2 |
| 03 | 31.85                | 259.4                | 572.34               | 0.45 | 0.05179                              | 0.00072 | 0.30954                             | 0.0032  | 0.04334                             | 0.0002  | 276                                  | 15  | 274                                 | 2  | 274                                 | 1 |
| 04 | 10.73                | 98.36                | 160.08               | 0.61 | 0.05618                              | 0.00222 | 0.37743                             | 0.01457 | 0.04873                             | 0.00041 | 459                                  | 90  | 325                                 | 11 | 307                                 | 3 |
| 05 | 22.62                | 175.14               | 404.65               | 0.43 | 0.05476                              | 0.00111 | 0.32444                             | 0.00631 | 0.04297                             | 0.00023 | 403                                  | 46  | 285                                 | 5  | 271                                 | 1 |
| 06 | 11.10                | 115.69               | 163.05               | 0.71 | 0.0528                               | 0.00151 | 0.3607                              | 0.00959 | 0.04954                             | 0.00037 | 320                                  | 47  | 313                                 | 7  | 312                                 | 2 |
| 07 | 5.26                 | 40.81                | 93.53                | 0.44 | 0.05216                              | 0.00147 | 0.31226                             | 0.0082  | 0.04341                             | 0.0003  | 292                                  | 47  | 276                                 | 6  | 274                                 | 2 |
| 08 | 107.01               | 765.27               | 1965.7               | 0.39 | 0.05439                              | 0.00071 | 0.32362                             | 0.00294 | 0.04315                             | 0.00019 | 387                                  | 13  | 285                                 | 2  | 272                                 | 1 |
| 09 | 19.11                | 114.88               | 353.94               | 0.32 | 0.05206                              | 0.00093 | 0.30989                             | 0.00529 | 0.04317                             | 0.00022 | 288                                  | 42  | 274                                 | 4  | 272                                 | 1 |
| 10 | 9.92                 | 75.54                | 177.8                | 0.42 | 0.05216                              | 0.00135 | 0.31182                             | 0.00742 | 0.04335                             | 0.0003  | 292                                  | 42  | 276                                 | 6  | 274                                 | 2 |
| 11 | 26.38                | 382.55               | 427.94               | 0.89 | 0.05486                              | 0.00127 | 0.32604                             | 0.0068  | 0.0431                              | 0.00028 | 407                                  | 35  | 287                                 | 5  | 272                                 | 2 |
| 12 | 11.88                | 90.6                 | 187.62               | 0.48 | 0.05547                              | 0.00148 | 0.35833                             | 0.00932 | 0.04685                             | 0.0003  | 431                                  | 61  | 311                                 | 7  | 295                                 | 2 |
| 13 | 7.72                 | 55.36                | 131.21               | 0.42 | 0.05344                              | 0.00159 | 0.33665                             | 0.00934 | 0.04569                             | 0.00035 | 348                                  | 49  | 295                                 | 7  | 288                                 | 2 |
| 14 | 16.75                | 116.75               | 278.88               | 0.42 | 0.05434                              | 0.0012  | 0.32718                             | 0.00702 | 0.04367                             | 0.00023 | 385                                  | 51  | 287                                 | 5  | 276                                 | 1 |
| 15 | 15.89                | 112.58               | 282.06               | 0.40 | 0.05182                              | 0.00179 | 0.30709                             | 0.01032 | 0.04298                             | 0.00033 | 277                                  | 81  | 272                                 | 8  | 271                                 | 2 |
| 16 | 20.78                | 121.7                | 337.8                | 0.36 | 0.05689                              | 0.00104 | 0.3704                              | 0.00651 | 0.04722                             | 0.00024 | 487                                  | 41  | 320                                 | 5  | 297                                 | 1 |
| 17 | 14.34                | 80.65                | 233.08               | 0.35 | 0.05549                              | 0.00127 | 0.36511                             | 0.00811 | 0.04772                             | 0.00028 | 432                                  | 52  | 316                                 | 6  | 301                                 | 2 |
| 18 | 29.14                | 228                  | 461.26               | 0.49 | 0.06143                              | 0.00125 | 0.39423                             | 0.00697 | 0.04655                             | 0.00028 | 654                                  | 28  | 337                                 | 5  | 293                                 | 2 |
| 19 | 16.16                | 157.12               | 276.2                | 0.57 | 0.05391                              | 0.00133 | 0.32068                             | 0.0077  | 0.04314                             | 0.00026 | 367                                  | 57  | 282                                 | 6  | 272                                 | 2 |
| 20 | 16.54                | 122.34               | 297.24               | 0.41 | 0.0526                               | 0.00088 | 0.31218                             | 0.00427 | 0.04306                             | 0.00021 | 312                                  | 22  | 276                                 | 3  | 272                                 | 1 |
| 21 | 11.12                | 100.62               | 156.34               | 0.64 | 0.05307                              | 0.00251 | 0.32312                             | 0.01508 | 0.04416                             | 0.00034 | 332                                  | 110 | 284                                 | 12 | 279                                 | 2 |
| 22 | 6.30                 | 66.55                | 104.18               | 0.64 | 0.05201                              | 0.00215 | 0.31098                             | 0.01229 | 0.04339                             | 0.00044 | 286                                  | 72  | 275                                 | 10 | 274                                 | 3 |
| 23 | 30.83                | 209.38               | 559.46               | 0.37 | 0.05284                              | 0.00085 | 0.31449                             | 0.00403 | 0.04319                             | 0.00021 | 322                                  | 20  | 278                                 | 3  | 273                                 | 1 |
| 24 | 8.01                 | 86.75                | 137.3                | 0.63 | 0.05214                              | 0.00222 | 0.30962                             | 0.01264 | 0.0431                              | 0.00045 | 292                                  | 74  | 274                                 | 10 | 272                                 | 3 |

