

江西金鸡窝铜矿床花岗闪长斑岩黑云母矿物学特征及其对岩石成因与成矿的指示

杜后发^{1,2}, 赖天功^{1,3}, 江媛媛⁴, 范鹏飞⁵, 龚维强⁶

(1. 核资源与环境省部共建国家重点实验室培育基地 东华理工大学, 江西 南昌 330013; 2. 中国地质大学 地球科学学院, 湖北 武汉 430074; 3. 核工业 240 研究所, 辽宁 沈阳 110032; 4. 核工业地质局 267 大队, 江西 九江 332000; 5. 核工业 230 研究所, 湖南 长沙 410011; 6. 江西铜业集团公司城门山铜矿, 江西 九江 332114)

摘要: 通过对金鸡窝铜矿区花岗闪长斑岩进行详细的岩相学研究和黑云母成分的电子探针原位分析, 厘定了黑云母形成的物理化学条件, 并探讨了其成岩成矿意义。电子探针研究显示: 花岗闪长斑岩中黑云母的 Ti 为 0.44~0.47 apfu, Mg/(Mg+Fe) 比值范围为 0.58~0.62, 结合其化学成分在 10 TiO₂-FeO*-MgO 图解和 Mg-(Fe²⁺+Mn)-(Al^{VI}+Fe³⁺+Ti) 图解中的投影, 认为该岩体中黑云母具有富镁贫铁特征, 属于原生黑云母。黑云母氧化系数 (f_O) 范围为 0.31~0.67, MF 值范围为 0.38~0.41, MgO 含量为 13.27%~14.28%, K₂O 为 3.59%~8.93%, Na₂O 为 0.26%~3.28%, FeO 为 15.74%~17.30%, TiO₂ 为 3.93%~4.19%, Al₂O₃ 为 13.52%~14.19%, 单位分子中阳离子数 Al^{IV} 为 2.00~2.24 apfu, Al^{VI} 为 0.15~0.41 apfu, 指示其岩体属于高钾质钙碱性系列的同熔型(或 I 型)花岗岩, 具有壳幔混源成因的特征。黑云母结晶温度为 734~748℃, 结晶压力为 71~89 MPa, 相当于深度 2.7~3.3 km, 平均深度为 3.0 km。黑云母化学成分投点主要落在 Fe₂O₃-Fe₃O₄ 缓冲线之上, 表明其形成于高氧逸度环境, 且有利于铜矿的形成。

关键词: 花岗闪长斑岩; 黑云母地球化学; 氧逸度; 成岩成矿作用; 壳幔混合

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Mineral chemistry of biotites from the granodiorite porphyry around the Jinjiwo copper deposit in the Jiurui ore district: Implications for petrogenesis and mineralization

DU Hou-fa^{1,2}, LAI Tian-gong^{1,3}, JIANG Yuan-yuan⁴, FAN Peng-fei⁵ and GONG Wei-qiang⁶

(1. State Key Laboratory Breeding Base of Nuclear Resources and Environment, East China Institute of Technology, Nanchang 330013, China; 2. Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China; 3. No. 240 Research Institute, CNNC, Shengyang 110032, China; 4. No. 267 Geological Party, Bureau of Geology, Jiujiang 332000, China; 5. No. 230 Research Institute, CNNC, Changsha 410011, China; 6. Chengmenshan Copper Mine of Jiangxi Copper Corporation, Jiujiang 332114, China)

Abstract: Based on detailed petrographical and mineralogical compositional features of biotite from the granodiorite porphyry around the Jinjiwo deposit in the Jiurui ore district, the authors not only established the physico-chemical conditions of the mineral formation but also explored its significance for rock and ore formation. Major element composition of the biotite phenocrysts of the samples was measured by the electron probe micro-analyzer

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作者简介: 杜后发(1982-), 男, 讲师, 博士生, 从事岩石学教学与科研工作, E-mail: dhf915@126.com。

(EPMA). The Ti content and the $\text{Mg}/(\text{Mg} + \text{Fe})$ ratios of the biotite from the Jinjiwo granodiorite porphyry are $0.44 \sim 0.47$ apfu (atoms per formula unit) and $0.58 \sim 0.62$, respectively, and the compositions of these biotite are plotted in both the domain of the primary magmatic biotite and that of the Mg-rich biotite. These features suggest that the biotite phenocrysts of the samples are all eastonite, and that these analyzed biotites display the Mg-rich and Fe-poor characteristics. The oxidation coefficient and the MF values of biotites are $0.31 \sim 0.67$ and $0.38 \sim 0.41$, respectively. Biotite has $13.27\% \sim 14.28\%$ MgO, $3.59\% \sim 8.93\%$ K_2O , $0.26\% \sim 3.28\%$ Na_2O , $15.74\% \sim 17.30\%$ FeO, $3.93\% \sim 4.19\%$ TiO_2 , and $13.52\% \sim 14.19\%$ Al_2O_3 , respectively. It contains about $2.00 \sim 2.24$ apfu of tetrahedral Al^{IV} and $0.15 \sim 0.41$ apfu of octahedral Al^{VI} . The TAl content of biotite can be used to figure out the solidification pressure of the granitoid. Considering the composition of biotites together with experimental results of the former research, which falls on or above $\text{Fe}_2\text{O}_3 - \text{Fe}_3\text{O}_4$ buffer in the $\text{Fe}^{3+} - \text{Fe}^{2+} - \text{Mg}$ diagram, the authors consider that the biotites from granodiorite porphyry in the study region were crystallized under the condition of temperatures $734 \sim 748^\circ\text{C}$ and pressures $71 \sim 89$ MPa, corresponding to solidification depth $2.7 \sim 3.3$ km. The above characteristics suggest that the Jinjiwo granodiorite porphyry belongs to high potassium Ca-alkaline series, showing the typical syntexis type (or I-type) granitoid derived from a crust-mantle mixing source, and that the pluton was formed in a relatively high oxygen fugacity environment, which was beneficial to copper mineralization.

Key words: granodiorite porphyry; geochemistry of biotite; oxygen fugacity; petrogenesis and mineralization; crust-mantle interaction

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九瑞矿集区是长江中下游铁铜金钼硫多金属成矿带的一个重要组成部分,区内金属矿产资源丰富,以铁、铜、金和钼为主,伴生铅、锌、银等矿种,是全国 47 个整装勘查区之一 (Yang *et al.*, 2011; 王会敏等, 2012; 蒋少涌等, 2013; 李旭辉等, 2014; Xu *et al.*, 2015)。九瑞矿集区经历了多期构造活动,形成了基底 NWW + NE 和盖层 NEE + NW 向构造岩浆带,制约着由北西至南东依次出露的邓家山、东雷湾、宝山、武山、丁家山和城门山等浅成-超浅成中酸性岩体的分布格局 (翟裕生等, 1992; 崔彬, 1995; Mao *et al.*, 2011; 蒋少涌等, 2013; Xu *et al.*, 2015)。前人对上述 6 个与铜金成矿作用密切相关的花岗质岩体开展了详细的锆石 LA-ICP-MS U-Pb 定年分析,显示含矿岩体的年龄相对集中,分布范围为 138.2 ± 1.8 Ma $\sim$ 148.0 ± 1.0 Ma (李亮等, 2009; Li *et al.*, 2010; 陈志洪等, 2011; Yang *et al.*, 2011; 徐耀明等, 2013); 而九瑞地区与岩体相关的成矿作用年龄仅有城门山铜钼矿、武山铜矿南矿带和宝山铜矿的辉钼矿 Re-Os 等时线年龄,介于 140 ± 2.0 Ma $\sim$ 147.7 ± 1.2 Ma (吴良士等, 1997; 李进文等, 2007; 贾丽琼等, 2015), 反映了九瑞矿集区晚中

