

引用格式: 高原, 王颖, 王海, 等, 2025. 赣南珠坑钨矿赋矿花岗岩独居石年龄、地球化学特征及成因探究[J]. 地质力学学报, 31(2): 325–339. DOI: [10.12090/j.issn.1006-6616.2024083](https://doi.org/10.12090/j.issn.1006-6616.2024083)

Citation: GAO Y., WANG Y., WANG H., et al., 2025. Monazite U-Pb age, geochemistry, and genesis of ore-bearing granites in the Zhukeng tungsten deposit, southern Jiangxi Province[J]. Journal of Geomechanics, 31(2): 325–339. DOI: [10.12090/j.issn.1006-6616.2024083](https://doi.org/10.12090/j.issn.1006-6616.2024083)

## 赣南珠坑钨矿赋矿花岗岩独居石年龄、地球化学特征及成因探究

高原<sup>1,2</sup>, 王颖<sup>3,4</sup>, 王海<sup>2,3</sup>, 徐喆<sup>1,2</sup>, 张勇<sup>3</sup>, 周渝<sup>1,2,3</sup>, 张芳荣<sup>1,2</sup>,  
孙超<sup>1,2</sup>, 贺彬<sup>1,2</sup>, 张思远<sup>3</sup>, 张福神<sup>1,2</sup>  
GAO Yuan<sup>1,2</sup>, WANG Ying<sup>3,4</sup>, WANG Hai<sup>2,3</sup>, XU Zhe<sup>1,2</sup>, ZHANG Yong<sup>3</sup>, ZHOU Yu<sup>1,2,3</sup>, ZHANG Fangrong<sup>1,2</sup>,  
SUN Chao<sup>1,2</sup>, HE Bin<sup>1,2</sup>, ZHANG Siyuan<sup>3</sup>, ZHANG Fushen<sup>1,2</sup>

1. 江西省地质调查勘查院基础地质调查所, 江西南昌, 330030;
2. 关键矿产资源勘查与开发江西省重点实验室, 江西南昌, 330009;
3. 核资源与环境国家重点实验室(东华理工大学), 江西南昌 330013;
4. 中国地质科学院地质力学研究所, 北京 10081

1. *Institute of Basic Geological Survey, Jiangxi Geological Survey and Exploration Institute, Nanchang 330030, Jiangxi, China;*
2. *Jiangxi Province Key Laboratory of Exploration and Development of Critical Mineral Resources, Nanchang 330009, Jiangxi, China;*
3. *State Key Laboratory of Nuclear Resources and Environment, East China University of Technology, Nanchang 330013, Jiangxi, China;*
4. *Institute of Geomechanics, China Academy of Geological Sciences, Beijing 10081, China*

### Monazite U-Pb age, geochemistry, and genesis of ore-bearing granites in the Zhukeng tungsten deposit, southern Jiangxi Province

**Abstract:** [Objective] The composite Zhukeng granite is composed of two-mica granite and muscovite granite and closely related to tungsten and niobium-tantalum deposits in southern Jiangxi Province. [Methods] Based on systematic litho-geochemical analysis and rock-forming age determination of muscovite granite and two-mica granite from the Zhukeng tungsten deposit, combined with regional studies concerning diagenesis and mineralization, the genesis and tectonic setting of the rock mass are discussed. [Result] The LA-ICP-MS analysis of monazite from the fine-grained muscovite granite yielded a  $^{206}\text{Pb}/^{238}\text{U}$  weighted average U-Pb age of  $156.7 \pm 1.3$  Ma. Major elements exhibit high silica contents ( $\text{SiO}_2$  ranging from 65.54% to 74.95%), high alkalis contents ( $\text{Na}_2\text{O}+\text{K}_2\text{O}$  ranging from 8.48% to 12.85%), high aluminum contents (A/CNK ratios ranging from 1.10 to 1.22), and low magnesium contents. The total rare earth elements ( $\Sigma\text{REE}$ ) range from  $61.12 \times 10^{-6}$  to  $173.98 \times 10^{-6}$ , and there are right-dipping light rare earth enrichment patterns with a weak negative Eu anomalies. The trace elements Rb, Ta, Th, Pb, Nd, and Hf are enriched, while Ba, Nb, Sr, and Ti are depleted,

基金项目: 东华理工大学核资源与环境国家重点实验室开放基金项目(2022NRE09); 江西省关键矿产资源勘查与开发重点实验室开放基金(GHKC2024KF08); 放射性地质与勘探技术国防重点学科实验室开放基金(2022RGET08); 国家自然科学基金项目(42062006); 江西省自然科学基金项目(20232BAB213065); 江西省地质局科技研究项目(2022JXDZKJKY02); 江西省“科技+地质”联合计划项目(2023KDG01003); 江西省地质局青年科学技术带头人培养计划项目(2022JXDZKJRC04)

This research is financially supported by the Open Fund Project of the State Key Laboratory of Nuclear Resources and Environment of East China University of Technology (Grant No. 2022NRE09), the Open Fund Project of Jiangxi Province Key Laboratory of Exploration and Development of Critical Mineral Resources (Grant No. GHKC2024KF08), the Open Fund Project of the Fundamental Science on Radioactive Geology and Exploration Technology Laboratory (Grant No. 2022RGET08), the National Natural Science Foundation of China (Grant No. 42062006), the Jiangxi Provincial Natural Science Foundation (Grant No. 20232BAB213065), the Jiangxi Provincial Geological Bureau of Science and Technology Research Project (Grant No. 2022JXDZKJKY02), the Jiangxi Province's Science-Technology and Geology Joint Project (Grant No. 2023KDG01003) and the Training Program for the Young Talents in Science and Technology from the Jiangxi Provincial Bureau of Geology (Grant No. 2022JXDZKJRC04).

第一作者: 高原(1985—), 男, 硕士, 高级工程师, 主要从事区域地质矿产调查、矿产勘查相关工作。Email: 382173369@qq.com

通信作者: 王海(1990—), 男, 博士, 助理研究员, 主要从事矿床学和找矿预测研究工作。Email: wanghai\_90s@163.com

收稿日期: 2024-08-06; 修回日期: 2025-02-26; 录用日期: 2025-02-27; 网络出版日期: 2025-02-28; 责任编辑: 吴芳

indicating a highly differentiated S-type granite. The LA-ICP-MS analysis of monazite U-Pb from the two-mica granite yielded an  $^{206}\text{Pb}/^{238}\text{U}$  weighted average age of  $159.5 \pm 0.5$  Ma. Major elements exhibit high silica contents ( $\text{SiO}_2$  ranging from 75.02% to 77.03%), high alkalis contents ( $\text{Na}_2\text{O}+\text{K}_2\text{O}$  ranging from 5.92% to 8.58%), high aluminum contents (A/CNK ranging from 1.14 to 1.65), and low magnesium contents. Total rare earth elements ( $\Sigma\text{REE}$ ) range from  $106.86 \times 10^{-6}$  to  $124.24 \times 10^{-6}$ , and there are right-dipping light rare earth enrichment patterns with a significant negative Eu anomalies. The trace elements Rb, Ta, Th, Pb, Nd, and Hf are enriched, while Ba, Nb, Sr, and Ti are depleted, suggesting a highly differentiated S-type granite. [Conclusion] By combining geochronological and lithochemical characteristics, the authors conclude that the Zhukeng tungsten deposit formed during an Upper Jurassic mineralization event caused by large-scale granitic magmatic activity related to subduction.

**Keywords:** southern Jiangxi Province; Zhukeng pluton; granite type tungsten deposit; monazite U-Pb dating; geochemistry

**摘要:** 珠坑岩体为赣南地区与钨矿和铌钽矿密切相关的由二云母花岗岩-白云母花岗岩构成的复式岩体。通过对赣南广昌县珠坑钨矿赋矿岩体白云母花岗岩、二云母花岗岩开展系统的岩石地球化学分析和成岩时代研究,结合区域成岩成矿研究结果,探讨岩体成因和构造背景。LA-ICP-MS分析结果显示,细粒白云母花岗岩中的独居石 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $156.7 \pm 1.3$  Ma, 主量元素具有典型的富硅( $\text{SiO}_2$ 含量为65.54%~74.95%)、富碱( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 含量为8.48%~12.85%)、高铝(A/CNK介于1.10~1.22)和贫Mg特征,稀土元素总量( $\Sigma\text{REE}$ )介于 $61.12 \times 10^{-6}$ ~ $173.98 \times 10^{-6}$ ,显示弱富集轻稀土,稀土元素配分曲线呈弱右倾,具有明显的负铕异常,Rb、Ta、Th、Pb、Nd、Hf富集,Ba、Nb、Sr和Ti亏损,属于高分异S型花岗岩;二云母花岗岩中的独居石 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $159.5 \pm 0.9$  Ma,主量元素具有典型的富硅( $\text{SiO}_2$ 含量在75.02%~77.03%)、富碱( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 含量为5.92%~8.58%)、高铝(A/CNK=1.14~1.65)和贫Mg特征,稀土总量 $\Sigma\text{REE}$ 介于 $106.86 \times 10^{-6}$ ~ $124.24 \times 10^{-6}$ ,显示轻稀土富集,稀土配分曲线呈右倾斜,具有明显负铕异常;Rb、Ta、Th、Pb、Nd、Hf富集,Ba、Nb、Sr和Ti亏损,属于高分异S型花岗岩。综合年代学和岩石地球化学特征,珠坑钨矿花岗岩侵位时代为晚侏罗世,为俯冲背景下大规模花岗岩岩浆活动作用产物。

**关键词:** 赣南; 珠坑岩体; 花岗岩型钨矿; 独居石 U-Pb 定年; 地球化学

**中图分类号:** P584; P597 **文献标识码:** A **文章编号:** 1006-6616(2025)02-0325-15

**DOI:** 10.12090/j.issn.1006-6616.2024083

## 0 引言

赣南地区位于南岭有色多金属成矿带东段与武夷山成矿带交汇部位,其成矿地质条件优越,区内发育大量钨、锡和稀土等矿产资源,被誉为有“世界钨都”“稀土王国”(王登红等, 2007; 陈毓川等, 2013; 李伟等, 2021; 郭志强等, 2024)。区内广泛出露的中生代花岗岩与成矿作用关系密切,引起了众多学者的关注(华仁民等, 2005; 王登红等, 2007; Wang et al., 2021; 徐喆等, 2023; Zhu et al., 2024)。近年来,得益于同位素地球化学、微量元素测试等技术方法的发展,该区积累了一批高精度成岩成矿年龄数据,推动了区域岩浆活动与成矿动力学背景的研究(毛景文等, 2008; 赵正等, 2017; Li et al., 2021; Liu et al., 2022; Ni et al., 2023; 李伟等, 2024),丰富了钨锡成矿理论,促进了找矿勘查工作取得了一系列重大突破。

