

新疆包古图斑岩铜矿 III-2 岩体氧逸度研究： 来自矿物成分的指示

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内容提要：包古图斑岩铜矿位于新疆西准噶尔地区，是区内规模最大的斑岩型矿床，成矿作用与晚石炭世中酸性侵入体密切相关。III-2 岩体位于矿区南部，该岩体全岩矿化，但品位较低，是探讨成矿岩浆性质的理想对象。本文结合岩石学和角闪石、锆石等矿物成分分析，通过与典型斑岩铜矿进行对比，探讨了成矿岩浆的氧逸度。研究表明，包古图 III-2 岩体以石英闪长(玢)岩和闪长岩为主，少量辉石闪长岩，主要由斜长石、角闪石、黑云母、石英和钾长石组成，含少量钛铁矿、榍石和磷灰石。石英闪长岩中早期结晶的自形角闪石属于钙质闪石， $Mg^{\#}$ 较高(0.72~1.00)，成分分析指示成矿岩浆的氧逸度为： $\Delta NNO+1.4\sim\Delta NNO+2.6$ ，位于斑岩铜矿含矿岩体的分布范围。从中分选出的锆石 REE 含量高($338\times 10^{-6}\sim 959\times 10^{-6}$)，具有左倾型稀土配分模式，轻稀土亏损，重稀土富集，显示强烈 Ce 正异常和 Eu 负异常。 Ce^{4+}/Ce^{3+} 比值为 29.55~89.50， Eu/Eu^* 比值为 0.32~0.47，分布于斑岩铜矿含矿岩体和未矿化岩体的叠加部位。研究结果显示，包古图斑岩铜矿 III-2 岩体成矿岩浆氧逸度较高，有利于成矿元素的溶解和迁移，对斑岩铜矿的形成有促进作用。

关键词：氧逸度；斑岩铜矿；成矿岩浆；包古图；西准噶尔

斑岩型矿床提供了全世界 70% 的 Cu，50% 的 Mo 以及 25% 的 Au(Sillitoe, 2010)。这类矿床的形成经历了从岩浆到热液的演化过程，成矿岩浆的氧逸度是制约斑岩成矿作用的关键因素之一(Richards, 2005; Sun Weidong et al., 2015; Williamson et al., 2016; Hattori, 2018)。世界上绝大多数的斑岩矿床都具有高氧逸度的成矿岩浆，在 Ni-NiO(NNO)氧逸度缓冲对和磁铁矿-赤铁矿(HM)氧逸度缓冲对之间，通常 $\log f_{O_2} > FMQ+2$ (Mungall, 2002; Richards, 2003; FMQ 为铁橄榄石-磁铁矿-石英氧逸度缓冲对)。部分矿床可见岩浆成因的硬石膏(Stern et al., 2007; Chambefort et al., 2008)，指示成矿体系高的氧逸度和硫含量。少数还原型斑岩矿床成矿岩浆氧逸度较低($\log f_{O_2} < FMQ$, Rowins, 2000; Smith et al., 2012)，含有岩浆成因硫化物(如磁黄铁矿)，未见硬石膏、赤铁矿

等高氧化态矿物。与氧化型斑岩矿床相比，还原型斑岩矿床数量少、储量低。Richards (2005)指出，高水含量、高氧逸度的岩浆，是产出巨型斑岩矿床的首要因素。Wang Rui et al. (2017)研究认为藏南侏罗纪冈底斯岛弧中超大型斑岩 Cu-Au 矿的形成与岛弧前缘富水、高氧逸度的岩浆有关。Bao Xinshang et al. (2018)指出成矿岩浆高的氧逸度和水含量是形成云南北衙巨型斑岩 Au 矿的制约因素。

新疆西准噶尔包古图地区发育多个矿化侵入体(I~V)，不同岩体蚀变矿化程度差别明显。其中 V 号岩体矿化强烈，产出斑岩型铜矿体，已探明 Cu 金属量 64Mt(平均品位 0.28%)，伴生 Mo 1.8Mt，Au 14t，Ag 377t(Zhang Rui et al., 2006)。关于包古图地区的斑岩型铜矿化作用，前人已做了大量工作，在矿床地质、成矿流体、成岩成矿时代等方面积累了

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Wei Shaoni, Zhu Yongfeng, An fang. 2020. Oxygen fugacity of the intrusion III-2 in the Baogutu porphyry copper deposit, Xinjiang: evidence from mineral compositions. Acta Geologica Sinica, 94(8):2367~2382.

大量研究成果 (Zhang Lianchang et al., 2006; Song Huixia et al., 2007; Shen Ping et al., 2012, 2015a; Wei Shaoni et al., 2015; Cao Mingjian et al., 2014, 2017), 但是关于成矿岩浆的氧化-还原特征仍然存在争议。Cao Mingjian et al. (2014) 指出包古图斑岩铜矿具有“还原型”斑岩铜矿床的特征, 成矿岩浆氧逸度较低 $\log f_{O_2} = \Delta NNO$ 。Shen Ping et al. (2015a) 通过含矿闪长岩的黑云母、角闪石成分和磷灰石的 SO_3 含量认为成矿岩浆的氧逸度为 $\log f_{O_2} > \Delta FMQ + 1$ (FMQ 为铁橄榄石-磁铁矿-石英氧逸度缓冲对)。Cao Mingjian et al. (2017) 给出了两个完全不同的氧逸度值: 锆石 Ce 含量指示成矿岩浆的氧逸度 $\log f_{O_2} = \Delta NNO + 0.6$, 黑云母 Fe^{2+} 、 Fe^{3+} 含量指示 $\log f_{O_2} < \Delta NNO$ (NNO 为 Ni-NiO 氧逸度缓冲对)。Zhu Bin et al. (2018) 认为有两个岩浆阶段, 早期氧化阶段形成磁铁矿和高 $Mg^\#$ 角闪石 ($\log f_{O_2} > \Delta NNO + 2.4$), 晚期还原阶段形成钛铁矿和低 $Mg^\#$ 黑云母 ($\log f_{O_2} < \Delta NNO - 0.6$), 并认为后期氧逸度的降低与有机碳的还原作用有关。Wei Shaoni et al. (2019) 结合锆石 Ce^{4+}/Ce^{3+} 比值、角闪石、黑云母成分特征和全岩 Fe^{3+}/Fe^{2+} 比值获得成矿岩浆的氧逸度为 $\Delta FMQ + 2.5 \sim \Delta FMQ + 2.7$ 。包古图 III-2 岩体位于矿区南部, 该岩体全岩矿化但整体品位较低, 是探讨成矿岩浆相关特征的理想对象。本文以 III-2 岩体为研究对象, 在前人研究的基础上, 通过角闪石、锆石等矿物成分分析, 探讨成矿岩浆的氧逸度及其成矿制约, 为斑岩体系成矿作用的完善提供资料。

1 区域地质

新疆西准噶尔地区是中亚成矿域的重要组成部分, 位于巴尔喀什-准噶尔地体的东端 (Zhu Yongfeng et al., 2013, 2016)。西准地区分布多条蛇绿岩带, 玛依勒蛇绿混杂岩形成于早-中寒武世, 为 SSZ 型蛇绿混杂岩 (Ren Rong et al., 2014)。塔尔巴哈台-库吉拜-洪古勒楞蛇绿混杂岩带和唐巴勒-白碱滩-百口泉蛇绿混杂岩带形成于奥陶纪, 代表了古洋壳残片 (Zhu Yongfeng et al., 2015)。达拉布特-萨尔托海蛇绿混杂岩带自中志留世持续至早泥盆世, 是西准地区最年轻的蛇绿岩带 (Chen Bo et al., 2011; Yang Gaoxue et al., 2012; Zhu Yongfeng et al., 2013)。泥盆纪砾岩-砂岩和早石炭世火山-沉积岩不整合覆盖在蛇绿岩及其相关复理石建造之上。下石炭统火山沉积地层是西准噶尔

地区的主要盖层, 包括希贝库拉斯组、包古图组和太勒古拉组 (图 1)。希贝库拉斯组主要由含砾砂岩和凝灰质粉砂岩组成。包古图组主要为凝灰质粉砂岩和凝灰岩, 凝灰岩的锆石 U-Pb 年龄为 328~342Ma (An Fang et al., 2009)。太勒古拉组由粉砂岩、凝灰岩和中-基性火山岩组成, 凝灰岩的锆石 U-Pb 年龄为 328Ma (Wang Rui et al., 2007)。

西准噶尔地区广泛发育晚古生代侵入岩 (图 1), 大型花岗质岩基侵位于蛇绿混杂岩和下石炭统火山-沉积地层之中, 侵位时间集中在 290~310Ma (Han Baofu et al., 2006; Zhu Yongfeng et al., 2013; Duan Fenghao et al., 2018)。闪长质到花岗质岩株和岩脉侵位于下石炭统火山-沉积地层中, 集中分布在包古图区域, 侵位时间为 310~320Ma (Liu Yulin et al., 2009; Shen Ping et al., 2012; Wei Shaoni et al., 2015)。辉长质到闪长质岩墙侵位于火山-沉积地层和花岗质岩基之中, 侵位时间集中在 240~280Ma (Li Xinzi et al., 2004; Yin Jiyuan et al., 2013)。这些侵入岩均显示高的 $\epsilon_{Nd}(t)$ 值 (Han Baofu et al., 1997; Gao Rui et al., 2014), 部分岩石显示出埃达克岩的特征, 被认为是洋脊俯冲的产物 (Geng Hongyan et al., 2009; Tang Gongjian et al., 2012), 但也有观点认为这些侵入岩形成于洋内俯冲 (Xu Yixian et al., 2016; Zhang Jien et al., 2011) 或后碰撞环境 (Han Baofu et al., 2006; Zhu Yongfeng et al., 2013; Zhang Huichao et al., 2018)。