生成成岩-成矿的时代基本相近,说明岩体的形成和矿床的矿化均发生于晚侏罗世时期。陈志洪等 (2011) 认为该期大规模岩浆-成矿作用与华南中生代构造体制转折结束后,受区域性伸展导致大规模成岩成矿的地球动力学环境制约。

金鸡窝铜矿区位于九瑞矿集区的南东端城门山大型铜硫矿床边缘及深部。研究区出露的多个岩体是城门山矿区花岗闪长斑岩岩株的东延部分 (图 1), 为燕山期浅成-超浅成相多次侵入构成的中酸性杂岩体,向北西倾伏,侵入于志留系至部分三叠系碎屑岩、碳酸盐岩地层中,受破碎带和断裂构造控制,总体走向呈 NEE、NE 向 (李旭辉, 1997; Pan and Dong, 1999; 毛景文等, 2009; Yang *et al.*, 2011; Zhou *et al.*, 2015), 形成了向东突出的半环形接触带。前人对该岩体开展了地质学、岩石学、地质年代学、岩石地球化学等研究工作 (吴良士, 1998; 毛景文等, 2004; Li *et al.*, 2010; 徐耀明等, 2013; Zhou *et al.*, 2015), 结果表明其形成于华南和华北板块碰撞阶段,且燕山早期第 3 阶段岩浆侵入活动最为发育,为九瑞地区岩浆活动的高峰期,岩石类型以中酸性岩为主,是来自下地壳、上地幔同熔作用的产物;

城门山矿区主岩体属顶蚀侵位岩体,而金鸡窝矿区岩体属于岩浆被动侵位,多呈板状或分枝状。然而,该岩体形成的温度、压力和氧逸度等物化条件尚缺详细的研究,制约了对岩浆物理性质和岩体侵位过程的理解;而花岗质岩石中黑云母的化学成分对热液流体敏感,且受寄主岩浆冷却结晶时的物化条件(f_{O_2} 、 T 、 p 等)控制(Munoz, 1992; Abdelrahman, 1994; Siahcheshm *et al.*, 2011),因此可提供寄主岩浆的性质、岩石成因、成岩物化条件等重要信息,亦可作为成矿岩体的判别标志(Abelrahman, 1994; 吕志成等, 2003; 楼亚儿等, 2006; 东前等, 2011; 徐耀明等, 2013),这些对认识岩石的形成与演化以及其与成矿关系有重要意义。本文在系统野外观察和岩相学观察的基础上,结合与成矿关系密切的花岗闪长斑岩体中黑云母成分的电子探针原位分析,确定黑云母类型、花岗岩的成因类型及岩浆的源区性质,推断黑云母形成的物理化学条件,并探讨寄主岩的岩石成因以及对成矿的指示意义。

1 地质概况及岩体特征

九瑞矿集区内的不同沉积建造,因其物化性质差异和岩浆演化控制了不同类型矿床的形成和矿种;与燕山期中酸性杂岩体有关的斑岩型铜钼矿体、斑岩体内围岩捕虏体形成的矽卡岩铜矿体和接触带矽卡岩型铜矿体(Zaw *et al.*, 2007; 谭辉跃等, 2008; Li *et al.*, 2010; 文春华等, 2012; Zhou *et al.*, 2015),属于岩浆热液型矿床;以及产于五通组碎屑岩和黄龙组碳酸盐岩界面中的块状硫化物型铜金多金属矿体,常见于侵入体附近,通常认为岩浆热液对块状黄铁矿体的叠加改造对其成矿起了重要作用(黄恩邦等, 1990; 王忠玲, 1991; 孟良义, 1996, 1997; Pan and Dong, 1999; Mao *et al.*, 2011; 徐耀明等, 2013)。前人对九瑞地区侵入杂岩体研究表明:在区域上,该区内铜矿床、矿化点与中酸性侵入体密切伴生,并显示特定的分布格局;在空间上,岩体和矿体的展布受多组断裂构造(NWW + NE、NW + NE、NEE + NW)复合控制,形成了由闪长岩、石英闪长玢岩→花岗闪长斑岩→石英斑岩较明显的演化系列,以及呈现明显分带性的铜、钼矿体(季绍新等, 1989; 王忠玲, 1991; 崔彬, 1995; 陈志洪等, 2011; 蒋少涌等, 2013);在时间上,分燕山早期和晚期阶段,其中早期第1、2阶段,以中性岩侵入为主,岩性

以闪长岩、石英闪长玢岩为主,规模较小,与金矿化为主;早期第3阶段岩浆活动较强烈,岩性以花岗闪长斑岩为主,与铜矿关系密切;晚期第1阶段主要为石英斑岩,与钼矿关系密切(黄恩邦等, 1990; 王忠玲, 1991; 吴良士, 1998; 包家宝等, 2002)。城门山铜钼矿是九瑞矿集区的典型代表,构成了长江中下游成矿带中独具特色的斑岩型-矽卡岩型-块状硫化物型“三位一体”的大型复成因矿床(季绍新等, 1989; 黄恩邦等, 1990; 翟裕生等, 1992; 陈国达, 2000; 花林宝等, 2010; 常印佛等, 2012; Zhou *et al.*, 2013; Xu *et al.*, 2014)。

研究区位于长山-城门湖倾伏背斜东端的北翼,背斜轴向总体为一走向北东东、向东倾斜,发育次级横跨褶皱和北东东向断层及层间破碎带,其中小褶皱构造虚脱部位是利成矿场所(李旭辉, 1997; Pan and Dong *et al.*, 1999; 罗建安等, 2007)。出露地层自南至北由老至新分布(图1),由志留系—三叠系组成,其中石炭系主要见于深部。地层走向与区内的一级褶皱轴线基本一致,为北东、北东东,倾向为北西、北北西,倾角为 $45^\circ \sim 65^\circ$ 。城门山矿田主岩体呈环状分布,与铜多金属矿关系密切的花岗闪长斑岩杂岩体,面积为 0.8 km^2 ,其年龄为 $144.5 \pm 1.2 \text{ Ma}$ (Li *et al.*, 2010);主岩体上升侵入时发生涡旋运动,其中部分成矿热液被甩至外围地层中,并呈帚状侵入到金鸡窝矿段,沿黄龙组与五通组间的“层滑系断裂”迁移富集,形成块状硫化物型铜多金属矿体(陆德复, 1997; 李旭辉等, 2014; 周智勇等, 2016);其北枝是城门山花岗闪长斑岩岩株的东延部分,受破碎带和断层控制,总体走向呈北东东向,呈长条状贯穿矿区东西;南枝分布于铰山南部,走向呈北东向,有分枝复合现象。