珠坑岩体位于江西省广昌县境内,是赣南地区

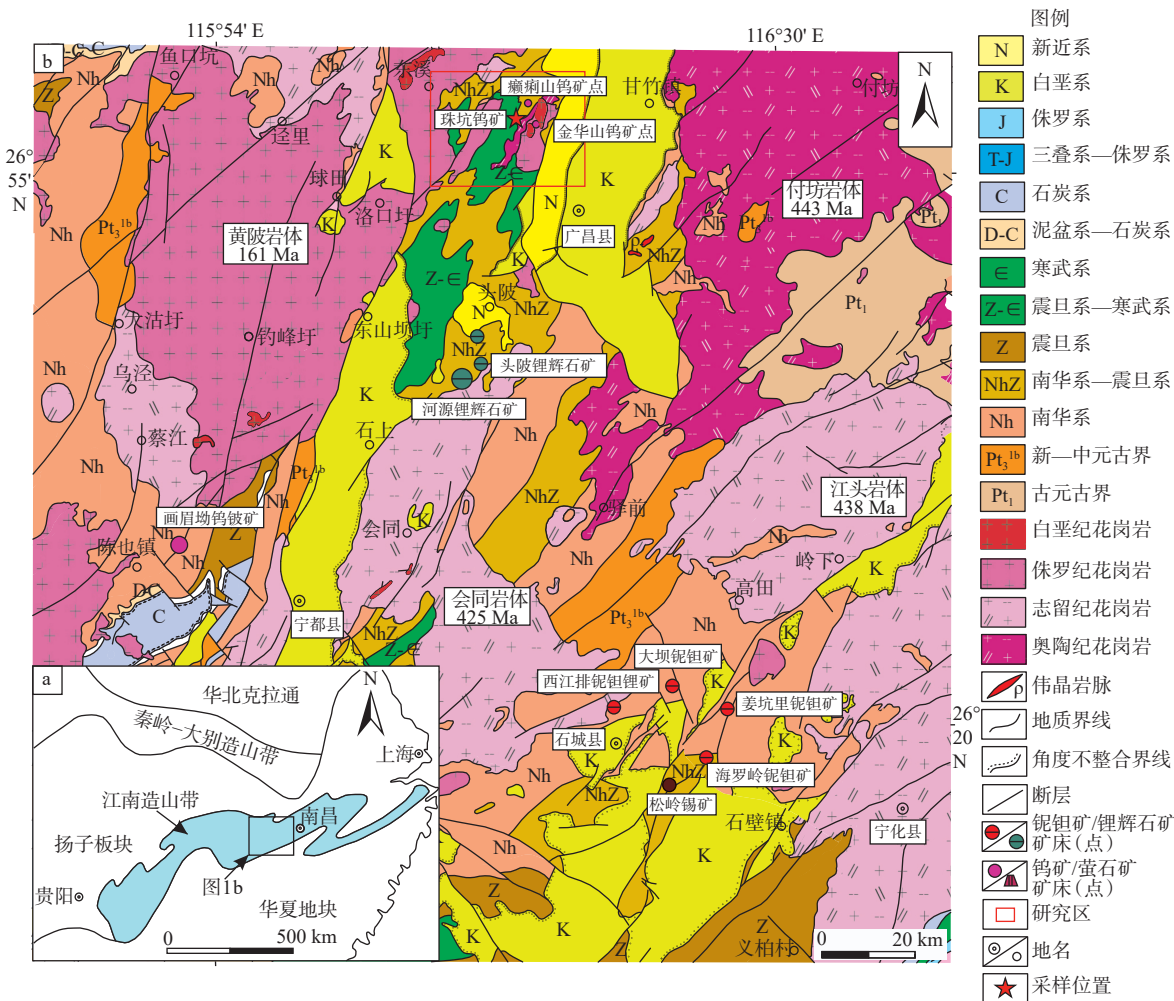
少有的二云母花岗岩-白云母花岗岩复式岩体,钨矿化主要发育在岩体接触带附近,铌钽矿化位于岩体顶部及边部钠长石化带中,显示珠坑岩体与钨矿和铌钽矿具有密切的成因联系。该区与钨锡多金属有关岩体成岩成矿年龄一直为研究热点,但由于岩体和矿床规模有限和受限于以往研究程度及分析测试水平较低,目前对珠坑岩体成岩成矿作用的研究较少,对其侵位时代、岩石类型和构造环境认识不足,一定程度上限制了对该类钨矿床的成因认识和区域找矿工作部署。文章通过对珠坑花岗岩体开展独居石 U-Pb 定年和岩石地球化学分析,查明了珠坑岩体的岩石学、岩石地球化学及同位素年代学特征,结合成矿动力学背景,为珠坑钨矿及铌钽等稀有金属勘查提供理论指导。

## 1 地质背景

广昌-石城地区大地构造位于华南板块武夷隆起中段西缘,区内岩浆-构造活动强烈,从新元古

代到晚中生代, 先后经历了陆内造山运动和大规模伸展作用, 形成大量有色、稀有贵金属矿床, 赋存于加里东期和燕山期花岗岩体中(图 1)。珠坑岩体位于鹰潭-安远北北东向深断裂带东侧广昌县珠坑附近, 面积约 0.64 km<sup>2</sup>(戴浩撞等, 2023)。岩体呈北东向串珠状侵入于南华纪-寒武纪变质岩地层中, 其岩性以二云母花岗岩和白云母花岗岩为主。

近, 面积约 0.64 km<sup>2</sup>(戴浩撞等, 2023)。岩体呈北东向串珠状侵入于南华纪-寒武纪变质岩地层中, 其岩性以二云母花岗岩和白云母花岗岩为主。



a—大地构造位置; b—区域地质图(据 1:25 万广昌幅地质图, 1:50 万江西省地质图修改)

图 1 广昌—石城构造地质图

Fig. 1 Tectonic geological map of the Guangchang-Shicheng area (modified after the 1:250000 geological map of Guangchang and the 1:500000 geological map of Jiangxi Province)

(a) Tectonic location map; (b) Schematic regional geological map

珠坑钨矿位于古竹复式向斜北东端隆起部位及珠坑岩体内外接触带上, 区域地层由老至新分别为南华系—震旦系洪山组(Nh<sub>2</sub>—Z<sub>1</sub>h<sup>2</sup>)冰碛砾岩、片岩, 寒武系外管坑组(C<sub>1-2</sub>w<sup>1</sup>)硅质岩、炭质板岩, 白垩系周田组(K<sub>2</sub>z<sup>1</sup>)和茅店组(K<sub>2</sub>z<sup>2</sup>)砂砾岩。区域内岩浆岩以早志留世及晚侏罗世中酸性侵入岩为主。区域上发育北东向、北西向和近东西向 3 组断裂, 共同控制着区域内稀有金属矿床(点)的分布(图 1)。珠坑钨矿由 11 条钨矿脉组成, 矿体形态主要呈脉

状, 延伸长度一般为 100~250 m, 最长可达 600 m, 脉距为 1~6 m, WO<sub>3</sub> 平均含量约为 0.1%~0.5%, 矿体主要产于角砾岩与细粒斑状白云母花岗岩内外接触带。矿石矿物以黑钨矿、方铅矿、闪锌矿、黄铜矿、黄铁矿为主; 脉石矿物以石英、长石、白云母和绿泥石为主; 矿石构造多呈块状, 细脉状和浸染状, 矿石结构主要为交代结构、自形半自形晶结构及交代残余结构等。矿床围岩蚀变以钠长石化、钾长石化、白云母化、云英岩化、硅化和绢云母化为主。

## 2 样品采集及分析方法

文章选取矿区内具有代表性的细粒白云母花岗岩和中细粒二云母花岗岩样品(22ZK01、22ZK13),开展独居石 U-Pb 测年工作,样品均采自露天采场,采样位置见图 2。细粒白云母花岗岩主要由钾长石(含量为 30%~60%)、斜长石(含量为 28%~

34%)、石英(含量为 25%~30%)、白云母(含量为 4%~6%)等矿物组成(图 3a),白云母自型程度较高,呈片状分布。中细粒二云母花岗岩中发育原生和热液 2 类白云母,其岩石主要由石英(含量为 20%~30%)、钠长石(含量为 20%~25%)、钾长石(含量为 8%~10%)、云母(含量为 8%~10%)等矿物组成(图 3b),热液白云母多呈自形一半自形,集合体呈片状分布。云英岩主要矿物成分为石英(含量

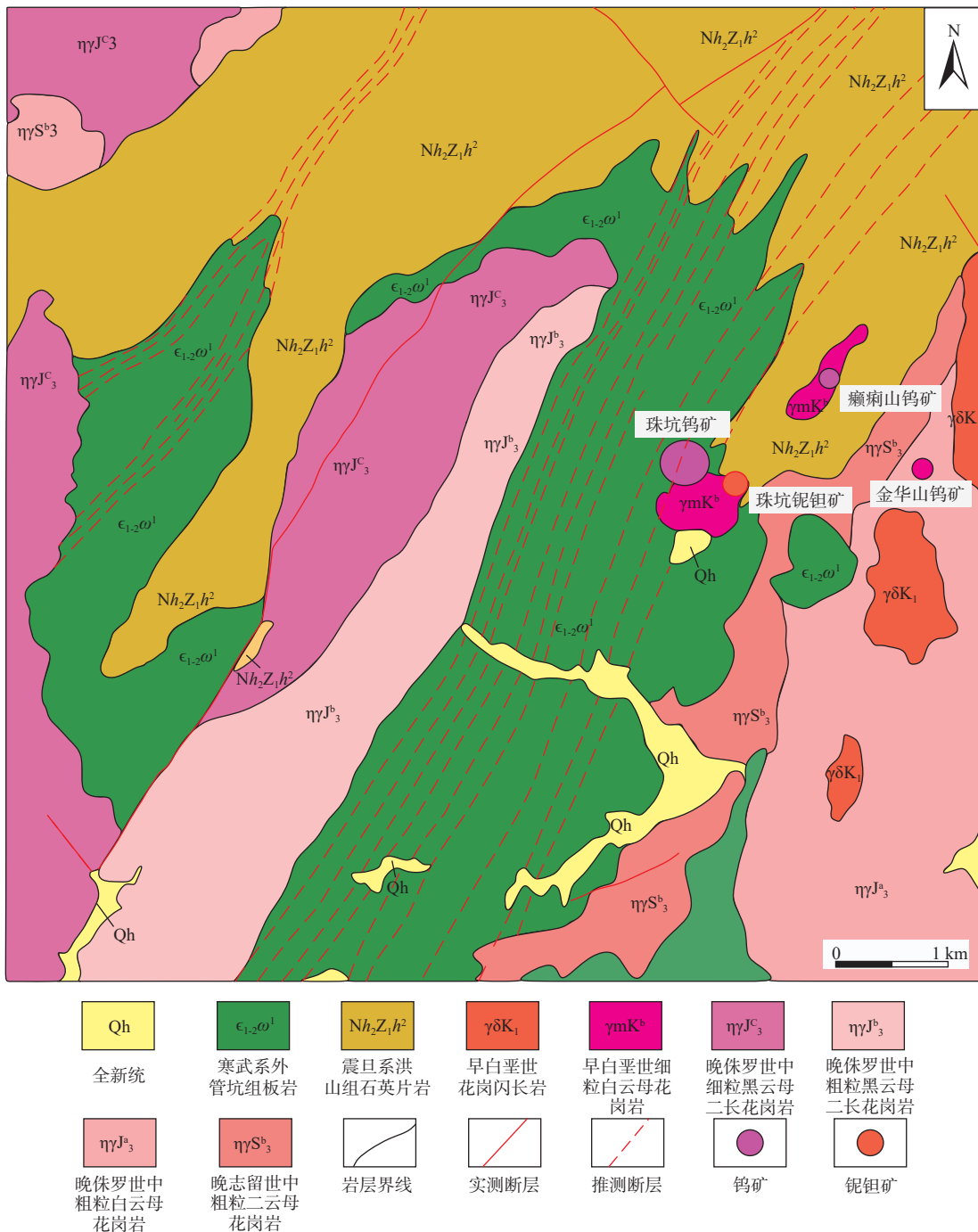
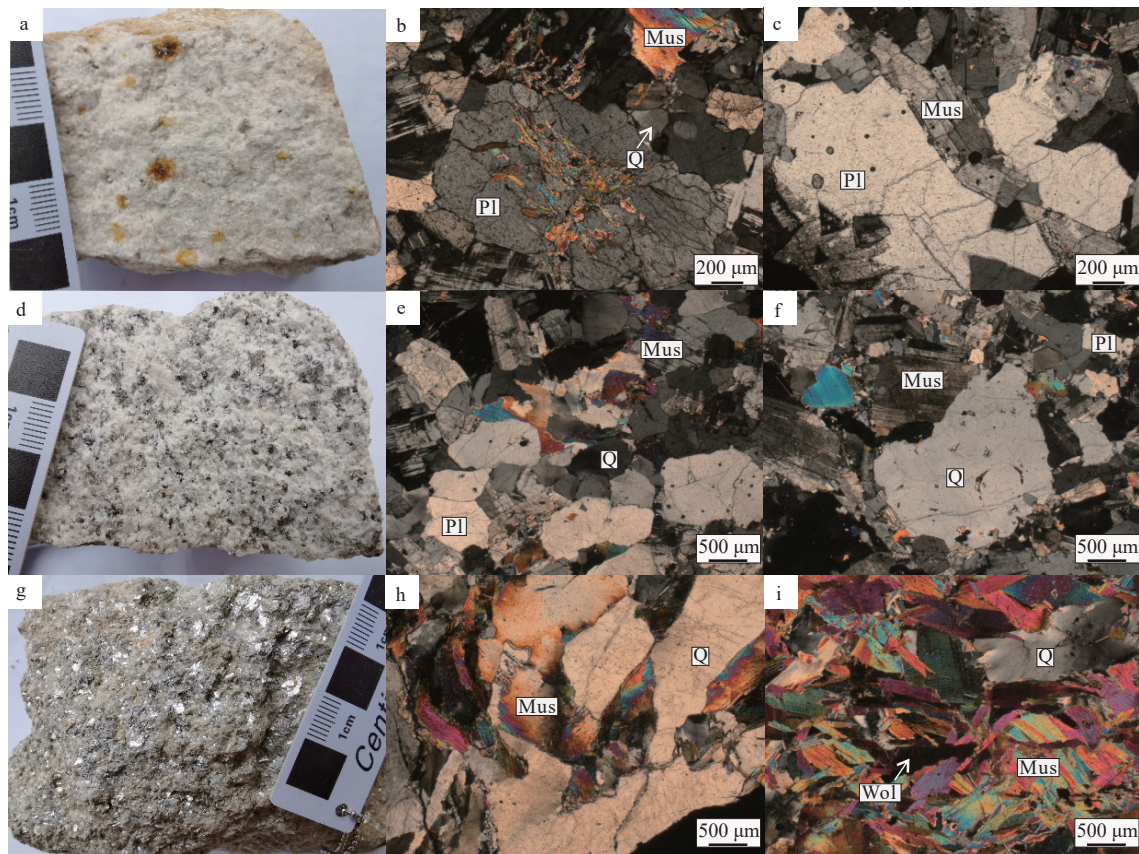