西准噶尔地区矿产资源丰富, 以 NE 走向的达拉布特断裂为界, 哈图-萨尔托海矿集区分布于断裂以北, 产出哈图金矿、宝贝金矿、辉绿山金矿、满崆山金矿、萨尔托海铬铁矿等众多矿床 (图 1); 包古图矿集区位于达拉布特断裂以南, 产出包古图金矿、包古图斑岩铜矿和宏远钼矿 (图 1, 图 2a)。包古图斑岩铜矿是西准地区唯一的大型铜矿床, 并伴生产出钼和金。铜矿体赋存于矿化岩体及其邻近的蚀变围岩中, 浅部主要是浸染状矿化, 深部为浸染状和细脉-网脉状矿化。热液蚀变和矿化具有明显的分带性, 从内向外依次发育 Ca-Na 硅酸盐蚀变带、钾质蚀变带、绢云母化带和青磐岩化带 (Shen Ping et al., 2009; Wei Shaoni, 2012)。此外, 在岩体与围岩接触带发育金矿化 (Zheng Bo et al., 2015) 和少量铋矿化 (Wei Shaoni et al., 2017)。辉钼矿 Re-Os 同位素指示成矿时代为 310~312Ma (Song Huixia et al., 2007; Shen Ping et al., 2012)。

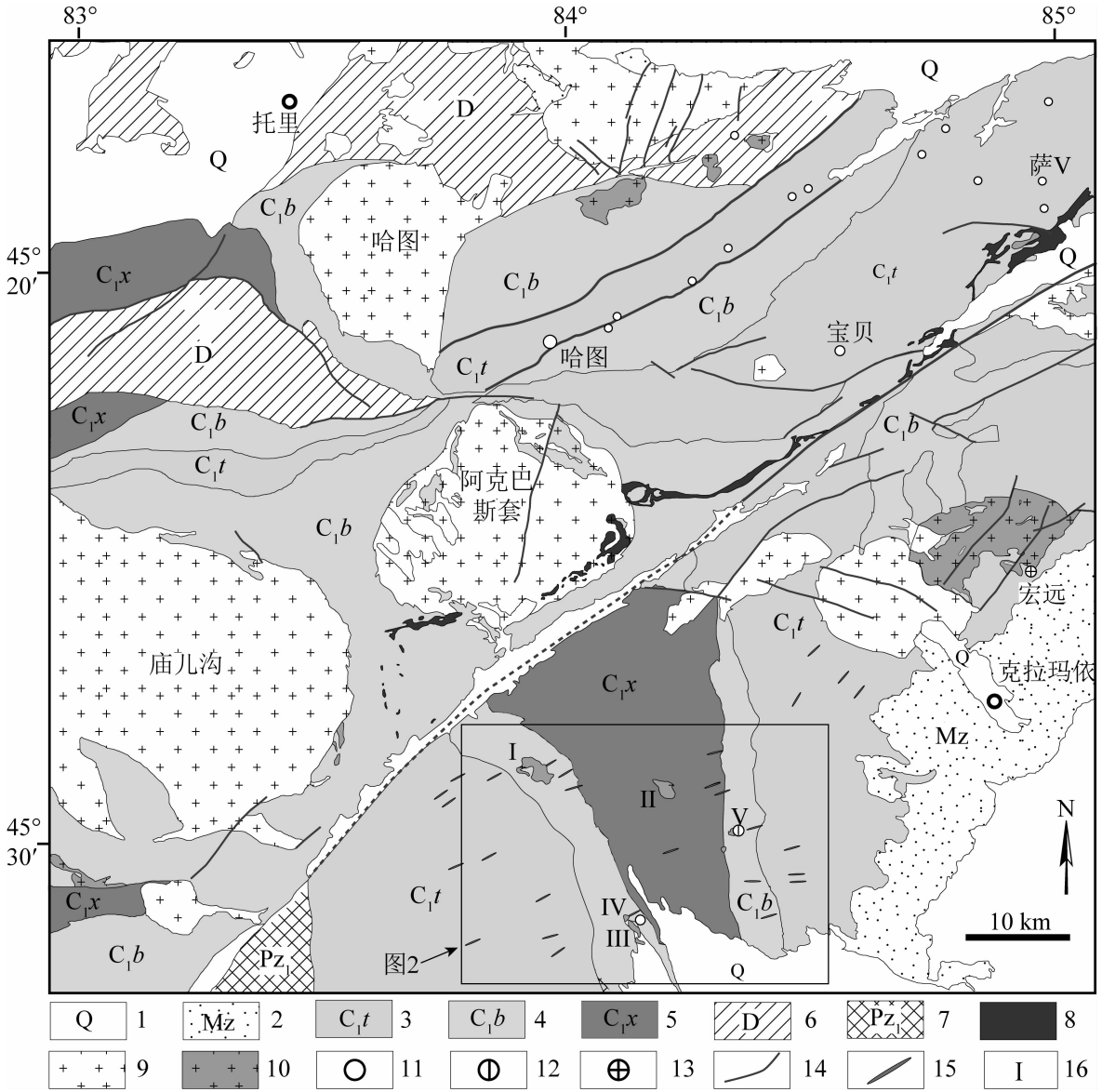


图 1 西准噶尔地质简图(据新疆维吾尔自治区地质矿产局, 1993)

Fig. 1 Simplified geological map of the west Junggar (modified after BGMRX, 1993)

1—第四系; 2—中生界地层; 3—下石炭统太勒古拉组; 4—下石炭统包古图组; 5—下石炭统希贝库拉斯组; 6—泥盆系地层; 7—下古生界地层; 8—超基性岩; 9—花岗岩; 10—花岗闪长岩; 11—金矿点; 12—铜矿; 13—钼矿; 14—断裂; 15—脉岩; 16—岩体编号

1—Quaternary; 2—Mesozoic Formation; 3—Tailegula Formation of Lower Carboniferous; 4—Baogutu Formation of Early Carboniferous; 5—Xibeikulasi Formation of Early Carboniferous; 6—Devonian Formation; 7—Lower Palaeozoic Formation; 8—ultramafic unit; 9—granite; 10—granodiorite; 11—gold occurrence; 12—copper deposit; 13—molybdenum deposit; 14—fault; 15—dyke; 16—intrusion number

2 矿区地质

包古图斑岩铜矿是西准噶尔地区规模最大的斑岩型矿床, 矿区范围内出露多个矿化岩体, I 号岩体邻近达拉布特断裂分布, 侵位于包古图组中。II 号岩体呈菱形展布, 出露于包古图地区中部, 侵位于希贝库拉斯组中。III 号岩体为 NW-SE 向展布的椭圆形, 出露面积 1.76km², 位于包古图地区南部。IV 号岩体位于 III 号岩体北侧, 二者均侵位于包古

图组中。V 号岩体出露面积 0.84km², 呈不规则钟状, 位于包古图地区东部, 东侧出露包古图组, 西侧出露太勒古拉组(图 2a)。各岩体蚀变矿化差异明显, I、II、IV 号岩体矿化较差, 仅发育少量浸染状黄铜矿和黄铁矿。V 号岩体矿化强烈, 发育浸染状、脉状和角砾状 Cu-Mo-Au 矿化, 矿体赋存于岩体及其与围岩接触带中。III 号岩体全岩矿化, 硫化物以浸染状(少数脉状)分布于岩体及其邻近围岩中, 但整体品位很低, 铜最高品位 0.94%, 金最高品位