新鲜岩石呈灰绿色,风化后略呈黄绿色,斑状结构,局部为聚斑结构,基质为显微花岗结构。斑晶主要由斜长石、石英和黑云母组成,其次为钾长石和角闪石,粒径为 $0.8 \sim 4 \text{ mm}$,约占全岩含量 $43\% \sim 52\%$;基质由长英质物质组成,粒径为 $0.01 \sim 0.2 \text{ mm}$,含量约 $48\% \sim 57\%$ 。部分斑晶被后期石英英脉穿插,且石英脉中见有黄铁矿、黄铜矿和闪锌矿。副矿物有锆石($0.04 \sim 0.16 \text{ mm}$)、磷灰石($0.03 \sim 0.20 \text{ mm}$)和金红石($0.01 \sim 0.15 \text{ mm}$)等。在地球化学组成上,该岩石 SiO_2 含量为 $55.43\% \sim 70.04\%$ (均值为 62.58%),略低于中国花岗闪长岩的平均值 64.98% (黎彤等, 1963);里特曼组合指数(δ)为 $0.51 \sim$

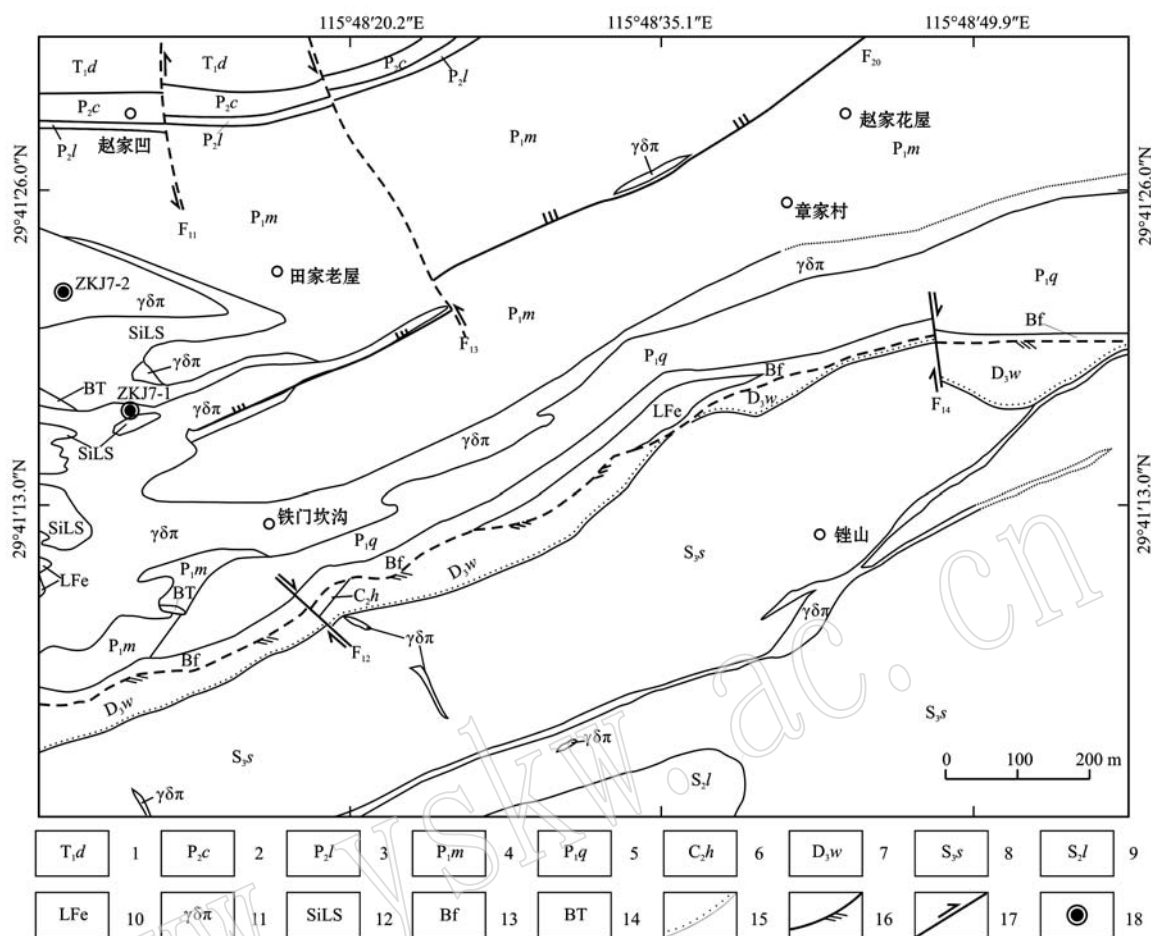


图 1 金鸡窝铜矿区地质简图(据李旭辉, 1997; 罗建安等, 2007)

Fig. 1 Geological sketch map of the Jinjiwo copper deposit (after Li Xuhui, 1997; Luo Jian'an *et al.*, 2007)

1—下三叠统大冶组; 2—上二叠统长兴组; 3—上二叠统龙潭组; 4—下二叠统茅口组; 5—下二叠统栖霞组; 6—中石炭统黄龙岗组; 7—上泥盆统五通组; 8—上志留统纱帽组; 9—中志留统罗惹坪组; 10—褐铁矿; 11—花岗闪长斑岩; 12—硅化灰岩; 13—构造角砾岩; 14—接触角砾岩; 15—不整合接触; 16—压性断层或逆冲断层(带齿盘为上冲盘); 17—扭性断层(箭头表示所在盘运动方向); 18—钻孔位置
1—Daye Formation of Lower Triassic; 2—Changxing Formation of Upper Permian; 3—Longtan Formation of Upper Permian; 4—Maokou Formation of Lower Permian; 5—Qixia Formation of Lower Permian; 6—Huanglong Formation of Middle Carboniferous; 7—Wutong Formation of Upper Devonian; 8—Shamao Formation of Upper Silurian; 9—Luoreping Formation of Middle Silurian; 10—limonite; 11—granodiorite porphyry; 12—silicified limestone; 13—tectonic breccia; 14—contact breccia; 15—unconformable contact; 16—compressional fault or thrust fault; 17—shear fault; 18—drill hole location

3.52(均值为 1.90), K_2O 含量为 3.59%~8.93%, Na_2O 含量为 0.26%~3.28%, $Al_2O_3 > (K_2O + Na_2O)$, $K_2O > Na_2O$, $K_2O + Na_2O$ 均值为 6.76% (数据未发表), 具富碱高钾低钠和铝过饱和的特点, 属于高钾质钙碱性系列, 反映了岩体的岩浆富碱高钾为钾化、钠化作用提供了基本物质, 与镜下薄片观察的钾化现象相吻合。LREE 元素富集, HREE 元素亏损, 无明显 Eu 异常, Y 为 $1.41 \times 10^{-6} \sim 12.3 \times 10^{-6}$ (均值为 6.98×10^{-6}), Yb 为 $0.78 \times 10^{-6} \sim 1.13 \times 10^{-6}$ (均值为 0.99×10^{-6}), Sr 为 $661 \times 10^{-6} \sim 1300 \times 10^{-6}$ (均值为 957×10^{-6}), La/Yb 为 11.2