对 20 粒锆石进行了 24 个测点的 LA-ICP-MS 定年分析,分析结果见表 2。位于锆石具有清晰环带结构上的 15 个测点的年龄数据几乎都落在一致曲线附近,组成一个年龄密集区(图 6a),其<sup>206</sup>Pb/<sup>238</sup>U 年龄值变化于 271 ± 1 ~ 276 ± 1Ma 之间,加权平均年龄值为 273 ± 2Ma;对应测点的 Th/U 含量分别为 40.81 × 10<sup>-6</sup> ~ 765.27 × 10<sup>-6</sup>, 93.53 × 10<sup>-6</sup> ~ 1965.7 × 10<sup>-6</sup>, Th/U 比值介于 0.32 ~ 0.89,显示了岩浆锆石的典型特征(Rubatto, 2002)。而位于锆石残核上的测定的年龄值明显偏高,但投点比较分散(图 6a),其中位于一致线上而且年龄值最大的一个测点的年龄值为 312 ± 2Ma, Th/U 比值为 0.71。依据这些特征可以认为,273 ± 2Ma 的年龄值应代表该花岗岩体的形成年龄,312 ± 2Ma 的年龄值可能代表其原岩的形成年龄。

## 4 讨论及结论

### 4.1 岩石类型及构造环境

根据样品的岩相学特点,按 Barbarin (1999) 的分类方案,巴雷公花岗岩应为富钾钙碱性花岗岩(KCG),代表一种构造体制的变化,发生在碰撞事件主峰期后的张持阶段或从挤压体制向拉张体制转变的过程中。该花岗岩的铝饱和指数 A/CNK 为 0.94 ~ 1.05,富碱(K<sub>2</sub>O + Na<sub>2</sub>O 为 8.25% ~ 8.72% > 8%),富钾(K<sub>2</sub>O/Na<sub>2</sub>O 为 1.34 ~ 1.56),表现为岛弧或晚造山-后造山环境的 I 型高钾钙碱性花岗岩的特征