图 2 珠坑钨矿矿区地质简图(据戴浩撞等, 2023 修改)

Fig. 2 Simplified geological map showing the Zhukeng tungsten deposit (modified after Dai et al., 2023)

为50%~65%)、白云母(含量为10%~15%)、黄玉(含量为20%~25%)、绿泥石(含量为2%~5%)及少

许黑钨矿及其他副矿物组成(图3c)。



Mus—白云母; Q—石英; Pl—斜长石; Wol—黑钨矿

a—细粒白云母花岗岩手标本; b—细粒白云母中白云母、石英、斜长石(正交偏光); c—细粒白云母中白云母、斜长石(正交偏光); d—中细粒二云母花岗岩手标本; e—中细粒二云母花岗岩中石英、白云母(正交偏光); f—中细粒二云母花岗岩中石英、白云母特征(正交偏光); g—云英岩手标本; h—云英岩中云母、石英镜下特征(正交偏光); i—云英岩中云母、石英、黑钨矿镜下特征(正交偏光)

图3 珠坑钨矿典型赋矿岩石特征及显微照片

Fig. 3 Microphotographs of representative ore-bearing rocks from the Zhukeng tungsten deposit

(a) Fine-grained muscovite granite; (b) Muscovite, quartz, plagioclase in fine-grained muscovite granite (crossed polarized light); (c) Muscovite, plagioclase in fine-grained muscovite granite (crossed polarized light); (d) Medium- to fine-grained two-mica granite; (e) Quartz and muscovite in medium- to fine-grained two-mica granite (crossed polarized light); (f) Quartz and muscovite in medium to fine-grained two-mica granite (crossed polarized light); (g) Greisen; (h) Mica, quartz in greisen (crossed polarized light); (i) Mica, quartz, wolframite in greisen (crossed polarized light)

Mus—muscovite; Q—quartz; Pl—plagioclase; Wol—wolframite

全岩主量元素、微量元素分析在自然资源部南昌矿产资源检测中心完成。主量元素使用X射线荧光光谱仪(仪器型号: PANalytical Axios)进行测定,各元素检查范围为:0.002%~99%。微量元素采用电感耦合等离子质谱法测定,仪器型号为Q-MS型质谱仪,采用内标法进行校正。独居石背散射(BSE)电子图像和激光剥蚀电感耦合等离子体质谱仪(LA-ICP-MS)原位U-Pb同位素定年在东华理工大学铀资源探采与核遥感全国重点实验室完成,

离子质谱仪型号为Agilent7900,激光剥蚀系统采用GeoLasHD193,激光剥蚀束斑、能量密度和剥蚀频率分别为16 μm、3 J/cm<sup>2</sup>和3 Hz,独居石标样TS-Mnz(Budzyń et al., 2021)作为外标校正分析过程中的独居石U-Pb同位素分馏,独居石使用标样Bananeira(Gonçalves et al., 2016)监控分析质量,NIST610作为外标校正微量元素分馏。数据处理采用ICPMSDataCal 11.0(Liu et al., 2008, 2010)完成,并在软件Isoplot4.15完成样品的U-Pb谐和图绘制和年龄加权平均计算。

### 3 测试结果

#### 3.1 独居石 U-Pb 测年结果

独居石均选自赋矿岩体中细粒白云母花岗岩(22ZK01)和细粒二云母花岗岩(22ZK13),独居石多呈无色透明或淡黄色,呈自形一半自形结构,粒径约为 55~350 μm,长宽比约为 1:1~3:1,在背散射电子图像(BSE)中绝大多数独居石颗粒颜色均一,少

量独居石存在裂隙和孔洞,无明显环带(图 4)。

每件样品均挑选 24 颗独居石开展 LA-ICP-MS U-Pb 测年,测试结果见表 1。2 件样品的独居石分析数据显示:细粒白云母花岗岩(22ZK01)共测得 19 个有效数据,其中 Th 含量介于  $49487 \times 10^{-6} \sim 216756 \times 10^{-6}$ , U 含量介于  $1966 \times 10^{-6} \sim 10828 \times 10^{-6}$ , Th/U 比值在 8~31 之间; $^{208}\text{Pb}/^{232}\text{Th}$  年龄值均分布于谐和线附近(图 5a),其  $^{208}\text{Pb}/^{232}\text{Th}$  加权平均年龄为  $156.7 \pm 1.3$  Ma (MSWD=1.7,  $n=19$ )。

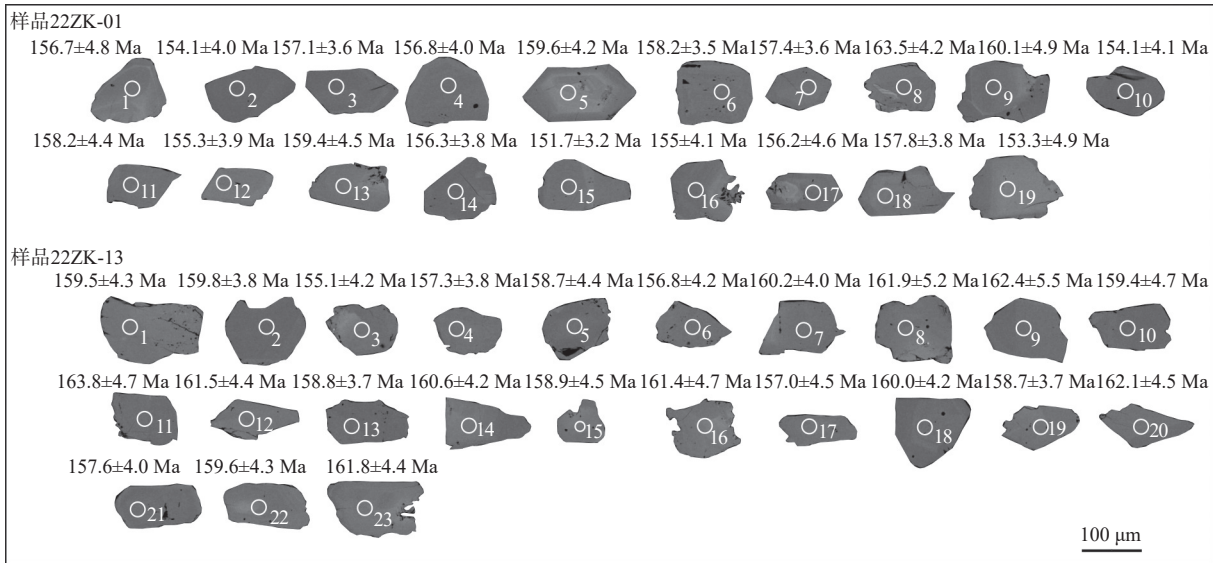


图 4 珠坑钨矿花岗岩体中独居石背散射 (BSE) 电子图像

Fig. 4 Backscattered electron (BSE) images of monazites from the Zhukeng tungsten ore granite

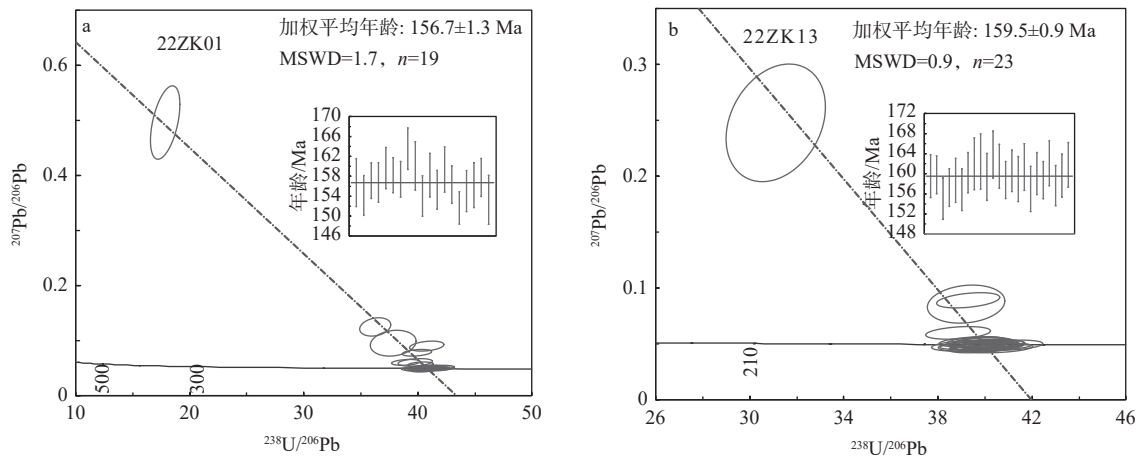


图 5 珠坑钨矿花岗岩中独居石 Tera-Wasserburg 谐和图和  $^{206}\text{Pb}/^{238}\text{U}$  加权平均年龄图; b—二云母花岗岩中独居石 Tera-Wasserburg 谐和图和  $^{206}\text{Pb}/^{238}\text{U}$  加权平均年龄图

Fig. 5 Tera-Wasserburg concordia diagrams and  $^{206}\text{Pb}/^{238}\text{U}$  weighted average age diagrams for monazite from granites of the Zhukeng tungsten deposit