~26.3(均值为 20.6), 与 C 型埃达克岩的地球化学特征相似(张旗等, 2001)。

2 样品采集及分析方法

花岗闪长斑岩采自金鸡窝铜矿区 ZKJ7-1、ZKJ7-2 钻孔岩芯, 选取新鲜岩石样品制成探针薄片。根据岩相学微观特征, 挑选特征鲜明的原生黑云母以待测试。黑云母主量元素测试分析过程按照国家电子探针定量分析标准(GB/T15617-2002)进行, 于东华理工大学核资源与环境教育部重点实验

室测试完成。主量元素电子探针分析所用仪器型号为 JXA-8100 型, 仪器工作条件为: 加速电压为 15.0 kV, 探针束电流为 20 nA, 束斑直径为 2 μm , 峰值计数时间设定为 20 s, 背景计数设定为 10 s。采用标样为钠长石(Na)、透长石(Si, Al, K)、透辉石(Ca, Mg)、

贵榴石(Fe)、金红石(Ti)、氟磷灰石(P)和蔷薇辉石(Mn)。按黑云母阳离子总数 8、阴离子理论负电价 23 的理论数值, 运用电价差值法(郑巧荣, 1983)计算出黑云母的 Fe^{3+} 、 Fe^{2+} 值, 然后以 22 个氧原子为基准计算黑云母的阳离子数及相关参数(结果见表 1)。

表 1 金鸡窝花岗闪长斑岩黑云母电子探针分析结果

 $w_B/\%$

Table 1 Electron microprobe analyses of representative primary biotite from the Jinjiwo pluton

测点号	13J-25-1	13J-25-2	13J-25-3	13J-25-4	13J-26-1	13J-26-2	13J-26-3	13J-29-1	13J-32-1
SiO_2	37.25	36.84	36.99	35.68	36.84	35.68	35.37	36.27	36.24
Al_2O_3	13.73	13.93	13.61	13.65	14.02	13.96	13.52	13.74	14.19
TiO_2	4.08	3.94	4.12	4.14	4.19	4.13	4.08	3.93	4.13
FeO^{T}	15.74	17.24	17.30	17.05	17.04	16.88	16.83	16.67	16.17
MnO	0.20	0.23	0.21	0.23	0.17	0.22	0.20	0.23	0.23
MgO	14.28	13.27	14.08	13.86	13.90	13.74	13.52	13.66	14.28
CaO	0.01	0.02	0.04	0.01	0.02	0.24	0.17	0.00	0.02
K_2O	8.09	8.54	8.07	9.69	8.70	9.32	9.39	8.65	9.77
Na_2O	0.62	0.55	0.28	0.23	0.26	0.29	0.33	0.32	0.28
NiO	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00	0.00
P_2O_5	0.00	0.00	0.00	0.02	0.01	0.04	0.05	0.00	0.00
Cr_2O_3	0.03	0.04	0.05	0.05	0.00	0.03	0.05	0.00	0.04
BaO	0.48	0.39	0.31	0.42	0.47	0.79	0.74	0.31	1.11
Fe_2O_3	6.21	7.77	6.00	12.23	7.45	11.36	11.78	7.97	12.04
Total	94.51	95.02	95.03	95.04	95.64	95.32	94.23	93.78	96.45
以 22 个氧原子为基准计算的阳离子数及相关参数									
Si^{4+}	5.54	5.48	5.51	5.30	5.45	5.30	5.31	5.46	5.30
Ti^{4+}	0.46	0.44	0.46	0.46	0.47	0.46	0.46	0.44	0.45
Al^{IV}	2.00	2.07	2.03	2.24	2.08	2.24	2.23	2.10	2.24
Al^{VI}	0.41	0.37	0.36	0.15	0.36	0.20	0.16	0.34	0.21
Fe^{3+}	0.70	0.87	0.67	1.37	0.83	1.27	1.33	0.90	1.33
Fe^{2+}	1.26	1.28	1.48	0.75	1.28	0.83	0.78	1.20	0.65
Mn^{2+}	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03
Mg^{2+}	3.17	2.94	3.12	3.07	3.07	3.04	3.03	3.06	3.11
Ca^{2+}	0.00	0.00	0.01	0.00	0.00	0.04	0.03	0.00	0.00
K^+	1.53	1.62	1.53	1.84	1.64	1.77	1.80	1.66	1.82
Na^+	0.18	0.16	0.08	0.07	0.08	0.08	0.10	0.09	0.08
Ni^{2+}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P^{5+}	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Cr^{3+}	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00
Ba^{2+}	0.03	0.02	0.02	0.02	0.03	0.05	0.04	0.02	0.06
$\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$	0.29	0.30	0.32	0.20	0.29	0.21	0.21	0.28	0.17
f_{O}	0.35	0.41	0.31	0.65	0.39	0.61	0.63	0.43	0.67
X_{Mg}	0.62	0.58	0.59	0.59	0.59	0.59	0.59	0.59	0.61
MF	0.38	0.42	0.41	0.41	0.41	0.41	0.41	0.41	0.39
χ	0.21	0.22	0.24	0.13	0.21	0.14	0.13	0.20	0.11
Ti 温度/ $^{\circ}\text{C}$	748	734	743	743	745	743	742	739	746
$\lg f_{\text{O}_2}$	-10.8	-11.7	-11.5	-11.5	-11.6	-11.5	-11.5	-11.4	-11.3
p/MPa	76	87	71	71	88	87	72	86	89
H/km	2.9	3.3	2.7	2.7	3.3	3.3	2.7	3.2	3.3

注: FeO^{T} 为电子探针测试 FeO 质量百分数, $X_{\text{Mg}} = \text{Mg}/(\text{Mg} + \text{Fe}^{2+} + \text{Fe}^{3+})$, $\text{MF} = (\text{Fe}^{2+} + \text{Fe}^{3+})/(\text{Mg} + \text{Fe}^{2+} + \text{Fe}^{3+})$, $\chi = \text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Fe}^{3+} + \text{Al}^{\text{VI}} + \text{Mn} + \text{Mg} + \text{Ti} + \text{Ca})$, 氧化系数 $f_{\text{O}} = \text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ 。

3 黑云母矿物学特征

3.1 黑云母的类型

按黑云母形成条件和产出方式,分为原生黑云母和交代型黑云母(图2)。原生黑云母,自形-半自形,晶体呈假六方片状,多色性显著, $N_g \subseteq Nm$ -暗褐、红褐色, N_p -浅黄褐色,粒径为0.5~1.02 mm,约占斑晶含量1%~2%,偶见{001}云母律双晶;该斑晶边缘常被熔蚀、穿孔,及其周围边缘见有不透明的暗化边,常见磷灰石、锆石和磁铁矿等矿物包体。角闪石斑晶,柱状,多色性明显, N_g -深绿色、 Nm -黄绿色、 N_p -浅黄绿色,角闪石斑晶局部被热液黑云母交代,其产状明显不同于原生黑云母,属次生黑云母。