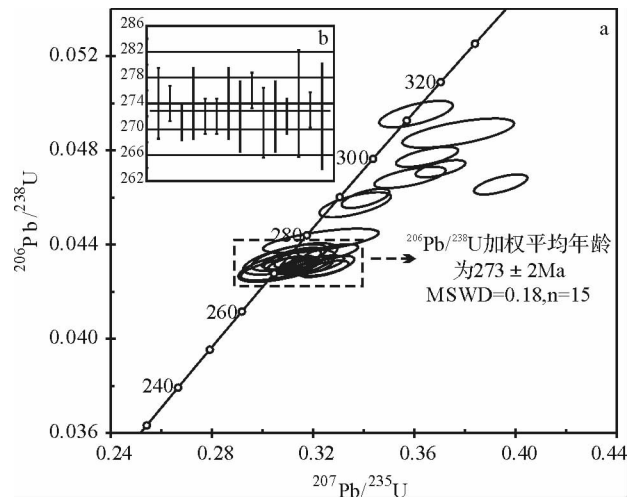


图6 锆石 LA-ICP-MS U-Pb 年龄谐和图(样品 05QQ97)  
Fig. 6 LA-ICP-MS U-Pb zircon Concordia diagram

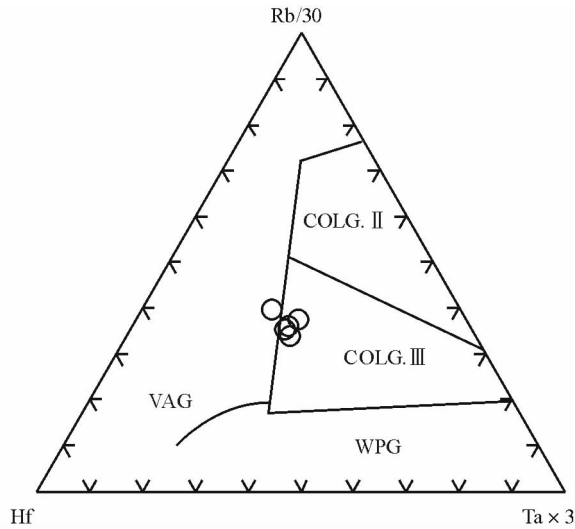


图7 (Rb/30)-Hf-(Ta × 3)图解 (Harris *et al.*, 1986)  
WPG-板内花岗岩; VAG-岛弧花岗岩; COLG II-同碰撞二长花岗岩; COLG III-晚-后碰撞钙碱性花岗岩  
Fig. 7 (Rb/30)-Hf-(Ta × 3) diagram for granites from Baleigong(after Harris *et al.*, 1986)

(Pitcher, 1993)。巴雷公高钾钙碱性花岗岩的稀土配分曲线显示的负铈异常较典型 A 型花岗岩弱;在微量元素蛛网图上,富集大离子亲石元素,亏损 Nb、Sr、P、Ti 等元素,具有向 A 型花岗岩过渡的后碰撞高钾花岗岩特征 (Whale *et al.*, 1987; 王涛, 2005),但还不属于典型的碰撞造山后的板内阶段的造山后花岗岩。在(Rb/30)-Hf-(Ta × 3)图解中,巴雷公高钾花岗岩也落入晚-后碰撞钙碱花岗岩区域(图7)。另外,岩体没有明显的变形,没有显示被断层错动的迹象,显示了后碰撞作用的伸展环境特征。

4.2 岩石成因及源区性质

巴雷公花岗岩富集 Rb、Th、K 大离子亲石元素,但亏损 Ba,与来自岛弧岩浆熔融的产物不同。巴雷公花岗岩的 SiO<sub>2</sub>、MgO、Fe<sub>2</sub>O<sub>3</sub><sup>T</sup> 和 TiO<sub>2</sub> 含量变化非常小,说明不存在明显的分离结晶过程;K/Rb 为 161.6 ~ 179.7 > 150,表明岩浆分异或水热作用不明显 (Dostal and Chatterjee, 2000)。另外,La/Sm-La 图解(图8)也显示巴雷公花岗岩没有经受明显的分离结晶,可以反映源区岩浆的特征和部分熔融时的 *P-T* 条件。巴雷公花岗岩低的 Sr 含量(118.43 × 10<sup>-6</sup> ~ 178.53 × 10<sup>-6</sup>)和明显的 Eu 异常说明在熔融过程中斜长石作为残留相,指示了其在低的 αH<sub>2</sub>O 条件下发生了熔融 (Tepper *et al.*, 1993)。