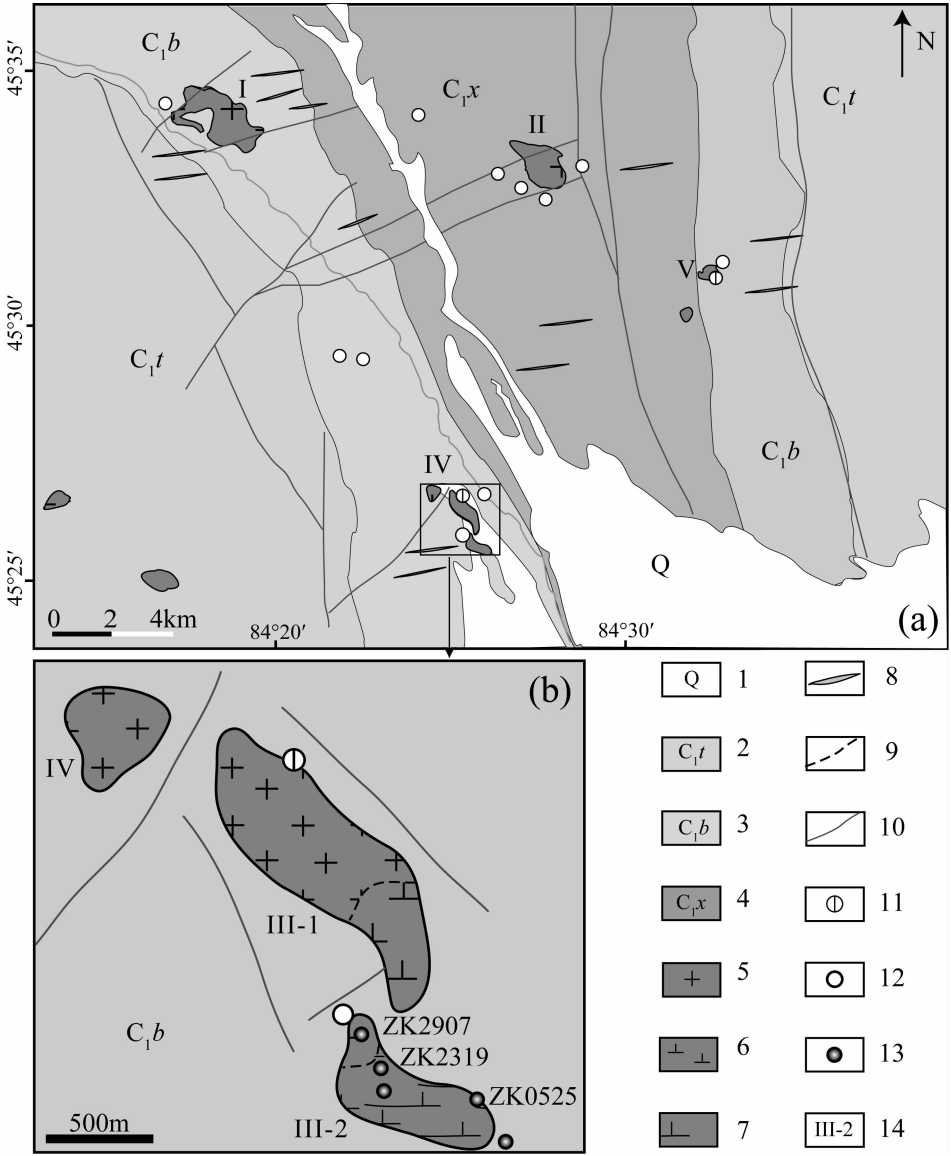


图 2 (a)—新疆包古图地区区域地质简图(修改自 Zheng Bo et al. , 2015);

(b)—III 号岩体地质简图(据武警黄金第八支队内部资料绘制)

Fig. 2 (a)—Geological map of the Baogutu region, Xinjiang (modified after Zheng Bo et al. , 2015);

(b)—simplified geological map of the intrusion III

(modified from internal data of No. 8 Gold Geological Party of Chinese People’s Armed Police Force)

- 1—第四系; 2—太勒古拉组; 3—包古图组; 4—希贝库拉斯组; 5—花岗闪长岩; 6—石英闪长岩;
7—闪长岩; 8—岩墙; 9—相变界线; 10—断层; 11—铜矿; 12—金矿; 13—钻孔; 14—岩体编号

- 1—Quaternary; 2—Tailegula Formation; 3—Baogutu Formation; 4—Xibeikulasi Formation; 5—granodiorite; 6—quartz diorite;
7—diorite; 8—dyke; 9—face transition limit; 10—fault; 11—copper deposit; 12—gold deposit; 13—drill hole; 14—intrusion number

4. 65g/t,绝大多数样品低于边界品位。根据野外地质工作,将 III 号岩体划分为北侧的 III-1 和南侧的 III-2 两部分,本次研究的样品采自南侧 III-2 岩体。

3 岩石学特征

包古图 III-2 岩体共施工钻孔 5 个,其中 4 个位于岩体内部,1 个位于岩体南东侧包古图组地层中

(图 2b),我们挑选其中三个进行了样品采集(图 3)。

ZK2907 位于 III-2 岩体北部,终孔深度 300m,显示岩体岩性为石英闪长岩,局部岩芯段暗色矿物含量变化大,过渡为黑云母石英闪长岩或角闪石英闪长岩。钻孔中见安山岩,斑晶为斜长石和角闪石,气孔发育,被绿泥石和方解石充填。ZK2319 位于 III-2 岩体东侧,终孔深度 918.45m,分布在岩体边

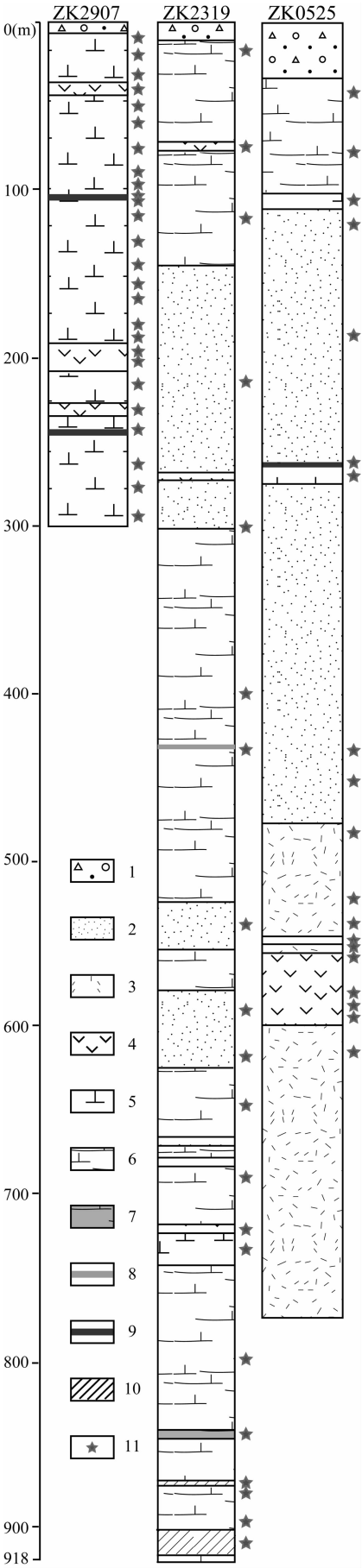


图 3 新疆包古图 III-2 岩体钻孔剖面图
Fig. 3 Section of drills in the Baogutu
intrusion III-2, Xinjiang

1—第四系; 2—砂岩; 3—凝灰岩; 4—安山岩; 5—石英闪长岩; 6—闪长岩; 7—辉石闪长岩; 8—石英脉; 9—方解石-石英脉; 10—构造破碎带; 11—采样位置
1—Quaternary; 2—sandstone; 3—tuff; 4—andesite; 5—quartz diorite; 6—diorite; 7—pyroxene diorite; 8—quartz vein; 9—calcicite-quartz vein; 10—tectonic fracture zone; 11—sample location

部,岩芯中岩体和地层交替出现。岩体岩性以闪长岩为主,少量石英闪长岩和辉石闪长岩,地层岩性包括安山岩、石英砂岩和长石石英砂岩。钻孔深度 873.6m 和终孔的位置发育角砾岩,角砾为闪长岩,胶结物为石英和浊沸石。ZK0525 位于 III-2 岩体东侧边界,终孔深度 772.95m,岩芯顶部见少量岩体,中部和下部均为下石炭统火山沉积地层。岩体岩性为闪长岩和石英闪长岩,地层岩性为石英砂岩、凝灰岩和安山岩。

地表和钻孔样品显示,III-2 岩体岩性以石英闪长(玢)岩和闪长岩为主,少量辉石闪长岩,主要由斜长石、角闪石、黑云母、石英和钾长石组成,局部位置发育单斜辉石,含少量钛铁矿、榍石和磷灰石(图 4)。斜长石(50%~65%)呈自形板状,聚片双晶发育,部分颗粒显示环带结构,结晶较早;角闪石(10%~20%)浅黄-浅绿多色性,自形、半自形,与斜长石共生产出(图 4a);黑云母(5%~10%)浅黄-棕褐多色性,粒度细小,半自形到自形,与斜长石和角闪石共生产出,结晶较晚(图 4b);钾长石(5%~10%)和石英(5%~20%)呈它形粒状,充填颗粒间隙;单斜辉石(<5%)仅出现在部分钻孔样品中,沿边部和裂隙被角闪石交代(图 4c)。石英闪长玢岩断续出现,斜长石和角闪石是主要的斑晶相,约占总体积的 5%~15%,基质由粒度细小的板条状斜长石搭成格架,角闪石、黑云母和石英充填其中(图 4d)。

4 测试方法

矿物电子探针分析工作在中国科学院地质与地球物理研究所电子探针与电镜实验室进行,使用仪器为 JXA-8100,测试条件为:加速电压 15kV、束流 2×10^{-8} A,束斑 $5\mu\text{m}$,修正方法 PRZ,使用的标样为美国 SPI 公司 53 种矿物,最低检出限~0.01%。