3.2 黑云母化学成分特征

原生黑云母的化学成分可反映岩浆-热液体系

冷却结晶的物化条件(Nachit *et al.*, 2005),而岩浆期后热液、蚀变形成的次生黑云母(角闪石转变为黑云母)的Ti含量低于原生黑云母(Zhang *et al.*, 2016)。马昌前等(1994)统计表明退变质和固相线下交代成因的黑云母具有低Ti特征, $Ti < 0.2$ apfu (atoms per formula unit);岩浆黑云母Ti含量范围为0.20~0.55 apfu, $Mg/(Mg + Fe)$ 比值介于0.30~0.55;进变质成因的黑云母Ti含量变化范围广, $Mg/(Mg + Fe)$ 比值均大于0.55。将本区黑云母的化学分析结果在 $10 TiO_2 - FeO + MnO - MgO$ 图解(Nachit *et al.*, 2005)(图3a)和 $Mg - (Fe^{2+} + Mn) - (Al^{VI} + Fe^{3+} + Ti)$ 图解(Foster, 1960)(图3b)进行投影,显示黑云母具有富镁、贫铁特征,属原生镁质黑云母,且在 $Mg/(Mg + TFe + Mn) - Si$ 原子数图解(Kanisawa, 1983)(图3c)中,均靠近金云母、羧铁云母端员。黑云母的 TiO_2 含量为3.93%~4.19%(均

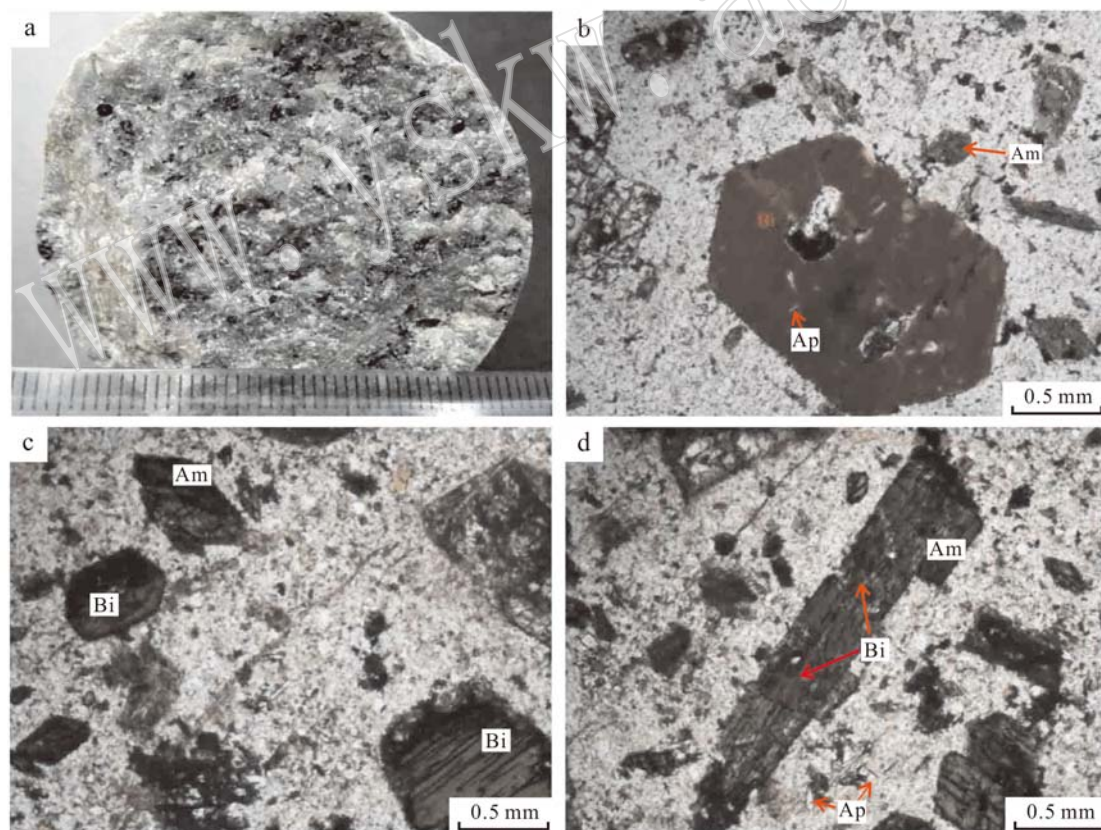


图2 金鸡窝矿区花岗闪长斑岩手标本及显微照片

Fig. 2 Rock sample and photomicrographs for the granodiorite porphyry from the Jinjiwo deposit

a—花岗闪长斑岩,斑状结构,由斑晶斜长石、黑云母(Bi)和角闪石(Am)和基质(长英质)组成; b—黑云母斑晶,晶体呈假六方片状,{001}晶面见有磷灰石(Ap)、磁铁矿等矿物包裹体(-); c—黑云母斑晶,{001}云母律双晶(-); d—交代型黑云母,角闪石部分被黑云母交代(-)

a—granodiorite porphyry, porphyry texture, phenocryst mainly composed of plagioclase, biotite and hornblende; b—subhedral to anhedral biotite usually containing inclusions of apatite, opaque minerals (-); c—{001} biotite twinning (-); d—re-equilibrated biotite, partial replacement of previous amphiboles (-)