(a) Tera-Wasserburg concordia diagram and  $^{206}\text{Pb}/^{238}\text{U}$  weighted average age diagram for monazite from a muscovite-granite; (b) Tera-Wasserburg concordia diagram and  $^{206}\text{Pb}/^{238}\text{U}$  weighted average age diagram for monazite from a two-mica granite

表 1 珠坑钨矿床花岗岩中独居石 LA-ICP-MS U-Pb 定年结果

Table 1 LA-ICP-MS U-Pb dating of monazite from granites in the Zhukeng tungsten deposit

测点号	元素含量/ $\times 10^{-6}$		Th/U	同位素比值						年龄/Ma			
	Th	U		$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 2\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 2\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 2\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 2\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 2\sigma$
<b>22ZK01 Mn</b>													
22ZK01-1	49487	2738	18	0.0503	0.0042	0.1702	0.0140	0.0246	0.0008	159.6	12.0	156.7	4.8
22ZK01-3	141827	6396	22	0.0485	0.0022	0.1624	0.0086	0.0242	0.0006	152.8	7.5	154.1	4.0
22ZK01-6	127159	5295	24	0.0479	0.0028	0.1630	0.0098	0.0247	0.0006	153.4	8.5	157.1	3.6
22ZK01-7	109783	4417	25	0.0485	0.0026	0.1651	0.0095	0.0246	0.0006	155.1	8.3	156.8	4.0
22ZK01-8	73144	5468	13	0.0780	0.0046	0.2698	0.0167	0.0251	0.0007	242.6	13.0	159.6	4.2
22ZK01-9	104244	4769	22	0.0562	0.0040	0.1928	0.0137	0.0248	0.0006	179.0	12.0	158.2	3.5
22ZK01-10	83859	4321	19	0.0470	0.0029	0.1601	0.0096	0.0247	0.0006	150.8	8.4	157.4	3.6
22ZK01-11	77157	3223	24	0.0602	0.0045	0.2135	0.0163	0.0257	0.0007	196.5	14.0	163.5	4.2
22ZK01-12	52965	3755	14	0.0596	0.0049	0.2073	0.0180	0.0251	0.0008	191.3	15.0	160.1	4.9
22ZK01-14	190005	6199	31	0.0487	0.0026	0.1623	0.0087	0.0242	0.0006	152.7	7.6	154.1	4.1
22ZK01-15	50266	2789	18	0.0483	0.0034	0.1645	0.0109	0.0248	0.0007	154.6	9.5	158.2	4.4
22ZK01-17	68132	4579	15	0.0508	0.0028	0.1718	0.0107	0.0244	0.0006	161.0	9.3	155.3	3.9
22ZK01-18	54822	2738	20	0.0500	0.0029	0.1723	0.0098	0.0250	0.0007	161.4	8.5	159.4	4.5
22ZK01-19	57463	4366	13	0.0496	0.0026	0.1678	0.0087	0.0245	0.0006	157.5	7.5	156.3	3.8
22ZK01-20	87754	10828	8	0.0486	0.0020	0.1594	0.0066	0.0238	0.0005	150.2	5.7	151.7	3.2
22ZK01-21	77647	4496	17	0.0499	0.0028	0.1674	0.0094	0.0243	0.0007	157.1	8.1	155.0	4.1
22ZK01-22	83390	5524	15	0.0907	0.0077	0.3036	0.0231	0.0245	0.0007	269.2	18.0	156.2	4.6
22ZK01-23	63875	4967	13	0.0491	0.0028	0.1677	0.0093	0.0248	0.0006	157.4	8.1	157.8	3.8
22ZK01-24	92367	4980	19	0.0493	0.0030	0.1644	0.0117	0.0241	0.0008	154.5	10.0	153.3	4.9
<b>22ZK13 Mn</b>													
22ZK13-1	92418	4349	21	0.0473	0.0027	0.1633	0.0090	0.0251	0.0007	153.6	7.8	159.5	4.3
22ZK13-2	68539	3173	22	0.0507	0.0034	0.1756	0.0120	0.0251	0.0006	164.2	10.0	159.8	3.8
22ZK13-3	90313	5008	18	0.0487	0.0031	0.1641	0.0114	0.0243	0.0007	154.2	10.0	155.1	4.2
22ZK13-5	142814	5535	26	0.0489	0.0025	0.1673	0.0101	0.0247	0.0006	157.1	8.8	157.3	3.8
22ZK13-6	71800	3431	21	0.0484	0.0037	0.1655	0.0119	0.0249	0.0007	155.5	10.0	158.7	4.4
22ZK13-7	138315	6736	21	0.0472	0.0024	0.1598	0.0079	0.0246	0.0007	150.6	6.9	156.8	4.2
22ZK13-8	97270	4266	23	0.0453	0.0026	0.1571	0.0094	0.0252	0.0006	148.2	8.2	160.2	4.0
22ZK13-9	70874	2998	24	0.0482	0.0037	0.1691	0.0135	0.0254	0.0008	158.7	12.0	161.9	5.2
22ZK13-10	122693	6382	19	0.0827	0.0115	0.3008	0.0477	0.0255	0.0009	267.0	37.0	162.4	5.5
22ZK13-11	117956	6247	19	0.0482	0.0027	0.1652	0.0079	0.0250	0.0007	155.2	6.9	159.4	4.7
22ZK13-12	14790	2305	6	0.0600	0.0045	0.2127	0.0158	0.0257	0.0007	195.8	13.0	163.8	4.7
22ZK13-13	96254	4551	21	0.0485	0.0028	0.1689	0.0091	0.0254	0.0007	158.5	7.9	161.5	4.4
22ZK13-14	74173	3637	20	0.0490	0.0029	0.1684	0.0101	0.0249	0.0006	158.1	8.8	158.8	3.7
22ZK13-15	90316	3706	24	0.0520	0.0035	0.1804	0.0117	0.0252	0.0007	168.4	10.0	160.6	4.2
22ZK13-16	43503	2313	19	0.0485	0.0045	0.1666	0.0144	0.0250	0.0007	156.4	13.0	158.9	4.5
22ZK13-17	57767	2544	23	0.0517	0.0033	0.1807	0.0119	0.0253	0.0007	168.7	10.0	161.4	4.7
22ZK13-18	87092	3769	23	0.0459	0.0028	0.1564	0.0105	0.0247	0.0007	147.6	9.2	157.0	4.5
22ZK13-19	85551	4319	20	0.0463	0.0031	0.1598	0.0101	0.0251	0.0007	150.5	8.9	160.0	4.2
22ZK13-20	112206	5464	21	0.0494	0.0029	0.1699	0.0104	0.0249	0.0006	159.4	9.0	158.7	3.7
22ZK13-21	127992	5537	23	0.0888	0.0051	0.3122	0.0185	0.0255	0.0007	275.9	14.0	162.1	4.5
22ZK13-22	50133	1902	26	0.0492	0.0046	0.1671	0.0147	0.0248	0.0006	156.9	13.0	157.6	4.0
22ZK13-23	83610	3777	22	0.0509	0.0034	0.1766	0.0126	0.0251	0.0007	165.2	11.0	159.6	4.3
22ZK13-24	60311	3043	20	0.0483	0.0034	0.1688	0.0120	0.0254	0.0007	158.4	10.0	161.8	4.4

中细粒二云母花岗岩(22ZK13)共测得23个有效数据,其中Th含量在 $14790 \times 10^{-6} \sim 142814 \times 10^{-6}$ 之间,U含量在 $1902 \times 10^{-6} \sim 6736 \times 10^{-6}$ 之间,Th/U比值在6~26之间, $^{208}\text{Pb}/^{232}\text{Th}$ 年龄值均集中分布于谐和线附近(图5b),其 $^{208}\text{Pb}/^{232}\text{Th}$ 加权平均年龄为 $159.5 \pm 0.9$  Ma (MSWD=0.9,  $n=23$ )。

### 3.2 岩石地球化学

#### 3.2.1 主量元素特征

珠坑钨矿细粒白云母花岗岩、中细粒二云母花岗岩、云英岩的主量、微量元素分析结果见表2和

表3,从数据表中可以看出。细粒白云母花岗岩具有典型的富硅、富碱特征, $\text{SiO}_2$ 含量为65.54%~74.95%(平均值为70.7%), $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 含量为8.48%~12.85%(平均值为10.3%), $\text{Na}_2\text{O}/\text{K}_2\text{O}$ 比值为0.39~2.82(平均为1.19),具有明显的富钠特征, $\text{Al}_2\text{O}_3$ 含量为14.19%~19.74%(平均值为16.78%),铝饱和指数 $A/\text{CNK}=\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ 介于1.10~1.22,在 $A/\text{CNK}-A/\text{NK}$ 图解中样品点均落入过铝质区域,属于过铝质花岗岩类, $\text{MgO}$ 含量为0.03%~0.04%,相对贫Mg。

表2 珠坑钨矿花岗岩体主量元素含量(%)

Table 2 Major element compositions (%) of granites from the Zhukeng tungsten deposit

样号	22ZK01	22ZK02	22ZK03	22ZK04	22ZK05	22ZK06	22ZK07	22ZK08	22ZK09	22ZK10	22ZK11	22ZK12	22ZK13	22ZK14	22ZK15	22ZK17	22ZK18	22ZK19
岩性	细粒白云母花岗岩								中细粒二云母花岗岩						云英岩			
$\text{SiO}_2$	74.68	74.95	74.83	75.81	65.54	68.58	65.66	66.14	75.30	75.02	75.34	75.41	75.51	76.92	77.03	58.57	56.46	64.18
$\text{TiO}_2$	0.03	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.05	0.05	0.06
$\text{Al}_2\text{O}_3$	14.97	14.61	14.68	14.19	19.74	18.51	18.55	19.00	13.88	14.09	13.84	13.69	13.84	12.93	12.32	22.39	26.54	21.39
FeO	0.42	0.47	0.28	0.34	0.21	0.17	0.27	0.16	0.36	0.39	0.38	0.46	0.39	0.52	0.60	2.74	1.99	1.55
MnO	0.09	0.10	0.08	0.09	0.05	0.04	0.05	0.04	0.12	0.10	0.12	0.16	0.13	0.21	0.10	1.41	0.34	0.28
MgO	0.03	0.04	0.04	0.03	0.03	0.03	0.04	0.03	0.06	0.05	0.05	0.06	0.06	0.10	0.12	0.09	0.07	0.21
CaO	0.19	0.20	0.11	0.17	0.77	0.72	0.80	0.58	0.50	0.45	0.44	0.52	0.43	0.54	0.84	1.32	0.03	0.03
$\text{Na}_2\text{O}$	5.05	4.46	4.68	4.73	5.42	7.85	3.48	4.87	4.40	4.00	4.26	3.62	4.35	2.86	0.50	0.40	0.42	0.29
$\text{K}_2\text{O}$	3.45	4.12	4.24	3.75	6.53	2.78	8.95	7.98	4.15	4.45	4.32	4.47	4.17	4.07	5.42	7.20	8.62	7.17
$\text{P}_2\text{O}_5$	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.01
DI	95.40	95.36	96.36	96.16	93.07	94.55	93.4	95.32	95.10	94.72	95.40	94.03	95.25	92.60	89.46	72.03	77.21	81.26
$\text{Na}_2\text{O}/\text{K}_2\text{O}$	1.46	1.08	1.10	1.26	0.83	2.82	0.39	0.61	1.06	0.90	0.99	0.81	1.04	0.70	0.09	0.06	0.05	0.04
$\text{Na}_2\text{O}+\text{K}_2\text{O}$	8.50	8.58	8.92	8.48	11.95	10.63	12.43	12.85	8.55	8.45	8.58	8.09	8.52	6.93	5.92	7.60	9.04	7.46
烧失量	0.92	0.90	0.78	0.69	1.33	1.02	1.38	1.03	0.91	1.17	0.94	1.11	0.80	1.37	1.88	3.72	3.95	3.27
A/CNK	1.22	1.22	1.18	1.18	1.18	1.12	1.15	1.10	1.14	1.19	1.14	1.21	1.15	1.35	1.65	2.31	2.64	2.58
A/NK	1.24	1.24	1.19	1.20	1.23	1.16	1.20	1.14	1.18	1.23	1.18	1.27	1.18	1.42	1.84	2.64	2.64	2.59