高钾花岗岩的富碱和过铝质特征是富角闪石源区深熔产生的深源花岗岩的典型特征 (Whitney, 1988)。巴雷公花岗岩 Nd/Th 比值分别为 1.64 ~ 3.19,平均为 2.62,与壳源岩石的比值(≈3, Bea *et al.*, 2001)相近,Th/U 比值为 5.95 ~ 7.11,与下地壳的 Th/U 比值(≈6.00, Rudnick and Gao, 2003)相近,Nb/Ta 比值 7.26 ~ 9.17,略低于地壳平均值(12 ~ 13, Barth *et al.*, 2000),与有角闪石和金红石残留的壳源花岗岩(≈9.00, Dostal and Chatterjee, 2000)近似,以上均说明巴雷公花岗岩源于中下地壳。高的 K<sub>2</sub>O/Na<sub>2</sub>O 和低的 Sr/Ba 比值指示该岩石是变质杂砂岩或中性岩浆岩在无水的条件下部分熔融的产物 (Harris and Inger, 1992),而其又不具有强过铝质特征(A/CNK 为 0.94 ~ 1.05)进一步说明其原岩不可能是变质杂砂岩。因此,可以推断巴雷公花岗岩可能是中下地壳中性岩石部分熔融的产物,残留相为斜长角闪岩(或麻粒岩)。

4.3 南天山后碰撞岩浆作用及古亚洲洋南部的闭合

目前对于南天山古洋盆的闭合及碰撞造山的时限还有

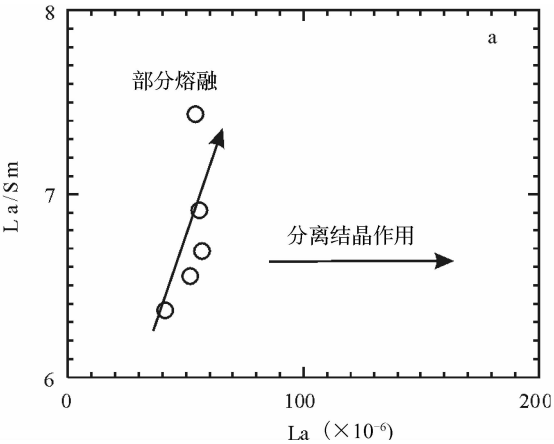


图8 巴雷公花岗岩 La-La/Sm (Allegre and Minster, 1978)  
Fig. 8 La-La/Sm diagram for granites from Baleigong

许多分歧。关于古洋盆的闭合时限有早一中泥盆世(王作勋等,1990)、晚泥盆-早石炭世(Allen *et al.*, 1992; 夏林圻, 2002; 高俊等, 2006)、晚泥盆世-石炭纪(高长林等, 1995)、晚泥盆-早二叠世(卢华复等, 1996)等观点。

特别是近年来,李曰俊等(2005)在与本文研究的花岗岩相邻的蛇绿岩硅质岩夹层中发现了早石炭世早期和晚二叠世两个放射虫化石组合;张立飞等(2005)根据西南天山超高压榴辉岩中的锆石 SHRIMP 定年,认为洋壳开始俯冲发生在早二叠世(280 ~ 290Ma),高压-超高压变质发生在三叠纪(220 ~ 230Ma)。从而认为南天山造山带是一条晚海西-印支运动期碰撞造山带,南天山西部古洋盆最终闭合与陆-陆碰撞造山的起始时间为二叠纪末—三叠纪初(李曰俊等, 2001)。