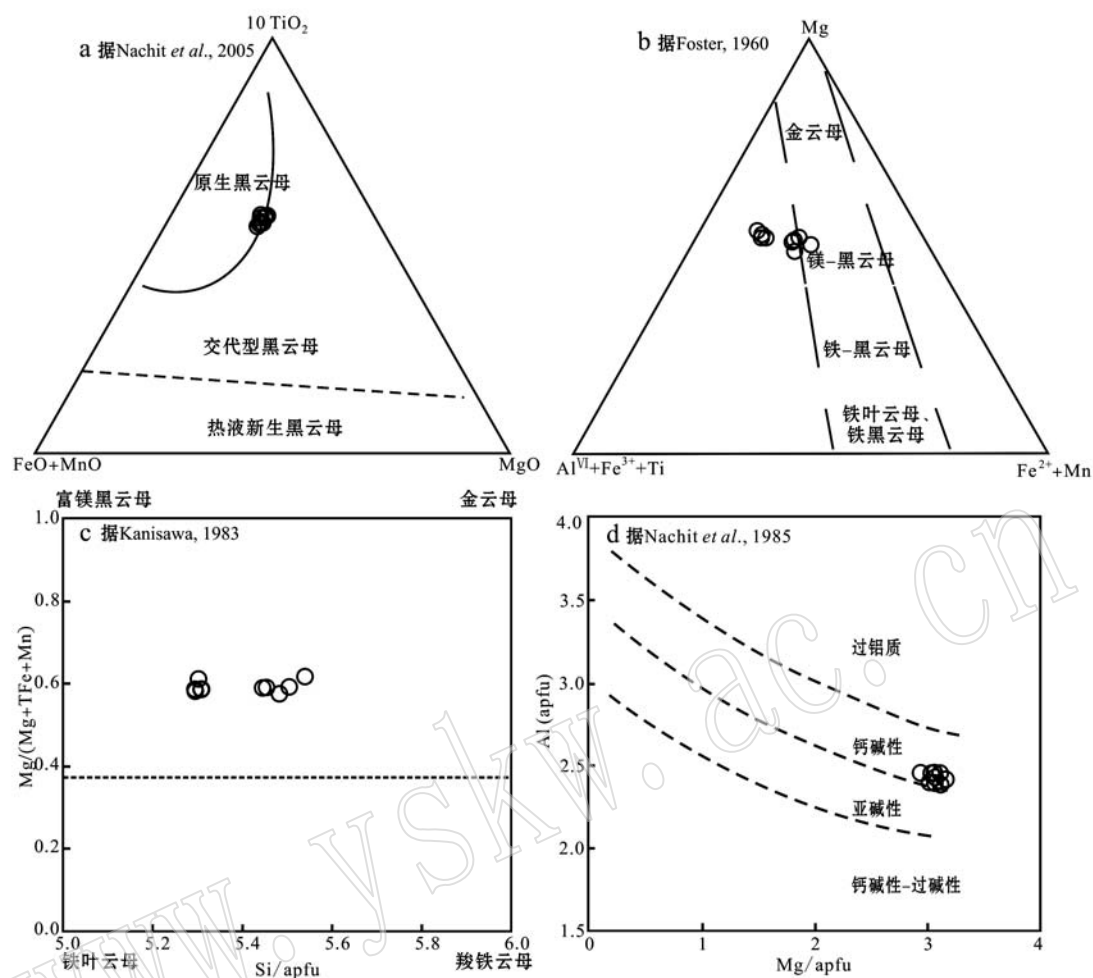


图3 黑云母地球化学成分图解

Fig. 3 Geochemical composition diagrams of biotites from the Jinjiwo granodiorite porphyry

值 4.08%), MgO 为 13.27% ~ 14.28% (均值 13.84%), TFeO 为 15.74% ~ 17.30% (均值 16.77%), 以 22 个氧原子为基准计算的 Ti 为 0.44 ~ 0.47 apfu (均值为 0.46 apfu), Mg/(Mg + Fe) 比值为 0.58 ~ 0.62 (均值 0.60), 表明该岩体中黑云母具有岩浆成因特征, 并可能经历了退变质作用或固相线下的交代作用。Fe²⁺/(Fe²⁺ + Mg) 比值是否均一作为反映氧化态岩浆的重要指标, 本区黑云母中的 FeO 质量分数较低, Fe²⁺/(Fe²⁺ + Mg) 比值均一, 范围为 0.2 ~ 0.3, 表明其未遭受后期流体改造 (Stone, 2000)。在硅酸熔体中晶出的黑云母中 Al 含量可反映岩浆熔体演化的过铝质岩浆体系, 且在一定 p 、 T 、 f_{O_2} 条件下, 黑云母化学成分中的铝含量由过碱性至过铝质花岗岩逐渐增加 (Stussi and Guney, 1996)。根据实验数据表明 (Monier, 1986), Al - Mg 呈负相关, 随着温度升高黑云母中铝的溶解度降低,

本区黑云母 Al^{IV} 为 2.00 ~ 2.24 apfu (均值 2.14 apfu), Al^{VI} 为 0.15 ~ 0.41 apfu (均值 0.28 apfu), Mg 为 2.94 ~ 3.17 apfu (均值为 3.07 apfu), 表明该岩体中黑云母的化学成分受类质同像影响, Al 在钙碱性花岗闪长斑岩中活泼性低常被 Mg 置换。在 Al - Mg 图解 (Nachit *et al.*, 1985) 中进行投影, 黑云母化学成分落入在钙碱性区域 (图 3d), 与花岗闪长斑岩全岩的里特曼组合指数一致 (δ 为 0.51 ~ 3.52, 平均 1.90), 属于钙碱性系列。

4 成岩物理化学条件

4.1 黑云母全铝压力计

经野外和室内显微观察, 花岗闪长斑岩中的暗色矿物由黑云母、角闪石组成, 其中角闪石均遭受不同程度绿泥石化或局部转变为黑云母, 而原生黑云

母未见明显蚀变。Uchida 等(2007)研究表明:在铅锌铜矿、铜铁矿、钨矿和未成矿花岗质岩石中黑云母的全铝含量随着利用角闪石、闪锌矿地质压力计和围岩矿物共生组合方法估计的上述花岗质岩石的结晶压力增大而升高,暗示了黑云母的全铝含量可作为探究热液矿床与未成矿花岗质岩石的有效指标,以及黑云母中的全铝含量与花岗质岩浆初始结晶压力具有很好的正相关特性;利用黑云母地质压力计,可估计热液矿床和未成矿花岗质岩石的结晶压力,其经验公式如下: $p(\times 100 \text{ MPa}) = 3.03 \times \text{Al} - 6.53(\pm 0.33)$, 其中, Al 是以 22 个氧原子为基准算出的黑云母的全铝阳离子数。花岗岩的结晶压力常用来估算岩体的侵位深度(张有军等, 2015), 侵位深度采用 $p = \rho gh$ 进行换算, 其中 g 取 9.8 m/s^2 , 上覆岩层的密度 ρ 近似取 2700 kg/m^3 。利用上述黑云母地质压力计, 本区含铜矿花岗闪长斑岩黑云母的结晶压力为 $71 \sim 89 \text{ MPa}$, 均值为 81 MPa , 相当于 $2.7 \sim 3.3 \text{ km}$, 平均深度为 3.0 km 。随着采集样品由浅至深, 其整体结晶压力由 $89 \sim 76 \text{ MPa}$ 在递减, 结晶深度由 $3.3 \sim 2.9 \text{ km}$ 逐步减小, 结果表明岩体浅部的成岩压力大, 而深部的成岩压力小; 可能是由于岩体上升侵位速度较快, 岩浆外部先冷凝固结并对内部熔融状的岩浆起到保温作用, 在快速上升过程中内部岩浆未达到固相线就已侵入浅部, 致使内部岩浆在浅部结晶成岩, 其成岩压力小。

4.2 黑云母的结晶温度、氧逸度

根据泥质变质岩中黑云母 Ti 和 X_{Mg} 的实验数据, Henry 等(2005)获得了黑云母 Ti 温度计公式, $t = [(\ln \text{Ti} - a - cX_{\text{Mg}}^3)/b]^{0.333}$, 适用于 $X_{\text{Mg}} = 0.28 \sim 1.00$, $\text{Ti} = 0.04 \sim 0.60$ (以 22 个氧原子为基准算出的黑云母中 Ti 阳离子数), $t = 400 \sim 800^\circ\text{C}$, 其中: $X_{\text{Mg}} = \text{Mg}/(\text{Mg} + \text{Fe}^{2+} + \text{Fe}^{3+})$, $a = -2.3594$, $b = 4.6482 \times 10^{-9}$, $c = -1.7283$ 。Sarjoughian 等(2014)通过对伊朗中部 Kuhe Dom 侵入体研究, 发现黑云母 Ti 温度计不仅适用泥质变质岩, 也适用于火成岩。本区花岗闪长斑岩黑云母的 $X_{\text{Mg}} = 0.58 \sim 0.62$, $\text{Ti} = 0.44 \sim 0.47$ (基于 22 个氧原子), 满足黑云母 Ti 温度计的适用条件。在 $\text{Ti} - X_{\text{Mg}}$ 图解上(图 4), 可知黑云母的结晶温度介于 $734 \sim 748^\circ\text{C}$, 均值为 742°C 。