注: DI为分异指数;  $A/\text{CNK}=\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ ;  $A/\text{NK}=\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})$

中细粒二云母花岗岩具有典型的富硅、富碱特征, $\text{SiO}_2$ 含量为75.02%~77.03%(平均值为75.79%), $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 含量为5.92%~8.58%(平均值为7.86%), $\text{Na}_2\text{O}/\text{K}_2\text{O}$ 比值为0.09~1.06,平均为0.80,具有明显的富钾特征, $\text{Al}_2\text{O}_3$ 含量为12.32%~14.09%(平均值为13.51%),铝饱和指数A/CNK介于1.14~1.65,属于过铝制花岗岩类, $\text{MgO}$ 含量为0.05%~0.12%,相对贫Mg。

总体上看,早期中细粒二云母花岗岩与晚期细粒白云母花岗岩均属于亚碱性系列,中细粒二云母花岗岩均落入典型花岗岩区,后期细粒白云母花

岩多数落入花岗岩区,部分落入石英二长岩和图正长岩区(图6a),两者均属于过铝质岩石(图6b)。

云英岩 $\text{SiO}_2$ 含量为54.46%~64.18%(平均值为59.73%), $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 含量为7.46%~9.04%(平均值为8.03%), $\text{Na}_2\text{O}/\text{K}_2\text{O}$ 比值为0.04~0.06(平均为0.05%),具有明显富钾特征, $\text{Al}_2\text{O}_3$ 含量为21.39%~26.54%(平均值为23.44%),铝饱和指数A/CNK介于2.31~2.64, $\text{MgO}$ 含量为0.09%~0.21%,相对贫Mg。

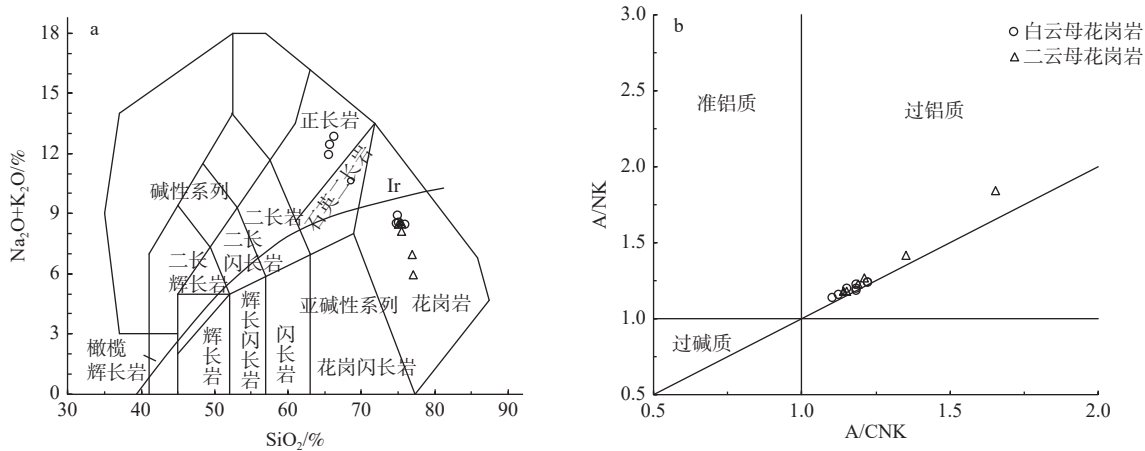
#### 3.2.2 稀土元素和微量元素特征

矿区赋矿花岗岩稀土和微量元素组成数据见表3,其稀土配分曲线分布见图7a。细粒白云母花

表 3 珠坑矿区花岗岩微量元素分析 ( $\times 10^{-6}$ ) 结果

Table 3 Trace element compositions ( $\times 10^{-6}$ ) of granites from the Zhukeng tungsten deposit

样品号	22ZK01	22ZK02	22ZK03	22ZK04	22ZK05	22ZK06	22ZK07	22ZK08	22ZK09	22ZK10	22ZK11	22ZK12	22ZK13	22ZK14	22ZK15	22ZK17	22ZK18	22ZK19
岩性	细粒白云母花岗岩										中细粒二云母花岗岩				云英岩			
Rb	897.00	978.00	799.00	814.00	837.00	442.00	1093.00	967.00	702.00	642.00	740.00	767.00	768.50	689.00	899.00	1756.00	2019.00	1750.00
Ba	19.20	28.60	35.00	25.20	95.50	33.50	109.50	84.20	29.00	38.10	24.40	25.80	28.80	48.80	88.10	70.80	37.80	89.50
Th	9.63	8.34	9.12	6.57	32.20	8.50	32.60	33.70	18.30	17.50	16.20	15.90	17.10	18.70	27.90	14.90	20.50	13.90
U	9.44	11.00	7.30	6.56	6.79	9.39	12.40	12.60	14.90	18.00	14.40	14.60	12.60	20.00	12.50	27.10	5.41	4.00
Pb	48.20	61.40	57.30	38.50	332.70	62.80	388.00	149.40	43.90	58.90	41.50	100.00	46.90	174.40	759.80	48.70	27.00	142.10
Sr	8.38	9.12	12.20	8.56	26.70	25.20	24.70	28.80	11.30	16.60	11.30	12.70	12.20	13.10	12.20	6.36	6.05	6.96
P	61.10	61.10	52.38	56.74	74.20	74.20	96.02	109.12	52.38	65.47	52.38	56.74	96.02	43.65	34.92	65.47	74.20	61.10
Nb	77.40	57.00	45.90	76.10	14.80	39.20	26.00	43.90	54.80	61.20	54.20	51.70	53.20	65.00	45.20	306.80	68.40	47.40
Ta	56.10	47.70	24.30	56.90	4.11	16.30	8.44	17.50	16.60	20.70	17.60	16.90	19.20	17.30	9.91	128.60	20.10	13.40
K	28639.49	34201.36	35197.51	31129.88	54207.49	23077.61	74296.64	66244.37	34450.40	36940.79	35861.62	37106.81	34616.42	33786.29	44993.05	59769.36	71557.21	59520.32
La	7.62	8.87	9.21	7.41	13.40	5.32	16.10	19.40	10.60	13.60	13.80	13.10	10.80	11.70	12.70	13.80	18.40	20.30
Ce	22.50	24.80	33.40	22.90	35.60	12.00	44.60	50.00	28.60	36.80	36.20	36.50	29.40	31.20	32.30	36.20	47.60	52.00
Pr	3.21	3.50	3.50	2.97	4.65	1.54	5.82	6.98	3.86	4.82	4.91	4.89	3.92	4.20	4.24	4.89	6.38	6.83
Nd	13.70	15.00	14.70	12.40	21.20	6.57	26.70	31.40	17.10	20.60	21.20	21.20	17.20	18.20	18.50	21.00	27.40	28.70
Zr	18.50	21.90	28.40	30.20	64.70	65.50	60.20	63.10	46.10	45.40	41.60	38.90	46.20	44.40	55.50	39.90	51.60	13.90
Hf	3.52	2.98	3.65	4.26	4.60	5.27	3.56	5.28	3.27	3.70	4.47	3.42	4.12	3.05	3.51	14.90	3.92	2.48
Sm	8.95	8.51	7.51	7.47	10.20	4.20	11.90	14.60	8.58	9.65	9.84	9.90	8.57	7.99	7.58	10.40	13.30	13.60
Eu	0.04	0.08	0.07	0.04	0.32	0.20	0.36	0.38	0.10	0.18	0.09	0.09	0.10	0.15	0.24	0.14	0.17	0.26
Gd	9.10	8.06	7.28	7.35	9.98	6.15	10.20	13.80	8.95	9.85	9.82	9.46	8.95	8.36	7.94	9.70	14.90	10.60
Ti	155.87	143.88	125.90	119.90	65.95	101.92	71.94	53.96	179.85	167.86	161.87	179.85	191.84	215.82	317.74	287.76	287.76	383.68
Tb	1.59	1.43	1.36	1.36	1.92	1.49	1.80	2.52	1.82	1.87	1.87	1.77	1.79	1.84	1.67	2.03	3.09	1.56
Dy	7.15	7.02	7.55	6.74	12.90	9.98	11.40	15.00	11.40	11.50	11.30	10.50	11.00	12.70	11.50	12.90	18.20	7.32
Ho	0.79	0.91	1.13	0.83	2.50	1.75	2.12	2.66	1.98	2.01	1.97	1.78	1.90	2.38	2.21	2.23	2.84	0.96
Er	1.45	1.96	2.70	1.69	6.98	4.58	5.82	6.92	5.23	5.16	5.10	4.57	5.04	6.32	6.01	6.15	6.81	1.99
Tm	0.19	0.30	0.44	0.25	1.19	0.78	0.98	1.11	0.90	0.86	0.86	0.76	0.84	1.06	0.98	1.21	1.06	0.26
Yb	1.28	2.10	3.22	1.80	8.86	5.70	7.32	8.00	6.75	6.40	6.47	5.75	6.39	7.76	7.12	10.20	7.30	1.75
Lu	0.18	0.30	0.45	0.25	1.37	0.87	1.12	1.21	1.01	0.94	0.95	0.85	0.96	1.11	1.06	1.56	1.03	0.23
Y	44.80	41.90	51.00	45.80	76.20	56.60	63.60	81.40	70.20	67.70	69.30	65.00	70.00	80.10	67.50	65.40	91.00	39.40
$\Sigma$ REE	77.75	82.84	92.51	73.46	131.07	61.12	146.24	173.98	106.87	124.24	124.38	121.12	106.86	114.97	114.05	132.41	168.48	146.36
LREE	56.02	60.76	68.39	53.19	85.37	29.83	105.48	122.76	68.84	85.65	86.04	85.68	69.99	73.44	75.56	86.43	113.25	121.69
HREE	21.72	22.08	24.13	20.27	45.70	31.30	40.76	51.22	38.04	38.59	38.34	35.44	36.87	41.53	38.49	45.98	55.23	24.67
LREE/HREE	2.58	2.75	2.83	2.62	1.87	0.95	2.59	2.40	1.81	2.22	2.24	2.42	1.90	1.77	1.96	1.88	2.05	4.93
La/N/YbN	4.27	3.03	2.05	2.95	1.08	0.67	1.58	1.74	1.13	1.52	1.53	1.63	1.21	1.08	1.28	0.97	1.81	8.32
$\delta$ Eu	0.01	0.03	0.03	0.02	0.10	0.12	0.10	0.08	0.03	0.06	0.03	0.03	0.03	0.05	0.09	0.04	0.04	0.07
$\delta$ Ce	1.12	1.09	1.44	1.20	1.11	1.03	1.13	1.05	1.10	1.11	1.08	1.12	1.11	1.09	1.08	1.08	1.08	1.08



a—SiO<sub>2</sub>-(K<sub>2</sub>O+Na<sub>2</sub>O)分类图(底图引自 Middlemost, 1994, 图中碱性与亚碱性系列分界线引自 Irvine et al., 1971); b—A/CNK-A/NK图解 (Maniar and Piccoli, 1989)