但是,高俊等(2006)根据西天山阿克牙子河上游含蓝闪石榴辉岩的一致 Sm-Nd 矿物-全岩等时线年龄和蓝闪石 Ar-Ar 坪年龄,判断榴辉岩的峰期变质可能发生在早石炭世(345Ma),碰撞结束时间为石炭纪末(300Ma 左右),并认为张立飞等(2005)获得的榴辉岩中锆石边部年龄(220 ~ 230Ma)可能是锆石在后期流体作用在低温下的生长,并且 Li *et al.* (2002)发现的放射虫化石的时间跨度长,难以据此判断南天山洋盆一直延续到二叠纪末,南天山应为一晚古生代造山带。另外,本文作者在野外考察中采集了该巴雷公蛇绿混杂岩夹层中的灰岩和硅质岩样品,由中国科学院南京地质古生物研究所对其进行了化石鉴定,在灰黑色灰岩发现了属于上石炭统的欣德刺(*Hindeodella* sp.)、奥泽克刺(*Ozarkodina* sp.)和欣德齿刺(*Hindeodus* sp.)等化石,硅质岩中尚未发现放射虫。同时,不容忽视的事实是南天山 D<sub>2</sub>—C<sub>1</sub>化石分布具有广泛性,从东部库勒湖(汤耀庆等, 1995)、黑英山(Liu Y., 2001)到西段的巴雷公,而二叠世化石仅仅出现在南天山阔克萨彦岭一带,分布非常局限。综合西天山 436 ~ 366Ma 的俯冲型花岗岩类(朱志新等, 2006; 杨天南等, 2006)、大哈拉军山组 353 ~ 313Ma 的岛弧火山岩资料(朱永峰等, 2005)和天山二叠纪后碰撞作用变形的古地磁资料(Bazhenov *et al.*, 1999),均说明南天山可能为一晚古生代造山带。

本文通过锆石原位 U-Pb 年代学分析,首次获得的巴雷公花岗岩岩体精确 <sup>206</sup>Pb/<sup>238</sup>U 年龄为 273 ± 2 Ma(中二叠世早期),该岩体为南天山后碰撞岩浆活动的一部分。目前,在南天山造山带获得了许多后碰撞花岗岩类的年代学数据。刘楚雄等(2004)在黑英山克其克勒霓霞正长岩和依南里克黑云霞石歪长伟晶岩分别获得单颗粒 TIMS 锆石 U-Pb 年龄为 275Ma、273Ma。吉尔吉斯斯坦南天山获得后碰撞花岗岩的年龄为 282 ~ 259Ma(Nenakhov *et al.*, 1992; Solomovich, 1996; Solomovich and Trifonov, 2002)。霍什布拉克碱长花岗岩体 TIMS 锆石 U-Pb 获得的侵位时代为 261.5 ± 2.7(杨富全等, 2001)。科克苏河钾长花岗岩锆石 U-Pb 年龄为 280 ~ 266Ma(高俊等, 2006)。姜常义等(1999)认为南天山地区的

碱性花岗岩的时代为 264 ~ 260Ma。综合已获得的年龄资料,说明南天山造山带后碰撞花岗质岩浆活动主要发生在 280 ~ 260Ma 之间,南天山西段古洋盆在中二叠世以前已经闭合,南天山西段地区也已进入后碰撞演化阶段,代表了古亚洲洋南部的闭合和中亚南部增生造山作用的结束。

东准噶尔后碰撞深成岩浆活动发生在 330 ~ 265Ma 之间,西准噶尔后碰撞深成岩浆活动时限为 340 ~ 275Ma 之间(韩宝福等, 2006)。东天山海西期主碰撞以后形成的花岗岩可以分为三个阶段:挤压-伸展转折阶段(310 ~ 285Ma)、碰撞后伸展阶段(285 ~ 250Ma)和板内阶段(250 ~ 208Ma)(顾连兴等, 2006)。阿尔泰山后造山花岗岩为 290 ~ 270Ma(童英等, 2006)。南天山造山带后碰撞花岗质岩浆活动主要发生在 282 ~ 259Ma 之间。由此可见,在中晚二叠世,后碰撞岩浆作用在中亚造山带内广泛发育,可能形成于一个统一的区域伸展背景。