Wones 等(1965)研究表明: 黑云母的 $(\text{Fe}^{3+} + \text{Fe}^{2+})/(\text{Fe}^{3+} + \text{Fe}^{2+} + \text{Mg})$ 比值(MF)变化可作为温度和氧逸度的函数。根据黑云母电子探针分析数

据, 求出 MF 值(表 1), 并投影于 $p_{\text{H}_2\text{O}} = 207.0 \text{ MPa}$ 条件下的黑云母 $\log f_{\text{O}_2} - t$ 稳定实验图解(Wones and Eugster, 1965)(图 5), 结合黑云母的结晶温度及矿

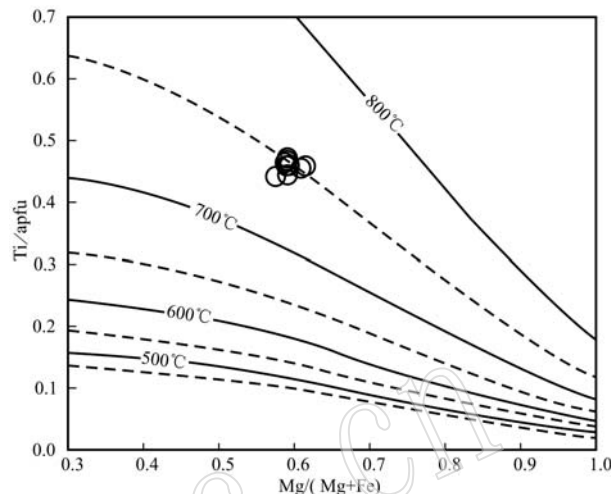


图 4 黑云母 $\text{Ti} - \text{Mg}/(\text{Mg} + \text{Fe})$ 估算图解
(底图据 Henry *et al.*, 2005)

Fig. 4 $\text{Ti} - \text{Mg}/(\text{Mg} + \text{Fe})$ diagram of biotite (after Henry *et al.*, 2005)

物共生组合(黑云母-钾长石-石英-角闪石-榍石), 投点落入黑云母+透长石+磁铁矿区内, 则得出花岗闪长斑岩氧逸度变化不大, f_{O_2} 为 $(10^{-10.8} \sim 10^{-11.7}) \times 10^5 \text{ Pa}$, 表明黑云母形成于较高氧逸度环境。在黑云母 $\text{Fe}^{3+} - \text{Fe}^{2+} - \text{Mg}$ 图解中(图 6), 黑云母成分投点主要落在 $\text{Fe}_2\text{O}_3 - \text{Fe}_3\text{O}_4$ 缓冲剂线之上, 同样指示其形成于高氧逸度环境(Wones, 1989)。

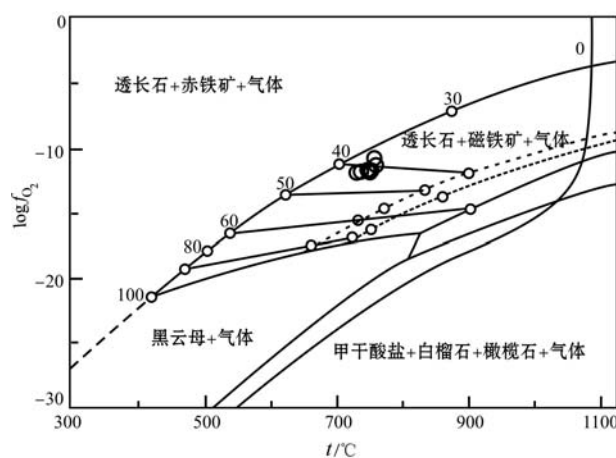


图 5 黑云母的 $\log f_{\text{O}_2} - t$ 图解(底图据 Wones and Eugster, 1965)

Fig. 5 $\log f_{\text{O}_2} - t$ diagram of biotite (after Wones and Eugster, 1965)

Chappell(1974)对澳大利亚 I 型和 S 型花岗岩研究表明: f_{O_2} 可作为 I 型和 S 型花岗岩划分的标志, I 型花岗岩氧逸度为 $(10^{-10} \sim 10^{-14}) \times 10^5$ Pa, S 型花岗岩为 $(10^{-15} \sim 10^{-20}) \times 10^5$ Pa; Abdelrahman(1994)指出 I 型花岗岩的黑云母是富镁的, S 型花岗岩的黑云母相对富铝, 故本区岩体应属于 I 型花岗岩, 且黑云母为镁质黑云母, 与前述结果相吻合。

5 讨论

黑云母单矿物地球化学特征与岩浆结晶时的物化条件及所处的构造环境具有成因联系(周作侠, 1986; 蒋国豪等, 2005; 楼亚儿等, 2006; 东前等, 2011; Li *et al.*, 2014; Zhang *et al.*, 2016)。因此, 研究黑云母成分特征可有效地反映寄主岩石的成因类型、形成环境、物质来源和成矿潜力等, 具有重要的成岩成矿指示意义。

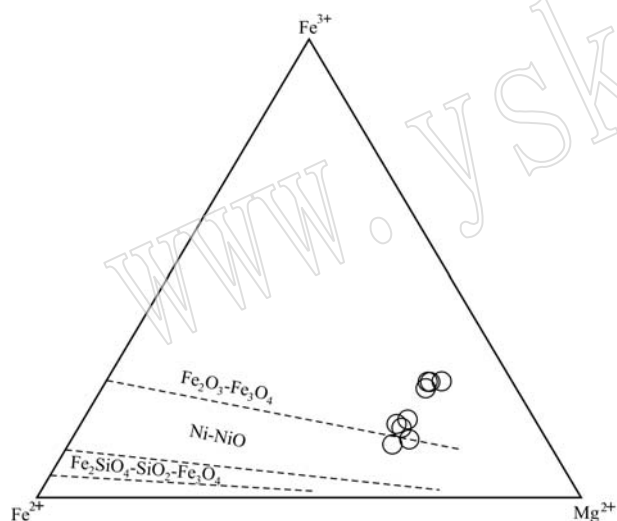


图6 黑云母的 Fe^{3+} - Fe^{2+} - Mg^{2+} 图解
(底图据 Wones and Eugster, 1965)

Fig. 6 Fe^{3+} - Fe^{2+} - Mg^{2+} diagram of biotite
(after Wones and Eugster, 1965)