锆石微量元素分析在西北大学大陆动力学国家重点实验室采用激光剥蚀-电感耦合等离子质谱分

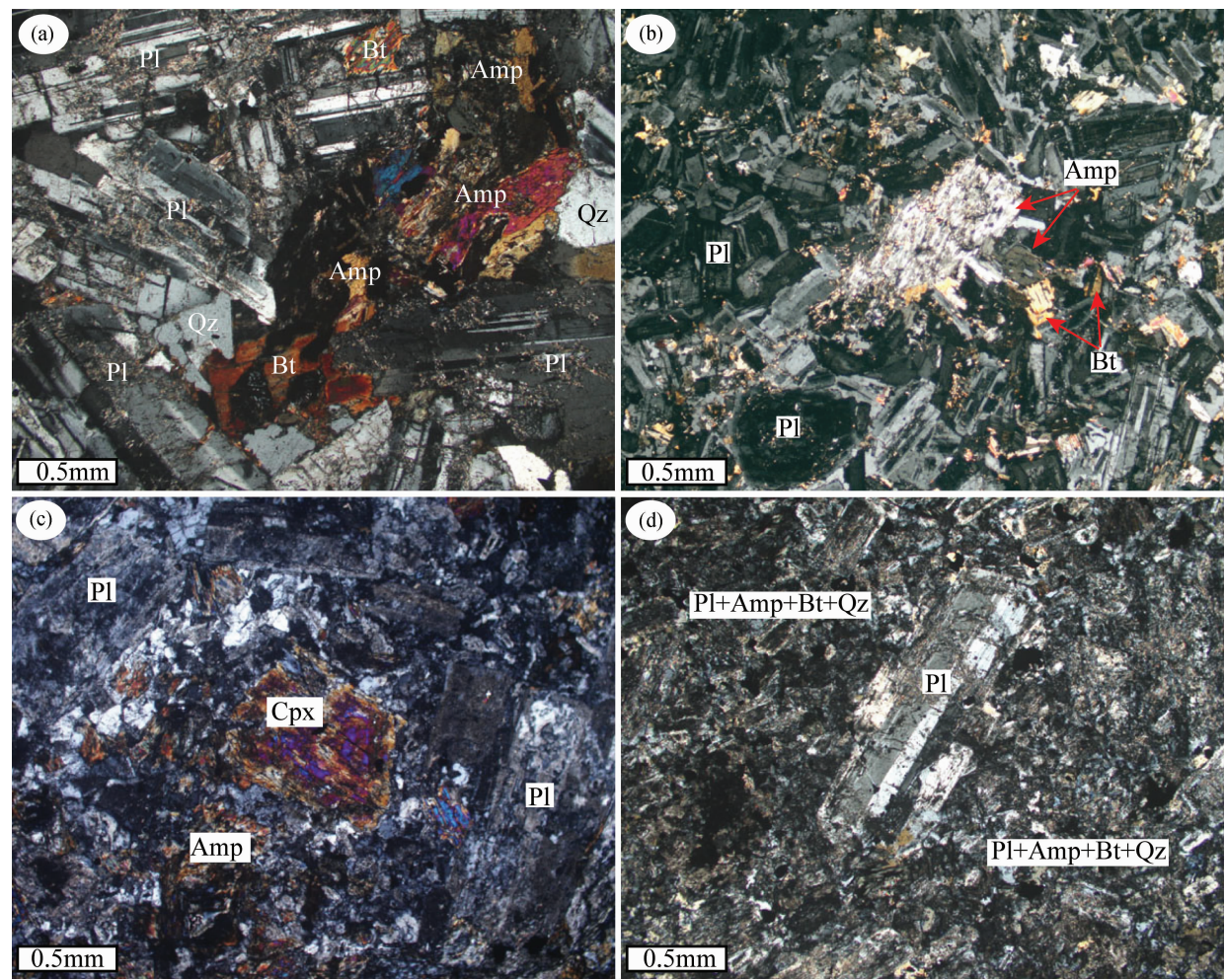


图 4 新疆包古图 III-2 岩体显微岩相学照片

Fig. 4 Microphotographs of the Baogutu intrusion III-2, Xinjiang

(a)—石英闪长岩中的板状斜长石和自形角闪石,正交光;(b)—闪长岩显微特征,自形斜长石、角闪石结晶较早,它形-半自形黑云母结晶较晚,正交光;(c)—辉石闪长岩显微特征,辉石沿边部蚀变为角闪石,正交光;(d)—闪长玢岩中的斜长石斑晶,正交光;Pl—斜长石;Qz—石英;Bt—黑云母;Amp—角闪石;Cpx—单斜辉石

(a)—Quartz diorite with tabular plagioclase and euhedral amphibole, cross-polarized light; (b)—diorite with early stage enehedral plagioclase and amphibole, late stage unehedral-subhedral biotite, cross-polarized light; (c)—pyroxene diorite with clinopyroxene replaced by amphibole, cross-polarized light; (d)—diorite porphyry with plagioclase phenocrysts, cross-polarized light; Pl—plagioclase; Qz—quartz; Bt—biotite; Amp—amphibole; Cpx—clinopyroxene

析(LA-ICPMS)。激光剥蚀系统为德国 MicroLas 公司生产的 GeoLas200M, ICP-MS 为美国 Agilent 公司生产的 Agilent7500a。激光束斑直径为 44 μ m, 采样方式为单点剥蚀, 每个样品点的气体背景采集时间为 30s, 信号采集时间为 40s。数据处理采用 GLITTER(4.0)程序, 元素含量计算时以 NIST 610 为外标, Si 作内标。

5 测试结果

角闪石是包古图矿化侵入体中主要的造岩矿物, 呈自形-半自形产出于岩体中。本次研究选取 III-2 岩体石英闪长岩中早期结晶的自形角闪石进

行电子探针分析, 所选矿物新鲜无蚀变。由测试结果可知(表 1), 包古图 III-2 岩体中的角闪石具有高的 MgO (12.82% ~ 16.59%)、FeO (12.24% ~ 17.58%) 和 CaO (9.71% ~ 10.62%) 含量, K₂O (0.22% ~ 0.57%) 和 Na₂O (0.77% ~ 1.22%) 含量较低。属于钙质闪石, 成分投点位于镁质普通角闪石区域(图 5), Mg[#] 较高(0.72 ~ 1.00)。

从石英闪长岩中分选出的锆石颗粒形态规则, 以长柱状为主, 大小 ~ 100 μ m。阴极发光图像显示典型的扇形结构, 指示其岩浆成因(图 6a)。测试结果表明(表 2), 包古图 III-2 岩体中的锆石 REE 含量较高 (338 $\times 10^{-6}$ ~ 959 $\times 10^{-6}$), Ti 含量变化范围为 8.17

表 1 新疆包古图 III-2 岩体角闪石电子探针分析结果 (%)

Table 1 Electron microprobe analysis results of amphibole from the Baogutu intrusion III-2, Xinjiang (%)										
测点号	J341-1*	J341-2*	J341-3*	J341-4	J341-5	J341-6	J341-7	J341-8	J341-9	J341-10
SiO ₂	49.08	48.01	50.25	50.83	51.53	49.85	49.84	50.98	51.01	49.20
TiO ₂	1.10	1.17	0.62	0.66	0.27	0.86	0.44	0.37	0.43	0.62
Al ₂ O ₃	4.04	4.98	4.52	4.21	3.89	5.03	4.25	4.29	3.84	5.49
MgO	12.82	12.90	15.86	16.34	16.59	16.27	15.10	15.44	16.12	14.68
MnO	0.59	0.38	0.92	0.85	1.07	0.61	0.74	0.92	0.90	0.62
FeO	17.58	16.60	13.17	12.76	12.94	12.24	14.41	14.66	14.13	14.70
Cr ₂ O ₃	0	0	0	0.02	0	0.02	0	0.02	0	0.02
NiO	0	0.01	0	0	0.01	0	0	0.01	0.04	0.03
CaO	10.34	10.58	10.61	10.18	10.01	10.62	10.39	9.71	9.83	10.43
Na ₂ O	1.01	1.21	1.01	1.14	0.84	1.12	0.85	0.87	0.77	1.22
K ₂ O	0.40	0.57	0.33	0.27	0.23	0.40	0.30	0.30	0.22	0.43
F	0	0	0	0	0	0	0	0	0	0
Cl	0.17	0.23	0.15	0.11	0.10	0.14	0.14	0.15	0.11	0.18
总量	97.09	96.58	97.40	97.33	97.46	97.14	96.42	97.68	97.36	97.56
O=23										
Si(T)	7.171	7.077	7.141	7.179	7.220	7.086	7.170	7.173	7.170	7.039
Al ^{IV} (T)	0.695	0.865	0.757	0.700	0.643	0.843	0.720	0.712	0.635	0.925
Ti(T)	0.120	0.058	0.066	0.070	0.029	0.071	0.048	0.039	0.046	0.036
Al ^{VI} (C)	0	0	0	0	0	0	0	0	0	0
Ti(C)	0	0.072	0	0	0	0.021	0	0	0	0.030
Cr(C)	0	0	0	0.002	0	0.002	0	0.002	0	0.002
Fe ⁺³ (C)	1.126	0.927	1.261	1.358	1.584	1.185	1.350	1.642	1.727	1.250
Mg(C)	2.792	2.834	3.361	3.440	3.416	3.448	3.238	3.239	3.273	3.130
Fe ²⁺ (C)	1.022	1.119	0.304	0.149	0	0.270	0.383	0.083	0	0.508
Mn(C)	0.060	0.047	0.075	0.051	0	0.074	0.028	0.034	0	0.075
Ca(C)	0	0.002	0	0	0	0	0	0	0	0.004
Mg(B)	0	0	0	0	0.050	0	0	0	0.104	0
Mn(B)	0.014	0	0.036	0.051	0.126	0	0.062	0.075	0.107	0
Ca(B)	1.619	1.668	1.615	1.540	1.503	1.616	1.602	1.464	1.480	1.594
Na(B)	0.381	0.332	0.385	0.460	0.497	0.384	0.398	0.536	0.520	0.406
Na(A)	0	0.015	0	0	0	0	0	0	0	0
K(A)	0.074	0.108	0.060	0.049	0.042	0.073	0.056	0.054	0.039	0.078
Mg [#]	0.73	0.72	0.92	0.96	1.00	0.93	0.89	0.98	1.00	0.86
P(kbar)	0.30	1.11	0.60	0.32	0.05	1.00	0.42	0.38	0.01	1.39
logf _{O₂}	-12.07	-12.37	-10.95	-10.86	-10.92	-10.69	-11.30	-11.14	-10.73	-11.44
△NNO	1.6	1.4	2.3	2.5	2.6	2.4	2.2	2.3	2.6	1.9
T(℃)	810	803	826	824	814	836	815	818	827	820