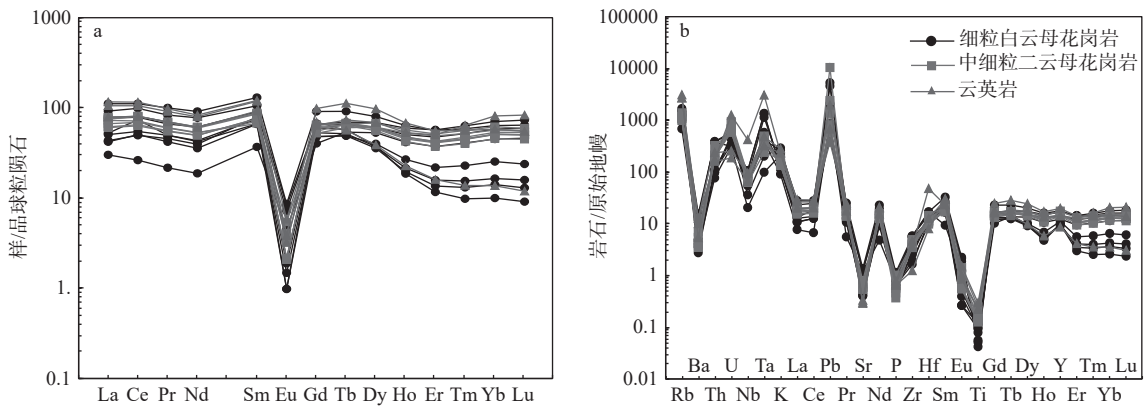
图 6 珠坑花岗岩体主量元素图解

Fig. 6 Major element diagrams of the Zhukeng tungsten deposit

(a) SiO<sub>2</sub>-(K<sub>2</sub>O+Na<sub>2</sub>O) diagram, after Middlemost, 1994 and the boundary between alkaline and sub-alkaline series in the figure follows Irvine et al., 1971; (b) A/CNK-A/NK plot, after Maniar and Piccoli (1989)

花岗岩稀土元素总量(ΣREE)介于 61.12×10<sup>-6</sup>~173.98×10<sup>-6</sup>, 平均为 104.87×10<sup>-6</sup>, La<sub>N</sub>/Yb<sub>N</sub> 比值为 0.67~4.27, 平均值为 2.17, 轻重稀土 LREE/HREE 比值为 0.95~2.83, 总体显示弱富集轻稀土, 其稀土元素配分曲线

呈弱右倾(图 7a), δEu 值为 0.01~0.12, 平均值为 0.06, 具有明显的负铕异常; 在微量元素初始地幔标准化蛛网图上, 细粒白云母花岗岩表现出富集 Rb、Ta、Pb、Nd、Hf, 亏损 Ba、Nb、Sr 和 Ti(图 7b)。



a—C1 球粒陨石标准化稀土元素配分曲线 (Sun and McDonough, 1989); b—微量元素原始地幔标准化蛛网图 (Sun and McDonough, 1989)

图 7 珠坑钨矿花岗岩岩体 C1 球粒陨石标准化稀土元素配分曲线, 及微量元素原始地幔标准化蛛网图

Fig. 7 C1 Chondrite-normalized REE distribution patterns (a, normalization values from Sun and McDonough, 1989) and primitive mantle-normalized trace element spidergram (b, normalization values from Sun and McDonough, 1989) of the granite in the Zhukeng tungsten deposit

(a) C1 Chondrite-normalized REE distribution pattern; (b) Primitive mantle-normalized trace element spidergram

中细粒二云母花岗岩稀土元素总量(ΣREE)介于 106.86×10<sup>-6</sup>~124.24×10<sup>-6</sup>, 平均值为 116.07×10<sup>-6</sup>, La<sub>N</sub>/Yb<sub>N</sub> 比值为 1.08~1.63, 平均值为 1.34, LREE/HREE 比值为 1.77~2.42, 总体显有明显负铕异常; 在微量元素初始地幔标准化蛛网图上, 中细粒二云母花岗岩表现出富集 Rb、Ta、Pb、Nd、Hf, 亏损 Ba、Nb、

Sr 和 Ti(图 7b)。

云英岩稀土元素总量(ΣREE)介于 132.41×10<sup>-6</sup>~168.48×10<sup>-6</sup>, 平均值为 149.08×10<sup>-6</sup>, La<sub>N</sub>/Yb<sub>N</sub> 比值为 0.97~8.32, 平均值为 3.70, LREE/HREE 比值为 1.88~4.93, 总体显示轻稀土富集, 其稀土配分曲线呈右倾(图 7a), δEu 值为 0.04~0.07, 平均值为 0.05, 具有明

显负锫异常;在微量元素初始地幔标准化蛛网图上,云英岩表现出富集 Rb、Ta、Pb、Nd、Hf,亏损 Ba、Nb、Sr 和 Ti(图 7b)。

## 4 讨论

### 4.1 岩体的形成时代

中生代以来,赣南地区受滨西太平洋构造域动力作用的影响,岩浆活动频繁。区域内出露众多花岗岩体(燕山期约占总数 70%),与钨锡多金属矿床关系密切。野外观察,中细粒二云母花岗岩与细粒白云母花岗岩无明显侵入关系,细粒白云母为二云母花岗岩渐变演化而来。此次研究对珠坑岩体中的细粒白云母花岗岩和中细粒二云母花岗岩中的独居石开展 U-Pb 同位素定年,细粒白云母花岗岩和中细粒二云母花岗岩<sup>206</sup>Pb/<sup>238</sup>U 加权平均年龄分别为 156.7±1.3 Ma 和 159.5±0.9 Ma,表明岩体主要形成于晚侏罗世时期,与区域上多个大型钨锡矿成矿有关花岗岩体成岩年龄相近,如九龙脑岩体成岩年龄在 157.7±2.7 Ma(郭春丽等, 2011; Guo et al., 2018)、梅树坪岩体成岩年龄在 157.2±1.7 Ma(王浩洋等, 2017)、红桃岭成岩年龄在 151.4±3.1 Ma(丰成友等, 2007)、淘锡坑岩体成岩年龄在 155.0±1.4 Ma(郭春丽等, 2008)、天门山成岩年龄在 157.2±2.2 Ma(Feng et al., 2011; Chen et al., 2021);西华山成岩年龄在 154.8±6.0 Ma(Guo et al., 2012; 郭小飞等, 2022)等。此外,珠坑岩体地球化学参数与南岭花岗岩含钨花岗岩特征较为相似,具有铝过饱和,贫 Ba+Sr 和 TiO<sub>2</sub>,轻重稀土比值低,强负 Eu 异常,富集 Y 和 Rb, Rb/Sr 比值较高和高分异特征(陈骏等, 2008),具有较好的钨矿找矿潜力。

### 4.2 岩体成因类型

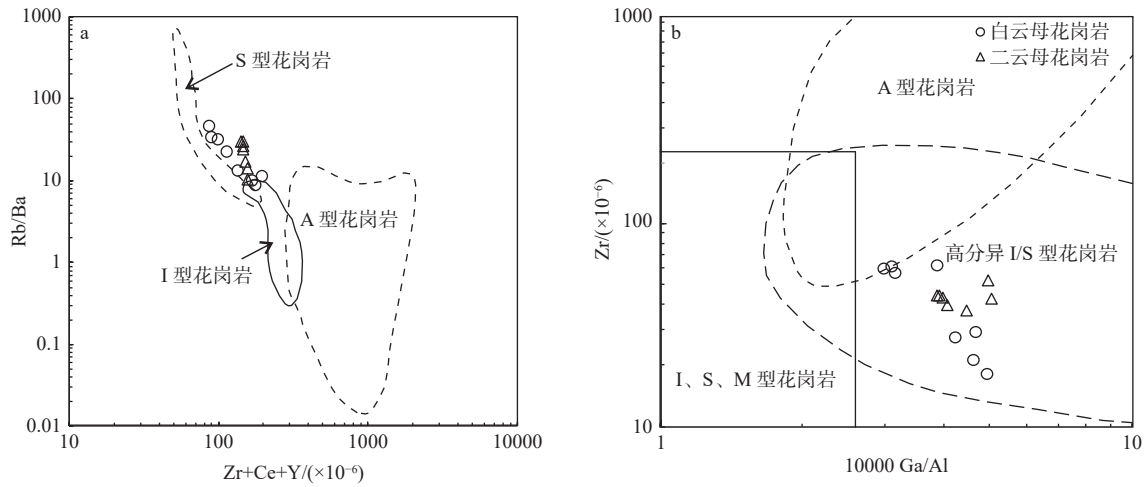
MISA 是常见的花岗岩成因分类(Chappell, 1999; 吴福元等, 2007),M 型花岗岩以铝不饱和(A/CNK<1.1)和高钠钾比值(Na<sub>2</sub>O/K<sub>2</sub>O>1)为特征,显著富集 Cr、Co、Ni、V 等过渡金属元素;I 型花岗岩多数由火成岩熔融形成,为活动大陆边缘产物 Na<sub>2</sub>O/K<sub>2</sub>O>1 且铝饱和指数<1.1,出现角闪石、磁铁矿等矿物(薛吉祥等, 2020);S 型花岗岩多由造山碰撞壳源沉积物部分熔融形成,通常铝饱和指数>1.1,出现白云母、堇青石、石榴子石等矿物;A 型花岗岩主要形成于非造山环境,主要来源于下地壳火成岩,具有富碱和无水特征(吴福元等, 2007)。

细粒白云母花岗岩其主量元素具有 SiO<sub>2</sub> 含量

较高, SiO<sub>2</sub> 含量在 65.54%~74.95% 之间(平均值为 70.7%),全岩碱含量 Na<sub>2</sub>O+K<sub>2</sub>O 含量在 8.48%~12.85% 之间(平均值为 10.3%), Na<sub>2</sub>O/K<sub>2</sub>O 比值为 0.39~2.82(平均值为 1.19),具有明显的富钠特征,铝饱和指数 A/CNK 介于 1.10~1.22,属于高钾钙碱性系列花岗岩;中细粒二云母花岗岩具有典型的富硅、富碱特征, SiO<sub>2</sub> 含量在 75.02%~77.03% 之间(平均值为 75.79%), Na<sub>2</sub>O+K<sub>2</sub>O 含量在 5.92~8.58% 之间(平均值在 7.86%), Na<sub>2</sub>O/K<sub>2</sub>O 比值为 0.09~1.06,平均值为 0.80,具有明显的富钾特征, Al<sub>2</sub>O<sub>3</sub> 含量在 12.32~14.09% 之间(平均值为 13.51%),铝饱和指数 A/CNK 介于 1.14~1.65,总体来看珠坑花岗岩具有高硅(w(SiO<sub>2</sub>)>70%)、富铝(A/CNK>1.1)。通常 S 型花岗岩绝大多数贫 Sr(<300×10<sup>-6</sup>), Yb 含量多数在 1×10<sup>-6</sup>~7×10<sup>-6</sup> 之间(张旗等, 2006),珠坑花岗岩 Sr 含量在 8.38×10<sup>-6</sup>~28.8×10<sup>-6</sup> 之间(平均值为 15.53×10<sup>-6</sup>); Yb 含量在 1.28×10<sup>-6</sup>~8.86×10<sup>-6</sup> 之间(平均值为 5.66×10<sup>-6</sup>)与 S 型花岗岩特征相近, A/CNK 值>1.1,珠坑花岗岩分异指数(DI)较高,其范围为 89.46~96.36,表明该岩体可能经历了明显的结晶分异作用。在 Zr+Ce+Y-Rb/Ba 图解上(图 8a),投点均靠近 S 型花岗岩区,初步认定珠坑花岗岩可能为 S 型花岗岩;在 10000Ga/Al-Zr 图解上,投点均落入高分异花岗岩区(图 8b),珠坑花岗岩显示出富硅、富碱,富集 Rb、Th、Pb 强烈亏损 Ba、Sr、P 和 Ti 和明显四分组效应,具有高分异花岗岩特征;此外,典型高分异 S 型花岗岩通常含有白云母、黄玉和电气石等矿物,珠坑花岗岩在标本和镜下可见白云母和黄玉;综合矿物学和岩石地球化学特征,珠坑花岗岩应属于高分异 S 型花岗岩。