5.1 岩石成因

徐克勤等(1982)通过对华南地区改造、同熔型花岗岩黑云母的化学组成分析, 指出不同成因花岗岩黑云母的 $Mg/(Mg + Fe^{2+} + Fe^{3+})$ 和氧化系数 (f_O)、 $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ 比值差异明显; 改造型花岗岩具有较低的 $Mg/(Mg + Fe^{2+} + Fe^{3+})$ 比值, 其范围为 $0.28 \sim 0.37$, 且有较低的氧化系数, 其变化范围为 $0 \sim 0.097$, 而同熔型花岗岩有较高的 $Mg/(Mg + Fe^{2+} + Fe^{3+})$ 比值, 其范围为 $0.38 \sim 0.63$, 且有较高

的氧化系数, 其范围为 $0.121 \sim 0.252$ 。本区黑云母 $Mg/(Mg + Fe^{2+} + Fe^{3+})$ 比值变化范围为 $0.58 \sim 0.62$, 均值为 0.60 , 氧化系数范围为 $0.31 \sim 0.67$, 表明该区花岗闪长斑岩属同熔型花岗岩, 与前述结果一致, 且黑云母是在较高温、高氧逸度环境条件下结晶而成的。

张玉学(1982)研究认为黑云母化学成分中的 MgO 含量有效地反映岩石物质来源及成岩成矿作用的某些地球化学特征, 并提出了黑云母成分与物质来源的关系判别图解。本区花岗闪长斑岩中的黑云母均为镁质黑云母, 镁含量较高, MgO 平均含量为 13.84% , 并将黑云母的化学分析结果在 $FeO^T/(MgO + FeO^T) - MgO$ 图解上进行投点, 均落入壳幔混源区(图7), 指示寄主岩石属于 I 型花岗岩, 具有壳幔源物质来源的特征, 并形成较明显的混合趋势线。

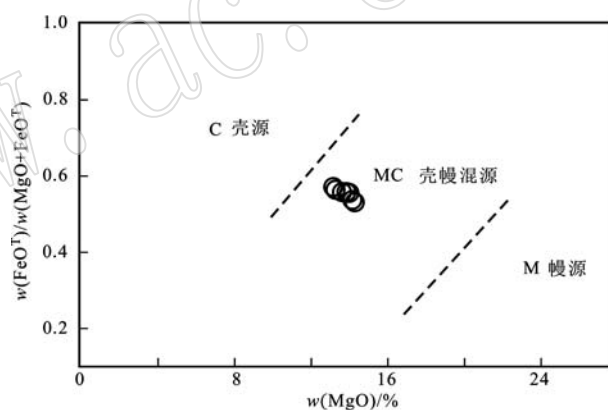


图7 黑云母成分与物质来源关系图解
(底图据张玉学, 1982)

Fig. 7 Diagram for the relationship between composition and source of biotite (after Zhang Yuxue, 1982)

5.2 对成矿的指示

黑云母具有特殊层状结构, 是许多成矿元素(Cu、Au、Mo等)的载体和富集矿物(蒋国豪等, 2005; 刘彬等, 2010), 其化学成分亦作为岩体演化系统的变化, 且能灵敏地指示不同矿化类型及其成矿关系(洪大卫, 1982)。熊小林等(2001)指出与斑岩型铜矿、浅成低温热液型铜矿有关的浅成-次火山中酸性侵入体中黑云母含有较丰富的成矿元素及挥发分, 其 $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ 比值能反映其结晶时岩浆的氧化还原状态, 可作为成矿物质、成矿流体来源的理想示踪矿物。在高氧逸度条件下, 岩浆中不产生硫化物过饱和, 绝大多数硫以 SO_4^{2-} 和 SO_2 的形式溶解于硅酸盐熔体中, 且 Cu、Au 等成矿元素更易随硫化物的氧化逐步于熔体

相中富集,并最终进入流体相,是有利于形成斑岩型-浅成低温热液型铜矿床的关键因素(熊小林等,2001; Halter *et al.*, 2005; 蒋少涌等,2008)。成矿岩体中的岩浆黑云母颜色普遍较深,多色性显著,形成于岩浆流体出溶和去气作用之前,且具有高氧逸度、富镁贫铁的特征(吕志成等,2003; 刘彬等,2010; 东前等,2011; 徐耀明等,2013)。

根据研究区含矿花岗闪长斑岩中黑云母成分特征,可知该岩体具有快速侵入特征、较高的成岩温度、氧化系数和氧逸度,且大部分氧逸度高于 $MH(Fe_3O_4 - Fe_2O_3)$ 缓冲线,黑云母以富镁贫铁为特征。上述结果与国内外已知的江西武山矽卡岩型铜矿(东前等,2011)、鄂东南铜山口斑岩-矽卡岩型铜矿(刘彬等,2010)、湘南宝山铜铅锌矿(弥佳茹等,2014)、大兴安岭中南段铜矿床(吕志成等,2003)、加拿大中西部新不伦瑞克省 Sisson Brook 钨钼铜(Zhang *et al.*, 2016)和印度尼西亚松巴哇岛巴都希贾乌铜金矿(Idrus *et al.*, 2007)中与成矿有关的花岗闪长斑岩中黑云母具有相似特征。徐耀明等(2013)对九瑞地区成矿和未成矿中酸性侵入岩中黑云母进行了研究,结果表明由黑云母成分估算的氧逸度显示未成矿侵入岩的氧逸度均未超过 $MH(Fe_3O_4 - Fe_2O_3)$ 缓冲线,而成矿侵入岩中的氧逸度大部分高于该缓冲线,故较高的氧逸度对成矿更为有利。金属成矿对氧逸度的依赖程度按 $W \rightarrow Mo \rightarrow Cu-Mo \rightarrow Cu-An$ 顺序逐渐增加,氧逸度选择性地促进成矿金属元素(尤其是亲铜元素)在残余熔体中富集,从而决定有关的花岗岩成矿专属性(Rowins, 2000; Pirajno, 2008)。李鹏举等(2013)对浙赣皖相邻区燕山期两类花岗岩的岩石学、地球化学及成矿元素研究认为燕山早期花岗闪长岩的氧逸度范围介于 $FMQ(Fe_2SiO_4 - Fe_3O_4 - SiO_2)$ 缓冲线和 $MH(Fe_3O_4 - Fe_2O_3)$ 缓冲线之间,平均值为 $FMQ + 2.7$,氧逸度较高,且普遍发育与金、银、铜、钼等亲氧元素有关的热液矿床,而晚期花岗岩氧逸度小于 FMQ ,平均值为 $FMQ - 1.1$,其铜金钼的含量偏低表现无矿。综上所述,氧逸度对部分成矿元素(Cu 、 Mo 、 Au 等)的成矿有重要影响,本区岩体形成于相对高温高氧逸度较浅环境,具有较大成矿潜力。

6 结论

金鸡窝铜矿床花岗闪长斑岩中黑云母属原生镁质黑云母,显示出富镁贫铁特征,未遭受后期流体作

用改造。黑云母结晶温度为 $734 \sim 748^\circ C$,压力为 $71 \sim 89$ MPa,相应的侵位深度为 $2.7 \sim 3.3$ km,平均深度为 3.0 km, $\log f_{O_2}$ 为 $-10.8 \sim -11.7$,表明该岩体形成于较高的温度、氧化系数和氧逸度环境,具有较大的成矿潜力。

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