注:Mg[#] = Mg²⁺ / (Mg²⁺ + Fe²⁺) ; 角闪石结晶压力根据 Schmidt (1992)公式计算; 角闪石结晶温度和氧逸度根据 Ridiofi et al. , (2010)公式计算。

×10⁻⁶ ~ 28.72 × 10⁻⁶ , Th/U 比值 1.39 ~ 2.42。在球粒陨石标准化的稀土配分模式图上重稀土强烈富集,具有明显的 Ce 正异常和 Eu 负异常(图 6b)。

6 讨论

6.1 成矿岩浆的氧逸度

6.1.1 角闪石成分氧逸度计

角闪石是钙碱性岩浆岩中最常见的造岩矿物,其稳定性与岩浆体系的氧逸度、水含量和熔体成分有关(Sisson et al. , 1993; Grove et al. , 2003)。Anderson et al. (1995)确定了不同氧逸度条件下,

角闪石 Fe/(Fe + Mg) 值和^{IV}Al 的变化范围。在 Fe/(Fe + Mg) - ^{IV}Al 图解中(图 7a),斑岩铜矿含矿和未矿化岩体均分布于高氧逸度区,指示成矿作用与高氧逸度的岩浆有关。包古图 III-2 岩体石英闪长岩中的角闪石分布于含矿岩体的区域内,说明包古图成矿岩浆具有较高的氧化状态。

Ridolfi et al. , (2010)通过实验研究给出了氧逸度与角闪石成分之间的关系式:

$$\Delta\text{NNO} = 1.644\text{Mg}^* - 4.01 \text{ (} R^2 = 0.89 \text{)}$$

其中 $\text{Mg}^* = \text{Mg} + \text{Si}/47 - {}^{\text{VI}}\text{Al}/9 - 1.3 {}^{\text{VI}}\text{Ti} + \text{Fe}^{3+}/3.7 + \text{Fe}^{2+}/5.2 - {}^{\text{B}}\text{Ca}/20 - {}^{\text{A}}\text{Na}/2.8 + {}^{\text{A}}[\text{ }]/$

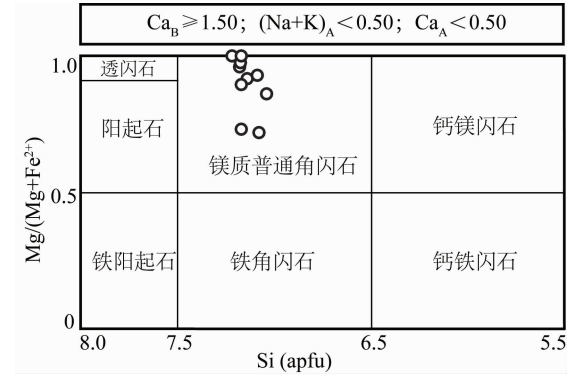


图 5 新疆包古图 III-2 岩体石英闪长岩角闪石分类图解(底图据 Leake et al. , 1997)

Fig. 5 Classification diagram of amphibole in quartz diorite from the Baogutu intrusion III-2, Xinjiang (after Leake et al. , 1997)

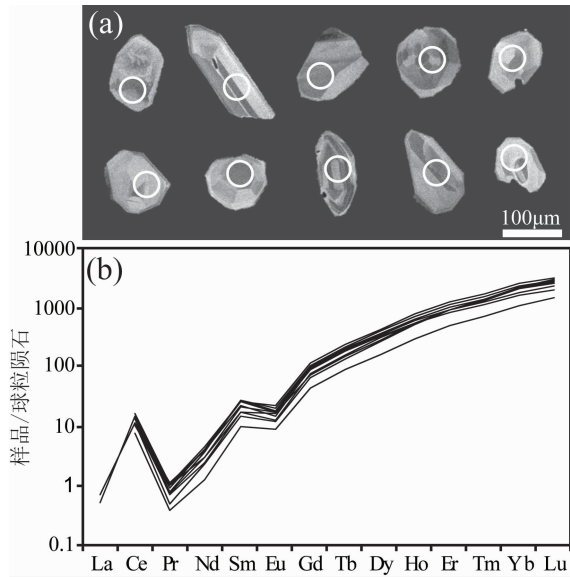


图 6 新疆包古图 III-2 岩体锆石 CL 图像(a)和球粒陨石标准化稀土配分模式图(b) (标准化值据 Sun et al. , 1989)

Fig. 6 Cathodoluminescence (CL) images (a) and chondrite-normalized REE patterns (b) for zircons from the Baogutu intrusion III-2, Xinjiang (normalization values are from Sun et al. , 1989)

9.5, NNO 为 Ni-NiO 氧逸度缓冲对。公式计算误差为 $\pm 0.22 \log f_{O_2}$, 在实验预估误差范围内 ($0.2 \sim 0.3 \log f_{O_2}$, Scaillet et al. , 1991; Pichavant et al. , 2002)。该氧逸度计适用于温度 $500 \sim 1200^{\circ}\text{C}$, 压力 $< 1200 \text{ MPa}$, 氧逸度 $\Delta \text{NNO} - 1$ 到 $\Delta \text{NNO} + 5$ 之间的岩浆。Ayati et al. (2012) 用该方法计算获得 Dalli 斑岩铜-金矿含矿闪长玢岩和花岗闪长斑岩的氧逸度为 $\Delta \text{NNO} + 1.3$ 。Li Jinxiang et al. (2018) 用该方法获得西藏多龙矿区含矿闪长岩的氧逸度为

$\Delta \text{NNO} + 1.8$, 未矿化花岗闪长岩的氧逸度为 $\Delta \text{NNO} + 1.2$ 。本文采用该公式计算获得包古图 III-2 岩体石英闪长岩的相对氧逸度为 $\Delta \text{NNO} + 1.4 \sim \Delta \text{NNO} + 2.6$ (表 1)。对比世界范围内斑岩铜矿含矿和未矿化岩体的角闪石成分发现, 含矿岩体氧逸度变化范围很大 ($\Delta \text{NNO} + 0.1 \sim \Delta \text{NNO} + 2.7$), 峰值集中在 $\Delta \text{NNO} + 1.2 \sim \Delta \text{NNO} + 1.4$ (图 7c); 未矿化岩体氧逸度变化范围较小 ($\Delta \text{NNO} + 0.2 \sim \Delta \text{NNO} + 2.1$), 峰值集中在 $\Delta \text{NNO} + 0.8 \sim \Delta \text{NNO} + 1.2$ (图 7d)。包古图 III-2 岩体分布在含矿岩体的范围内。

角闪石成分还可提供结晶温度和压力信息, 根据 Schmidt (1992) 给出的角闪石全铝压力计 ($P = -3.01 + 4.76 \text{ Al}_{\text{Tot}}$) 获得包古图 III-2 岩体角闪石的结晶压力为 $0.01 \sim 1.39 \text{ kbar}$ 。同时根据 Ridolfi et al. (2010) 提出的角闪石单矿物温度计 ($T = -151.487 \text{ Si}^* + 2041$) 获得角闪石的结晶温度为 $803 \sim 836^{\circ}\text{C}$ 。结合 NNO 缓冲对与温度、压力之间的关系式 (Huebner et al. , 1970) 确定出岩浆体系的 $\log f_{O_2}$ 值为 $-12.37 \sim -10.69$, 投影于斑岩铜矿含矿岩体的分布范围内 (图 7b)。