### 4.3 地球动力学背景

华南中生代花岗岩主要由地壳物质的部分熔融形成,幔源物质参与较少,并且印支-燕山期大规模岩浆侵位发生在挤压-伸展转换的后碰撞阶段的拉张环境,具有多旋回幕式脉动侵位特征(谭俊等, 2007; 王莉娟等, 2013; 党飞鹏等, 2023)。有关华南中生代构造框架研究表明,中生代以来,印支、华北和华南板块的碰撞引发大规模的构造运动和岩浆活动,并伴随大规模成矿作用发生(毛景文等, 1999; 刘珺等, 2008; Hu and Zhou, 2012; Mao et al., 2013; Wang et al., 2021)。华南地区构造碰撞主要发生在 240~220 Ma, W-Sn-Nb-Ta 成矿作用与后碰撞花岗岩关系密切,其成矿时代主要集中在 214~239



a—(Zr+Ce+Y)-(Rb/Ba) 图解; b—10000Ga/Al-Zr 图解

图8 珠坑钨矿花岗岩岩石类型判别图 (Whalen et al., 1989)

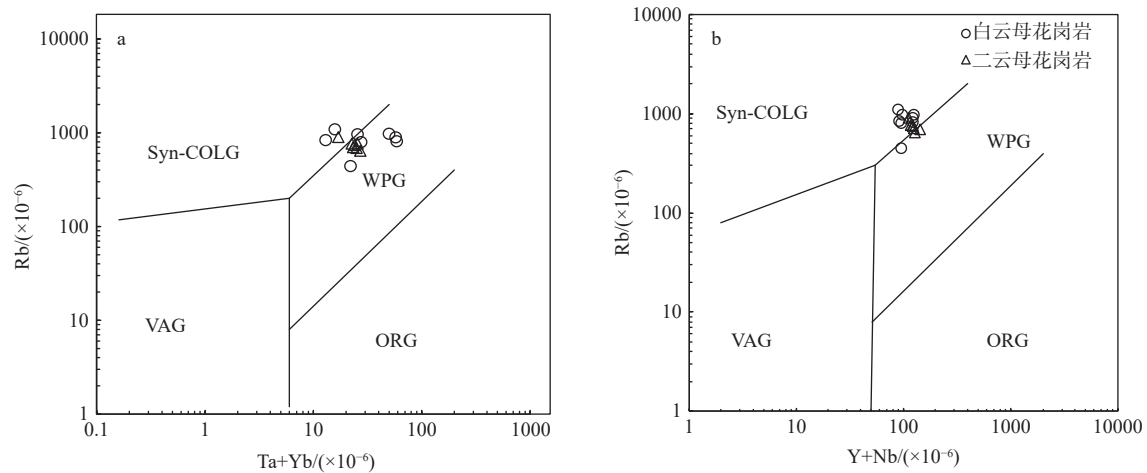
Fig. 8 Rock-type discrimination diagrams for the Zhukeng tungsten deposit (Whalen et al., 1989)

(a) (Zr+Ce+Y)-(Rb/Ba) diagram; (b) 10000×Ga/Al-Zr diagram

Ma(毛景文等, 2008); 在早侏罗世 205~180 Ma 进入调整期, 岩浆活动和成矿作用相对较弱 (Zhou et al., 2006)。

在侏罗世晚期(180 Ma 左右), 中国东部大陆边缘受伊泽奈奇板块向北西俯冲作用影响, 逐渐成为活动大陆边缘, 在俯冲过程中板片熔融形成埃达克质岩浆, 并伴随大量斑岩-矽卡岩铜多金属矿成矿作用, 其成矿时间集中在 170~160 Ma。晚侏罗世(160~150 Ma)期间, 随着持续俯冲造山作用, 在弧后地区形成一系列北东向岩石圈伸展带和深大断

裂, 同期南岭地区发生大规模中酸性岩浆作用, 钨锡多金属成矿作用进入高峰(毛景文等, 2008; Sun et al., 2012; 王浩洋等, 2017)。珠坑花岗岩侵入时代为晚侏罗世(156~159 Ma), 此时华南处于俯冲造山阶段, 在微量元素 (Ta+Yb)-Rb 图解中(图 9a), 珠坑花岗岩投点主要落在碰撞花岗岩与板内花岗岩分界区域; 在全岩微量元素 (Y+Nb)-Rb 图解中(图 9b), 多数样品分布在碰撞花岗岩与板内花岗岩环境的分界偏同碰撞花岗岩处, 表明珠坑岩体主要形成于俯冲背景下挤压碰撞环境。



WPG—板内花岗岩; VAG—火山弧花岗岩; ORG—洋脊花岗岩; Syn-COLG—同碰撞花岗岩

a—(Ta+Yb)-Rb 构造环境判别图解; b—(Y+Nb)-Rb 构造环境判别图解

图9 (Ta+Yb)-Rb 和 (Y+Nb)-Rb 构造环境判别图解 (Pearce, 1996)

Fig. 9 (Ta+Yb)-Rb and (Y+Nb)-Rb tectonic discrimination diagrams for the Zhukeng granites (Pearce, 1996)

(a) (Ta+Yb)-Rb tectonic discrimination diagram; (b) (Y+Nb)-Rb tectonic discrimination diagram

## 5 结论

(1) 珠坑花岗岩体 LA-ICP-MS U-Pb 测年显示, 细粒白云母花岗岩中独居石加权年龄为  $156.7 \pm 1.3$  Ma, 中细粒二云母花岗岩中独居石加权年龄为  $159.5 \pm 0.9$  Ma, 表明珠坑岩体侵入时代为晚侏罗世。

(2) 珠坑花岗岩体具有富硅、富碱、富铝、贫钛、贫镁特征, 强负 Eu 异常, 富集大离子亲石元素 Rb、Th、U、Pb、Nd、Hf, 显著亏损 Ba、Sr、P、Ti、Nb, 属于高分异 S 型花岗岩, 其地球化学参数与南岭含钨花岗岩特征较为相似, 具有较好的钨矿找矿潜力。**致谢:** 实验测试得到东华理工大学核资源与环境国家重点实验室万卫、吉鸿杰和钟福军的指导和建设; 两位匿名审稿人对文章提出了建设性修改意见, 在此一并表示感谢!

## References

- BUDZYŃ B, SLÁMA J, CORFU F, et al., 2021. TS-Mnz-A new monazite age reference material for U-Th-Pb microanalysis[J]. *Chemical Geology*, 572: 120195.
- CHAPPELL B W, 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites[J]. *Lithos*, 46(3): 535-551.
- CHEN J, LU J J, CHEN W F, et al., 2008. W-Sn-Nb-Ta-bearing granites in the Nanling range and their relationship to metallogenesis[J]. *Geological Journal of China Universities*, 14(4): 459-473. (in Chinese with English abstract)
- CHEN Y C, CHEN Z H, ZENG Z L, et al., 2013. Research on the site selection of Nanling scientific drilling-1[J]. *Geology in China*, 40(3): 659-670. (in Chinese with English abstract).
- CHEN Y J, CHEN B, DUAN X X, et al., 2021. Origin of highly fractionated peraluminous granites in South China: implications for crustal anatexis and evolution[J]. *Lithos*, 402-403: 106145.
- DAI H T, ZHANG Y, PAN J Y, et al., 2023. Characteristics and geological significance of muscovite in Zhukeng tungsten deposit, southern Jiangxi province[J]. *Journal of East China University of Technology (Natural Science)*, 46(5): 472-485. (in Chinese with English abstract).
- DANG F P, LYU C, TANG X S, et al., 2023. Geochronology and petrogeochemical characteristics of U-bearing granites in the Dongshang deposit, northwestern Jiangxi, China and its geological significance[J]. *Journal of Geomechanics*, 29(6): 898-914. (in Chinese with English abstract)
- FENG C Y, XU J X, ZENG Z L, et al., 2007. Zircon SHRIMP U-Pb and molybdenite Re-Os dating in Tianmenshan—Hongtaoling tungsten-tin Orefield, southern Jiangxi Province, China, and its geological implication[J]. *Acta Geologica Sinica*, 81(7): 952-963. (in Chinese with English abstract)
- FENG C Y, ZENG Z L, ZHANG D Q, et al., 2011. SHRIMP zircon U-Pb and molybdenite Re-Os isotopic dating of the tungsten deposits in the Tianmenshan-Hongtaoling W-Sn orefield, southern Jiangxi Province, China, and geological implications[J]. *Ore Geology Reviews*, 43(1): 8-25.
- GONÇALVES G O, LANA C, SCHOLZ R, et al., 2016. An assessment of monazite from the Itambé pegmatite district for use as U-Pb isotope reference material for microanalysis and implications for the origin of the “Moacyr” monazite[J]. *Chemical Geology*, 424: 30-50.
- GUO C L, LIN Z Y, WANG D H, et al., 2008. Petrologic characteristics of the granites and greisens and muscovite  $^{40}\text{Ar}/^{39}\text{Ar}$  dating in the Taoxikeng tungsten polymetallic deposit, Southern Jiangxi Province[J]. *Acta Geologica Sinica*, 82(9): 1274-1284. (in Chinese with English abstract)
- GUO C L, CHEN Y C, LI C B, et al., 2011. Zircon SHRIMP U-Pb dating, geochemistry, Sr-Nd isotopic analysis of the late Jurassic granitoids in the Jiulongnao W-Sn-Pb-Zn ore-concentrated areas in Jiangxi Province and their geological significance[J]. *Acta Geologica Sinica*, 85(7): 1188-1205. (in Chinese with English abstract)
- GUO C L, CHEN Y C, ZENG Z L, et al., 2012. Petrogenesis of the Xihuashan granites in southeastern China: constraints from geochemistry and in-situ analyses of zircon U-Pb-Hf-O isotopes[J]. *Lithos*, 148: 209-227.
- GUO N X, ZHAO Z, GAO J F, et al., 2018. Magmatic evolution and W-Sn-U-Nb-Ta mineralization of the Mesozoic Jiulongnao granitic complex, Nanling Range, South China[J]. *Ore Geology Reviews*, 94: 414-434.
- GUO X F, WANG Q L, JING Y H, et al., 2022. Zircon U-Pb geochronology and Hf isotope characteristics of the Xihuashan granites in southern Jiangxi Province and their geological significance[J]. *Geology and Exploration*, 58(3): 585-596. (in Chinese with English abstract)
- GUO Z Q, QIN J H, WANG D H, et al., 2024. Geochronology and geochemical characteristics of magmatic rocks and their relationship with mineralization in Taoxiba deposit, southern Jiangxi Province[J]. *Mineral Deposits*, 43(3): 655-687. (in Chinese with English abstract)
- HU R Z, ZHOU M F, 2012. Multiple Mesozoic mineralization events in South China: an introduction to the thematic issue[J]. *Mineralium Deposita*, 47(6): 579-588.
- HUA R M, CHEN P R, ZHANG W L, et al., 2005. Three major metallogenic events in Mesozoic in South China[J]. *Mineral Deposits*, 24(2): 99-107. (in Chinese with English abstract)
- IRVINE T N, BARAGAR W R A, 1971. A Guide to the Chemical Classification of the Common Volcanic Rocks[J]. *Canadian Journal of Earth Sciences*, 8(5): 523-548.
- LI W, LIU C H, TAN Y, et al., 2021. Zircon U-Pb age, petro-geochemical and mineralization characteristics of Keshuling granites in southern Jiangxi Province[J]. *Geological Review*, 67(5): 1309-1320. (in Chinese with English abstract)
- LI W, TANG J X, LU J, et al., 2024. Geochemical characteristics, U-Pb age and Hf isotope of zircons from granite porphyry in Tieshanlong tungsten ore field, southern Jiangxi Province[J]. *Geological Review*, 70(1): 175-188. (in Chinese with English abstract)
- LIU J, MAO J W, YE H S, et al., 2008. Zircon LA-ICPMS U-Pb dating of Hukeng granite in Wugongshan area, Jiangxi Province and its geochemical characteristics[J]. *Acta Petrologica Sinica*, 24(8): 1813-1822. (in