#### 4.4 后碰撞岩浆作用的地球动力学机制

南天山造山带后碰撞花岗质岩浆活动具有从高钾钙碱系列向碱性系列演化的特征。从高钾钙碱系列(282 ~ 266Ma)向碱性系列(266 ~ 259Ma)演化的特征暗示了陆壳的连续伸展减薄,代表了后碰撞阶段的造山带垮塌过程。一般同碰撞距离后碰撞约 20 ~ 30Ma(Sylvester, 1998),而我国南天山造山带西段的碰撞造山和峰期变质阶段处于 345 ~ 300Ma 之间(早石炭世—石炭纪末)(高俊等, 2006),因此,巴雷公高钾花岗岩(273 ± 2Ma)为南天山造山带碰撞造山峰期变质后垮塌过程中的第一个阶段,或为碰撞造山到后造山的一个转折阶段。这种现象在许多造山带中都有报道(Harry *et al.*, 1993; Ferre' and Leake, 2001)。

除沉积岩外,地壳岩石脱水熔融需要 850℃ 以上的温度(Patiño Douce and McCarthy, 1998)。高钾花岗岩的形成暗示着一个陆陆碰撞后的地壳加厚过程(Treloar *et al.*, 1992)。中天山南缘断裂是南天山洋消减闭合的板块缝合带,也是一条超高压变质带,为南天山碰撞造山过程中变质程度最高的位置,处于造山带深部山根的上方。巴雷公高钾花岗岩紧邻于巴雷公蛇绿混杂岩,说明它就位于碰撞汇聚带的轴部,即来自于地壳加厚最强烈的位置。由此推测,在南天山古洋盆的洋壳向中天山-伊犁板块下的俯冲过程中,塔里木板块和中天山-伊犁板块的碰撞,由于山根下部俯冲板块的的脱离,引起地幔物质的上涌;地幔物质底侵带来的热量引发中下地壳的部分熔融,形成高钾花岗质熔浆上升侵位,随着地壳的伸展减薄形成造山结束阶段的碱性花岗岩。在准噶尔、东天山和塔里木盆地北缘二叠纪基性火山岩和辉绿岩墙广泛分布,具有广泛的底侵作用,代表了一种弥散型的大陆伸展作用(姜常义等, 1999)。巴雷公二叠纪后碰撞花岗岩的存在暗示南天山地区也可能存在同时代的陆壳增生。

## 5 结论

西南天山阔克萨彦岭地区巴雷公花岗岩为富钾钙碱性花岗岩(KCG),具有岛弧或晚造山-后造山环境的I型高钾钙碱性花岗岩的特征和向A型花岗岩过渡的后碰撞高钾花岗岩特征,来源于中下地壳物质的部分熔融,残留相为斜长角闪岩。

LA-ICP-MS微区原位U-Pb定年结果表明巴雷公花岗岩的结晶侵位年龄为 $273 \pm 2\text{Ma}$ 。综合目前南天山研究成果,推测南天山造山带后碰撞花岗岩质岩浆活动主要发生在282~259Ma之间,具有从高钾钙碱系列(282~266Ma)向碱性系列(266~259Ma)演化的特征,暗示了一个后碰撞阶段的造山带垮塌、陆壳连续伸展减薄的过程。巴雷公高钾花岗岩应为南天山造山带碰撞造山峰期变质后垮塌过程中的第一个阶段或碰撞造山到后造山的一个转折阶段的中下地壳熔融的产物,指示南天山西段古洋盆在中二叠世以前已经闭合,西南天山已进入后碰撞演化阶段,代表了古亚洲洋南部的闭合和中亚南部增生造山作用的结束。

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