6.1.2 锆石 $\text{Ce}^{4+}/\text{Ce}^{3+}$ 、 Eu/Eu^* 比值

锆石是中酸性侵入岩常见的副矿物, 其分布广泛、地球化学性质稳定, 记录了结晶时的年龄、温度、氧逸度等信息。REE 元素中的 Ce 和 Eu 是变价元素 (REE 为 REE^{3+} , Ce 可以呈现 Ce^{4+} , Eu 可以呈现 Eu^{2+}), 其价态与岩浆的氧化还原状态有关。高氧逸度状态下, 大量的 Ce^{3+} 被氧化为 Ce^{4+} , 而 Ce^{4+} 与 Zr^{4+} 离子半径相似、电价相同, 可以类质同相置换的方式进入锆石晶格。因此, 在球粒陨石标准化的稀土配分模式图上锆石显示 Ce 的正异常, 锆石的 $\text{Ce}^{4+}/\text{Ce}^{3+}$ 比值可用于指示岩浆的氧化状态。在 Ce 异常计算过程中, Ce^{3+} 通常根据相邻的 La 和 Pr 计算获得。但是, 由于锆石中这两个元素的含量很低, 接近 LA-ICP-MS 的测试极限, 通过这种方法很难准确获得 Ce^{3+} 的含量值。因此, 我们选择 Ballard et al. (2002) 给出的公式:

$$\left(\frac{\text{Ce}^{4+}}{\text{Ce}^{3+}}\right)_{\text{锆石}} = \frac{(\text{Ce}_{\text{熔体}} - \text{Ce}_{\text{锆石}} / D_{\text{Ce}^{3+}}^{\text{锆石/熔体}})}{(\text{Ce}_{\text{锆石}} / D_{\text{Ce}^{4+}}^{\text{锆石/熔体}} - \text{Ce}_{\text{熔体}})}$$

来进行锆石 Ce 异常的计算。需要注意的是, 该公式在使用过程中, $\text{Ce}_{\text{熔体}}$ 由全岩样品的 Ce 含量给出。这就意味着, 如果有富含稀土元素的矿物 (如榍石、独居石、金红石等) 先于或与锆石同时结晶, 就会对该公式的计算结果产生显著影响。Zou Xinyu

表 2 新疆包古图 III-2 岩体锆石 LA-ICP-MS 测试结果 ($\times 10^{-6}$)

Table 2 LA-ICP-MS trace element data of zircons from the Baogutu intrusion III-2, Xinjiang ($\times 10^{-6}$)

测点号	09BGT- 26-1	09BGT- 26-3	09BGT- 26-5	09BGT- 26-6	09BGT- 26-8	09BGT- 26-11	09BGT- 26-12	09BGT- 26-13	09BGT- 26-14	09BGT- 26-15
Al	1.78	580.08	12.02	7.82	3.48	211.39	3.65	3.52	2.21	1.34
Si	153225	153225	153225	153225	153225	153225	153225	153225	153225	153225
P	308	240	213	168	256	248	297	269	274	261
Ti	10.85	18.11	8.32	8.17	8.51	28.72	8.52	9.41	10.83	9.86
Y	1333	935	1198	435	1006	979	983	1079	928	1082
Zr	408301	409601	416716	418951	419753	414501	420298	419762	417104	411367
Nb	0.67	0.30	0.47	0.27	0.31	0.63	0.63	0.47	0.61	0.50
La	bdl	0.17	bdl	bdl	bdl	0.12	bdl	bdl	bdl	bdl
Ce	10.31	6.91	8.60	4.02	6.42	8.96	8.42	7.15	7.04	8.37
Pr	0.11	0.11	0.08	0.03	0.10	0.10	0.07	0.07	0.05	0.09
Nd	2.11	1.79	1.76	0.52	1.97	1.43	1.13	1.40	1.07	1.93
Sm	4.12	3.50	4.14	1.33	4.25	2.67	2.67	3.26	2.31	4.07
Eu	1.28	0.87	1.16	0.43	1.04	0.97	0.73	1.00	0.71	0.99
Gd	23.46	19.51	21.89	7.53	20.60	14.85	16.10	18.59	13.32	20.89
Tb	8.76	6.89	8.03	2.90	7.27	5.62	6.06	7.07	5.02	7.57
Dy	109.41	82.87	99.69	35.14	88.31	71.90	77.24	88.78	67.25	92.95
Ho	43.93	31.36	39.73	14.23	33.80	30.65	31.48	35.21	29.22	36.18
Er	203	139	185	67.95	152	152	151	166	149	164
Tm	43.18	28.60	39.00	15.19	31.46	34.77	33.44	35.79	34.12	34.70
Yb	429	276	382	157	308	370	345	363	363	345
Lu	80.91	50.84	71.55	31.11	57.00	75.10	66.46	69.39	73.34	63.42
Hf	7525	8155	8354	7858	8440	7532	8354	7559	7395	7876
Ta	0.20	0.11	0.17	0.12	0.14	0.18	0.25	0.16	0.23	0.19
Th	48.97	39.14	43.76	18.74	32.41	53.70	39.74	32.89	30.10	35.72
U	79.29	54.41	69.23	40.98	52.45	84.12	79.17	59.03	72.80	60.41
REE	959	648	863	338	713	769	740	797	745	780
Eu/Eu*	0.40	0.32	0.37	0.42	0.34	0.47	0.34	0.39	0.39	0.33
Ce ⁴⁺ /Ce ³⁺	51.46	31.22	53.36	78.93	29.55	64.32	78.40	54.59	89.50	44.25
T(℃)	782	836	756	754	758	890	758	768	781	772
δK	−1.97	−0.37	−0.25	−0.18	−0.27	0.05	−0.17	−0.22	0.03	−0.24

注:锆石 Ce⁴⁺/Ce³⁺ 和 Eu_N/Eu_N^{*} 比值根据 Ballard et al. (2002)计算; 锆石结晶温度根据 Ferry et al. (2007)计算; 偏离系数 δK 根据 Zou et al. (2019)计算。

et al. (2019)给出了一个偏离系数 δK,用于限定全岩成分对熔体成分的偏离程度。并指出,只有 δK<3 的锆石才能给出可信的 Ce⁴⁺/Ce³⁺ 比值。包古图 III-2 岩体锆石的 δK 值为 −1.97~0.05,指示全岩成分可有效代表熔体成分。进一步计算获得包古图 III-2 岩体锆石的 Ce⁴⁺/Ce³⁺ 比值为 29.55~89.50。

与 Ce 异常类似,锆石的 Eu 异常也可指示岩浆的氧化状态。在氧化条件下,大量的 Eu²⁺被氧化为 Eu³⁺,Eu³⁺ 在锆石中的分配系数远大于 Eu²⁺,锆石 Eu 含量升高,显示弱负或无 Eu 异常。需要注意的是,锆石的 Eu/Eu^{*} 比值容易受到斜长石、角闪石、磷灰石等早期矿物相影响。Eu 在斜长石中的分配系数较高,早期结晶的斜长石会强烈消耗岩浆中的 Eu,导致锆石显示强负 Eu 异常。角闪石和磷灰石中 Eu 的分配系数较小,二者的早期结晶会导致锆

石 Eu 负异常减弱。分析发现,III-2 岩体全岩样品 Eu/Eu^{*} 比值中等(0.92~1.44,平均 1.21,We Shaoni, 2012),球粒陨石标准化的稀土配分模式图上显示弱的 Eu 正异常。这说明早期结晶的矿物相对体系 Eu 异常的影响相互抵消,锆石的 Eu/Eu^{*} 比值可用于指示岩浆的氧化状态。根据 Eu/Eu^{*} = (Eu_N/(Sm_N×Gd_N)^{1/2}) 计算获得包古图 III-2 岩体锆石的 Eu/Eu^{*} 比值为 0.32~0.47。

关于锆石 Ce⁴⁺/Ce³⁺ 和 Eu/Eu^{*} 比值对岩浆氧逸度的定量指示意义,不同学者有不同的观点。例如,Ballard et al. (2002)认为 Ce⁴⁺/Ce³⁺>300、Eu/Eu^{*}>0.4 是划分智利北部含矿与不含矿岩体的界线。Liang Huaying et al. (2006)给出 Ce⁴⁺/Ce³⁺>120 为区分玉龙含矿和不含矿侵入体的界限值。Wang Rui et al. (2014)认为岗底斯东部中新世成