- Chinese with English abstract)
- LIU X X, ZHANG J, HUANG F, et al., 2022. Tungsten deposits in southern Jiangxi Province: constraints on the origin of wolframite from in-situ U-Pb isotope dating[J]. *Ore Geology Reviews*, 143: 104774.
- LIU Y S, HU Z C, GAO S, et al., 2008. *In situ* analysis of major and trace elements of anhydrous minerals by LA-ICP-MS without applying an internal standard[J]. *Chemical Geology*, 257(1-2): 34-43.
- LIU Y S, GAO S, HU Z C, et al., 2010. Continental and oceanic crust recycling-induced melt-peridotite interactions in the Trans-North China Orogen: U-Pb Dating, Hf isotopes and trace elements in zircons from mantle xenoliths[J]. *Journal of Petrology*, 51(1-2): 537-571.
- MANIAR P D, PICCOLI P M, 1989. Tectonic discrimination of granitoids[J]. *GSA Bulletin*, 101(5): 635-643.
- MAO J W, HUA R M, LI X B, 1999. A preliminary study of large-scale metallogenesis and large clusters of mineral deposits[J]. *Mineral Deposits*, 18(4): 291-299. (in Chinese with English abstract)
- MAO J W, XIE G Q, GUO C L, et al., 2008. Spatial-temporal distribution of Mesozoic ore deposits in South China and their metallogenic settings[J]. *Geological Journal of China Universities*, 14(4): 510-526. (in Chinese with English abstract)
- MAO J W, CHENG Y B, CHEN M H, et al., 2013. Major types and time-space distribution of Mesozoic ore deposits in South China and their geodynamic settings[J]. *Mineralium Deposita*, 48(3): 267-294.
- MIDDLEMOST E A K, 1994. Naming materials in the magma/igneous rock system[J]. *Earth-Science Reviews*, 37(3-4): 215-224.
- NI P, PAN J Y, HAN L, et al., 2023. Tungsten and tin deposits in South China: temporal and spatial distribution, metallogenic models and prospecting directions[J]. *Ore Geology Reviews*, 157: 105453.
- PEARCE J, 1996. Sources and settings of granitic rocks[J]. *Episodes*, 19(4): 120-125.
- SUN S S, MCDONOUGH W F, 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes[M]//SAUNDERS A D, NORRY M J, eds. *Magmatism in the ocean basins*. London: Geological Society, London, Special Publications: 42(1): 313-345.
- SUN W D, YANG X Y, FAN W M, et al., 2012. Mesozoic large scale magmatism and mineralization in South China: preface[J]. *Lithos*, 150: 1-5.
- TAN J, WEI J H, LI Y J, et al., 2007. Some reviews on diagenesis and metallogeny of the Mesozoic crustal remelting granitoids in the Nanling region[J]. *Geological Review*, 53(3): 349-362. (in Chinese with English abstract)
- WANG D H, CHEN Y C, CHEN Z H, et al., 2007. Assessment on mineral resource in Nanling region and suggestion for further prospecting[J]. *Acta Geologica Sinica*, 81(7): 882-890. (in Chinese with English abstract)
- WANG H Y, ZHAO Z, CHEN W, et al., 2017. Geological characteristics, rock and ore forming age and prospecting of Meishuping tungsten-molybdenum deposit in Jiangxi[J]. *Earth Science Frontiers*, 24(5): 109-119. (in Chinese with English abstract)
- WANG L J, WANG J B, WANG Y W, et al., 2013. Geological characteristics of host granite intrusions of the W-Sn-Nb-Ta deposit, Nanling area, China[J]. *Mineral Exploration*, 4(6): 598-608. (in Chinese with English abstract)
- WANG R C, NI P, WANG X L, 2021. Mesozoic magmatism and mineralization in Southeastern China: an introduction[J]. *Journal of Asian Earth Sciences*, 219: 104921.
- WU F Y, LI X H, YANG J H, et al., 2007. Discussions on the petrogenesis of granites[J]. *Acta Petrologica Sinica*, 23(6): 1217-1238. (in Chinese with English abstract)
- XU Z, ZHANG Y, PAN J Y, et al., 2023. Petrogeochemical and geochronological characteristics of Hailuoling granite-type niobium-tantalum deposit in Shicheng, Jiangxi Province and its geological significance[J]. *Acta Geologica Sinica*, 97(6): 1874-1899. (in Chinese with English abstract)
- XUE J X, LIU Z H, LIU J X, et al., 2020. Geochemistry, geochronology, Hf isotope and tectonic significance of late Jurassic Huangdi Pluton in Xiuyan, Liaodong Peninsula[J]. *Earth Science*, 45(6): 2030-2043. (in Chinese with English abstract)
- ZHANG Q, WANG Y, LI C D, et al., 2006. Granite classification on the basis of Sr and Yb contents and its implications[J]. *Acta Petrologica Sinica*, 22(9): 2249-2269. (in Chinese with English abstract)
- ZHANG Y, PAN J Y, MA D S, 2020. Lithium element enrichment and inspiration for prospecting for rare-metal mineralization in the Dahutang tungsten deposit: constraints from mineralogy and geochemistry of hydrothermal alteration[J]. *Acta Geologica Sinica*, 94(11): 3321-3342. (in Chinese with English abstract)
- ZHAO Z, WANG D H, CHEN Y C, et al., 2017. Jiulongnao metallogenic model" and the demonstration of deep prospecting: the extended application of "Five levels+Basement" [J]. *exploration mode*. *Earth Science Frontiers*, 24(5): 08-16. (in Chinese with English abstract)
- ZHOU X M, SUN T, SHEN W Z, et al., 2006. Petrogenesis of Mesozoic granitoids and volcanic rocks in South China: a response to tectonic evolution[J]. *Episodes*, 29(1): 26-33.
- ZHU J J, ZHANG L, DANG F P, et al., 2024. The genesis of intersection-type uranium deposits in south China: insights from zircon and pitchblende U-Pb geochronology and pyrite sulfur isotopes of the Egongtang uranium deposit, southern Jiangxi[J]. *Applied Geochemistry*, 175: 106178.

## 附中文参考文献

- 陈骏, 陆建军, 陈卫锋, 等, 2008. 南岭地区钨锡铌钽花岗岩及其成矿作用[J]. *高校地质学报*, 14(4): 459-473.
- 陈毓川, 陈郑辉, 曾载淋, 等, 2013. 南岭科学钻探第一孔选址研究[J]. *中国地质*, 40(3): 659-670.
- 戴浩樞, 张勇, 潘家永, 等, 2023. 赣南珠坑钨矿白云母矿物特征及其地质意义[J]. *东华理工大学学报(自然科学版)*, 46(5): 472-485.
- 党飞鹏, 吕川, 唐湘生, 等, 2023. 赣西北洞上铀矿床产铀花岗岩的时代、岩石地球化学特征及其地质意义[J]. *地质力学学报*, 29(6): 898-914.
- 丰成友, 许建祥, 曾载淋, 等, 2007. 赣南天门山-红桃岭钨锡矿田成矿时代精细测定及其地质意义[J]. *地质学报*, 81(7): 952-963.
- 郭春丽, 蒯志永, 王登红, 等, 2008. 赣南淘锡坑钨多金属矿床花岗岩和云英岩岩石特征及云英岩中白云母<sup>40</sup>Ar/<sup>39</sup>Ar定年[J]. *地质*

- 学报, 82(9): 1274-1284.
- 郭春丽, 陈毓川, 黎传标, 等, 2011. 赣南晚侏罗世九龙脑钨锡铅锌矿集区不同成矿类型花岗岩年龄、地球化学特征对比及其地质意义[J]. 地质学报, 85(7): 1188-1205.
- 郭小飞, 王庆龙, 荆一洪, 等, 2022. 赣南西华山成矿花岗岩锆石 U-Pb 年代学和 Hf 同位素特征及其地质意义[J]. 地质与勘探, 58(3): 585-596.
- 郭志强, 秦锦华, 王登红, 等, 2024. 赣南淘锡坝矿床岩浆岩年代学、地球化学特征及其与成矿关系[J]. 矿床地质, 43(3): 655-687.
- 华仁民, 陈培荣, 张文兰, 等, 2005. 论华南地区中生代 3 次大规模成矿作用[J]. 矿床地质, 24(2): 99-107.
- 李伟, 刘翠辉, 谭友, 等, 2021. 赣南柯树岭岩体锆石 U-Pb 年龄、岩石地球化学及成矿作用特征[J]. 地质论评, 67(5): 1309-1320.
- 李伟, 唐菊兴, 鲁捷, 等, 2024. 赣南铁山垅钨矿田花岗岩斑岩地球化学特征、锆石 U-Pb 年龄及 Hf 同位素特征[J]. 地质论评, 70(1): 175-188.
- 刘珺, 毛景文, 叶会寿, 等, 2008. 江西省武功山地区浒坑花岗岩的锆石 U-Pb 定年及元素地球化学特征[J]. 岩石学报, 24(8): 1813-1822.
- 毛景文, 华仁民, 李晓波, 1999. 浅议大规模成矿作用与大型矿集区[J]. 矿床地质, 18(4): 291-299.
- 毛景文, 谢桂青, 郭春丽, 等, 2008. 华南地区中生代主要金属矿床时空分布规律和成矿环境[J]. 高校地质学报, 14(4): 510-526.
- 谭俊, 魏俊浩, 李艳军, 等, 2007. 南岭中生代陆壳重熔型花岗岩类成岩成矿的有关问题[J]. 地质论评, 53(3): 349-362.
- 王登红, 陈毓川, 陈郑辉, 等, 2007. 南岭地区矿产资源形势分析和找矿方向研究[J]. 地质学报, 81(7): 882-890.
- 王浩洋, 赵正, 陈伟, 等, 2017. 江西梅树坪钨钼矿床地质、成岩成矿时代与找矿方向[J]. 地学前缘, 24(5): 109-119.
- 王莉娟, 王京彬, 王玉往, 等, 2013. 我国南岭地区钨锡铌钽矿床成矿花岗岩主要地质特征[J]. 矿产勘查, 4(6): 598-608.
- 吴福元, 李献华, 杨进辉, 等, 2007. 花岗岩成因研究的若干问题[J]. 岩石学报, 23(6): 1217-1238.
- 徐喆, 张勇, 潘家永, 等, 2023. 江西石城海罗岭花岗岩型钨钼矿床岩石地球化学、年代学特征及其地质意义[J]. 地质学报, 97(6): 1874-1899.
- 薛吉祥, 刘正宏, 刘杰勋, 等, 2020. 辽东岫岩晚侏罗世荒地岩体的地球化学、年代学与 Hf 同位素及构造意义[J]. 地球科学, 45(6): 2030-2043.
- 赵正, 王登红, 陈毓川, 等, 2017. “九龙脑成矿模式”及其深部找矿示范: “五层楼+地下室”勘查模型的拓展[J]. 地学前缘, 24(5): 8-16.
- 张旗, 王焰, 李承东, 等, 2006. 花岗岩的 Sr-Yb 分类及其地质意义[J]. 岩石学报, 22(9): 2249-2269.