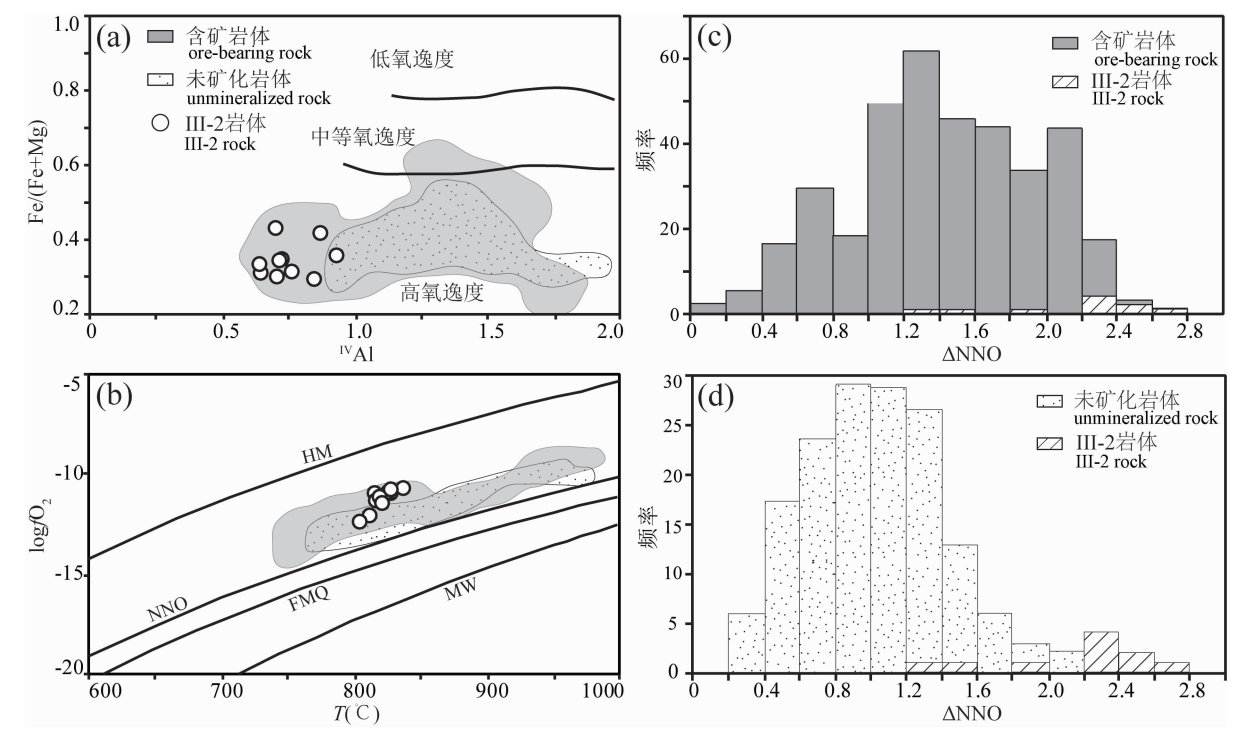


图 7 新疆包古图斑岩铜矿角闪石成分及相关参数图解

Fig. 7 Plots and histograms of compositions and parameters estimated from amphiboles from porphyry copper deposits in Baogutu, Xinjiang

(a)一角闪石 $\text{Fe}/(\text{Fe}+\text{Mg})\text{-IV Al}$ 图解(据 Anderson et al. , 1995); (b)一氧逸度-温度图解(b, $P=1\text{kbar}$); (c)一含矿岩体 ΔNNO 直方图; (d)一未矿化岩体 ΔNNO 直方图. 文献数据来自 Ayati et al. , 2012, Wang Rui et al. , 2014, Shen Ping et al. , 2015a, Sun Jia et al. , 2017, Li Jinxiang et al. , 2018, Wei Shaoni et al. , 2019, Zarasvandi et al. , 2019. HM—赤铁矿-磁铁矿缓冲对(Spencer et al. , 1981), NNO—镍-氧化镍缓冲对(Huebner et al. , 1970), FMQ—铁橄榄石-磁铁矿-石英缓冲对(Huebner, 1971), MW—方铁矿-磁铁矿缓冲对(Eugster et al. , 1962)

(a)— $\text{Fe}/(\text{Fe}+\text{Mg})\text{vs. IV Al}$ diagram of amphibole (after Anderson et al. , 1995); (b)— $\log f_{\text{O}_2}\text{ vs. }T$ diagram ($P=1\text{kbar}$); (c)— ΔNNO histogram for ore-bearing intrusions; (d)— ΔNNO histogram for barren intrusions. Literature data from Ayati et al. , 2012, Wang Rui et al. , 2014, Shen Ping et al. , 2015a, Sun Jia et al. , 2017, Li Jinxiang et al. , 2018, Wei Shaoni et al. , 2019, Zarasvandi et al. , 2019. HM—hematite-magnetite buffer (Spencer et al. , 1981), NNO—nickel-nickel oxide buffer (Huebner et al. , 1970), FMQ—fayalite-magnetite-quartz buffer (Huebner, 1971), MW—wustite-magnetite buffer (Eugster et al. , 1962)

矿岩浆的 $\text{Ce}^{4+}/\text{Ce}^{3+}>50$ 。我们将包古图 III-2 岩体锆石 $\text{Ce}^{4+}/\text{Ce}^{3+}$ 和 Eu/Eu^* 比值与世界范围内的典型斑岩铜矿床进行了对比(表 3,图 8)。由对比结果可知,含矿岩体的 $\text{Ce}^{4+}/\text{Ce}^{3+}$ 和 Eu/Eu^* 比值变化范围很大, $\text{Ce}^{4+}/\text{Ce}^{3+}$ 比值在 0~100 范围内出现明显峰值,在 100~900 范围内连续分布,在 100~200 和 500~700 范围内出现次级峰值(图 8a), Eu/Eu^* 比值的峰值出现在 0.6~0.7 范围内(图 8b)。不含矿岩体的 $\text{Ce}^{4+}/\text{Ce}^{3+}$ 和 Eu/Eu^* 比值分布范围较小, $\text{Ce}^{4+}/\text{Ce}^{3+}$ 比值的峰值出现在 0~100 范围内,高 $\text{Ce}^{4+}/\text{Ce}^{3+}$ 比值(>300)的样品很少(图 8c), Eu/Eu^* 比值的峰值分布在 0.2~0.3 范围内(图 8d)。包古图 III-2 岩体锆石 $\text{Ce}^{4+}/\text{Ce}^{3+}$ (29.55~89.50)和 Eu/Eu^* 比值(0.32~0.47)中等,位于斑

岩铜矿含矿岩体和未矿化岩体的叠加部位(图 8e, f)。

6.2 成矿指示

斑岩矿床的形成,是铜、金、硫等成矿组分从岩浆源区迁移至地壳浅部富集沉淀的过程,岩浆溶解和迁移成矿组分的能力与其氧化状态密切相关。低氧逸度状态下($f_{\text{O}_2}<\text{FMQ}+2$,Mungall, 2002; Sun Weidong et al. , 2015),岩浆中的硫主要以硫化物(S^{2-})的形式存在。硫化物在岩浆中的溶解度很低,而 Cu、Au 等亲铜元素在硫化物熔体和硅酸盐熔体间的分配系数很高($D_{\text{Cu}}=1334\pm210$,Patten et al. , 2013; $D_{\text{Au}}=4500\sim11200$, Mungall and Brenan, 2014),因此少量结晶的硫化物即可消耗岩浆中的大量亲铜元素。在高氧逸度状态下($f_{\text{O}_2}>$

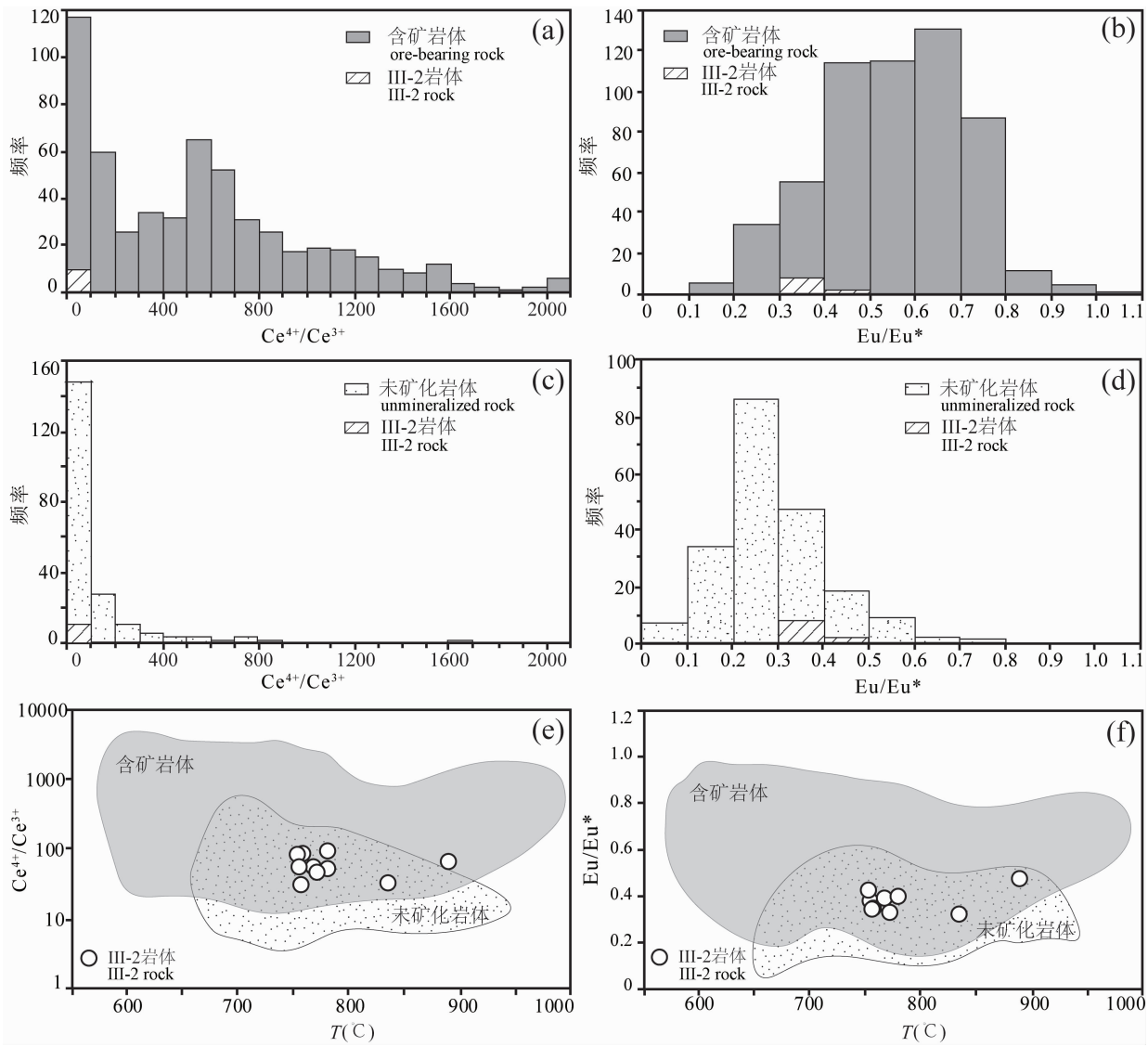


图 8 新疆包古图斑岩矿床锆石微量元素比值图解

Fig. 8 Zircon trace element ratio histograms for porphyry deposits in Baogutu, Xinjiang

(a)—含矿岩体锆石 Ce^{4+}/Ce^{3+} 比值直方图; (b)—含矿岩体锆石 Eu/Eu^* 比值直方图; (c)——未矿化岩体锆石 Ce^{4+}/Ce^{3+} 比值直方图; (d)——未矿化岩体锆石 Eu/Eu^* 比值直方图; (e)——包古图 III-2 岩体锆石 Ce^{4+}/Ce^{3+} —T 图解; (f)——包古图 III-2 岩体锆石 Eu/Eu^* —T 图解。文献数据来源见表 3。锆石结晶温度根据 Ferry et al. (2007) 计算

(a)—Zircon Ce^{4+}/Ce^{3+} ratio histogram for ore-bearing intrusions; (b)—zircon Eu/Eu^* ratio histogram for ore-bearing intrusions; (c)—zircon Ce^{4+}/Ce^{3+} ratio histogram for barren intrusions; (d)—zircon Eu/Eu^* ratio histogram for barren intrusions; (e)—zircon Ce^{4+}/Ce^{3+} vs. temperature diagram for the Baogutu intrusion III-2; (f)—zircon Eu/Eu^* vs. temperature diagram for the Baogutu intrusion III-2. See table 3 for data source of the shaded region. Temperature was calculated using the Ti-in-zircon thermometer based on Ferry et al. (2007)

FMQ + 2, Mungall, 2002; Sun Weidong et al., 2015), 岩浆中的硫主要以硫酸盐(SO_4^{2-})的形式存在, 硫的溶解度大大增加(高出硫化物一个数量级, Jugo et al., 2010), 同时拟制或分解早期结晶的硫化物相, 确保原始岩浆中保有丰富的 Cu、Au 含量。Shen Ping et al. (2015b) 通过对巴尔喀什-准噶尔成矿带斑岩型矿床的研究认为, 成矿岩浆的氧逸度与矿床规模之间存在正相关关系, 氧逸度越高, 矿床

规模越大。Zhang Chanchan et al. (2017) 对比了世界范围内七个典型斑岩矿床锆石 Ce^{4+}/Ce^{3+} 比值与铜储量之间的关系, 获得了相同的认识。

角闪石成分氧逸度计指示包古图 III-2 岩体的氧逸度值为: $\Delta NNO + 1.4 \sim \Delta NNO + 2.6$, 与世界范围内其他斑岩矿床角闪石数据对比发现, 包古图斑岩铜矿位于含矿岩体的氧逸度变化范围(图 7)。同时, 包古图 III-2 岩体具有中等的锆石 Ce^{4+}/Ce^{3+}

表 3 新疆包古图斑岩矿床锆石 Ce^{4+}/Ce^{3+} 和 Eu/Eu^* 比值总结

Table 3 Summary of zircon Ce^{4+}/Ce^{3+} and Eu/Eu^* ratios from porphyry deposits in Baogutu, Xinjiang

含矿岩体	Ce^{4+}/Ce^{3+}	Eu/Eu^*	$T(^{\circ}C)$	参考文献
Chuquicamata El Abar	91~2341	0.23~0.95	—	Ballard et al., 2002
El Teniente	26.8~2718	0.17~0.64	613~813	Muñoz et al., 2012
Kalmakyr	387~1621	0.16~1.02	—	Zhao Xiaobo et al., 2017
Bozshakol	77~528	0.54~0.79	683~748	Shen Ping et al., 2015b
Nurkazghan	74~362	0.43~0.61	717~792	Shen Ping et al., 2015b
Kounrad	81~592	0.43~0.57	678~766	Shen Ping et al., 2015b
Aktogai	98~248	0.41~0.60	736~806	Shen Ping et al., 2015b
Erdenet	75~256	0.27~0.33	748~812	Shen Ping et al., 2015b
Koksai	129~204	0.51~0.58	682~721	Shen Ping et al., 2015b
土屋-延东	74~332	0.28~0.40	648~693	Shen Ping et al., 2015b
Borly	29~158	0.24~0.51	719~824	Shen Ping et al., 2015b
岗底斯含矿岩浆岩	18.62~141.86	0.19~0.87	604~782	Wang Rui et al., 2014
玉龙	5~765	—	—	Liang Huaying et al., 2006
扎拉杂	26~729	—	—	Liang Huaying et al., 2006
莽总	18~1230	—	—	Liang Huaying et al., 2006
多霞松多	10~1314	—	—	Liang Huaying et al., 2006
马拉松多	17~1304	—	—	Liang Huaying et al., 2006
普朗	65~1128	0.5~0.7	649~863	Kong Dexin et al., 2016
烂泥塘	162.59~620.52	0.54~1.00	581~918	Yu Yifan et al., 2016
德兴	176~1922	0.51~0.82	588~1085	Zhang Hong et al., 2013; Zhang Chanchan et al., 2017
沙溪	186~1972	0.62~0.87	607~715	Deng Jianghong et al., 2016
罗卜岭	152~2621	0.4~0.9	610~752	Li Bin et al., 2017; Li Congying et al., 2017
包古图	15.91~163.30	0.25~0.57	657~947	Shen Ping et al., 2015b; Wei Shaoni et al., 2019; 本研究
未矿化岩体				
Chuquicamata El Abar	5~1689	0.05~0.72	—	Ballard et al., 2002
岗底斯	6.04~66.75	0.08~0.61	665~889	Wang Rui et al., 2014
沙溪	6~372	0.19~0.44	680~936	Deng Jianghong et al., 2016

(29.55~89.50) 和 Eu/Eu^* 比值 (0.32~0.47), 位于斑岩铜矿含矿岩体和未矿化岩体的叠加部位(图 8)。现有数据和对比结果显示, 包古图斑岩铜矿成矿岩浆氧逸度较高, 对成矿元素的溶解和迁移有利。

7 结论

- (1)包古图斑岩铜矿 III-2 岩体岩性均一, 以石英闪长(玢)岩和闪长岩为主。早期结晶的角闪石富 $Mg(Mg^{\#} = 0.72 \sim 1.00)$, 角闪石成分氧逸度计指示成矿岩浆的氧逸度为 $\triangle NNO + 1.4 \sim \triangle NNO + 2.6$, 位于斑岩铜矿含矿岩体的分布范围。
- (2)锆石富含稀土, 具有左倾型的稀土配分模式。锆石 Ce^{4+}/Ce^{3+} 比值为 29.55~89.50, Eu/Eu^* 比值为 0.32~0.47, 位于斑岩铜矿含矿岩体和未矿化岩体的叠加部位。
- (3)包古图斑岩铜矿 III-2 岩体成矿岩浆氧逸度较高, 有利于成矿元素的溶解和迁移。

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Oxygen fugacity of the intrusion III-2 in the Baogutu porphyry copper deposit, Xinjiang: evidence from mineral compositions

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Abstract

Baogutu porphyry copper deposit, the largest porphyry type deposit of the area, is located in the west Junngar, Xinjiang. The ore-forming processes are closely associated with the late Carboniferous intermediate-acidic intrusions. The intrusion III-2, located in the south of the mine, with the characteristics of wholly mineralized and low grade, is an ideal sample for investigation of the nature of the ore-forming magma. In this paper, oxygen fugacity of ore-forming magma was discussed on the basis of petrology and mineral compositions of amphibole and zircon, by comparison with typical porphyry copper deposits. The results show that the Baogutu intrusion III-2 is mainly composed of quartz diorite (porphyry) and diorite, with a small amount of pyroxene diorite. Plagioclase, amphibole, biotite, quartz and potassium feldspar are the major ore-forming minerals, with minor ilmenite, sphene and apatite. Early stage euhedral amphiboles from quartz diorite are classified as calcic amphibole with high $Mg^{\#}$ (0.72~1.00). The oxygen barometer based on amphibole compositions provides $\log f_{O_2}$ values ranging from $\Delta NNO+1.4$ to $\Delta NNO+2.6$, which is in the variation range of ore-bearing intrusions from porphyry copper deposits worldwide. Zircons from quartz diorite are characterized by high REE content ($338 \times 10^{-6} \sim 959 \times 10^{-6}$). With depleted LREE and enriched HREE, these zircons display left-leaning REE patterns and strongly positive Ce and negative Eu anomalies. The moderate Ce^{4+}/Ce^{3+} (29.55~89.50) and Eu/Eu^* ratios (0.32~0.47) are in the overlapping portion of ore-bearing and ore-barren intrusions from porphyry copper deposits. These data indicate that the oxygen fugacity of the ore-forming magma of the Baogutu intrusion III-2 are relatively high, which is beneficial for the dissolution and migration of metal elements, and also facilitates the formation of porphyry copper deposits.

Key words: oxygen fugacity; porphyry copper deposit; ore-forming magma; Baogutu; West Junngar