

西藏甲玛 3000 m 科学深钻矽卡岩 矿物分带及地质意义

王梦蝶¹⁾, 唐菊兴^{* 2)}, 林彬²⁾, 唐攀³⁾, 唐晓倩⁴⁾, 孙渺⁵⁾, 李发桥⁵⁾, 祁婧⁵⁾,
傅渊慧⁶⁾, 张忠坤⁶⁾, 崔浩¹⁾, 杨征坤⁶⁾, 熊妍¹⁾

1) 成都理工大学地球科学学院, 四川成都, 610059;

2) 中国地质科学院矿产资源研究所, 自然资源部成矿作用与资源评价重点实验室, 北京, 100037;

3) 西南科技大学环境与资源学院, 固体废物处理与资源化教育部重点实验室, 四川绵阳, 621010;

4) 北京中矿联咨询中心, 北京, 100044; 5) 中国地质大学(北京), 北京, 100083;

6) 西藏华泰龙矿业开发有限公司, 西藏拉萨, 850200

内容提要: 甲玛铜多金属矿床是冈底斯成矿带东段具有重大经济价值及科学研究意义的超大型斑岩-矽卡岩矿床, 完整地保存了矽卡岩矿床形成和演化的重要信息。前人研究多集中于矽卡岩的水平分带, 而对于矽卡岩矿物垂直分带以及其与金属矿化的耦合关系等方面研究薄弱。本文重点对甲玛 3000 m 科学深钻中矽卡岩矿体进行了精细的矿物学研究, 系统揭示了矽卡岩矿体的矿物学空间分带特征以及与金属矿化的耦合关系。结果表明, 矽卡岩从浅部至深部具有清晰的分带现象, 即矽卡岩化角岩→透辉石石榴子石矽卡岩→硅灰石石榴子石矽卡岩→石榴子石硅灰石矽卡岩→透辉石石榴子石矽卡岩→石榴子石硅灰石矽卡岩→矽卡岩化大理岩→硅灰石石榴子石矽卡岩→透辉石石榴子石矽卡岩→硅灰石石榴子石矽卡岩→矽卡岩化大理岩→硅灰石石榴子石矽卡岩→透辉石石榴子石矽卡岩→内矽卡岩(含石榴子石花岗闪长斑岩)。金属矿物组合从浅部向深部, 变化为辉钼矿±黄铜矿→斑铜矿±黄铜矿±辉铜矿±硫铋铜矿±辉钼矿→辉钼矿±黄铜矿, 对应成矿元素变化为 Mo±Cu±Au±Ag→Cu(Mo)±Au±Ag→Mo±Cu±Au±Ag。研究表明, 侵入岩及围岩的空间位置、构造环境、多期次热液流体叠加是控制矽卡岩矿物分带的重要因素。同时, 矿物学特征表明, 矽卡岩中高品位金的富集与斑铜矿等铜硫化物密切相关, 也可能与多期次流体叠加和富金岩浆源区有关。

关键词: 矽卡岩分带; 斑岩-矽卡岩矿床; 矽卡岩矿物学; 甲玛; 西藏

矽卡岩(Skarn)是一类主要由富钙或富镁的硅酸盐矿物组成的蚀变岩石(Einaudi et al., 1982; Meinert et al., 2005), 其矿物组合及化学成分的变化规律可以指示矽卡岩矿床中交代蚀变作用的强弱、热液流体的运移方向以及成矿的演化过程等(赵一鸣等, 1982; Meinert et al., 1987, 2005), 同时对于矿床勘查评价也具有重要指示意义(Meinert, 1992, 1997)。西藏甲玛矿床具有斑岩型、矽卡岩

型、角岩型、Manto 型和独立金矿体多元矿体结构, 为冈底斯成矿带碰撞背景下斑岩成矿系统的典型代表(林彬等, 2019)。前人在矿床地质特征与矿床模型(唐菊兴等, 2010, 2011; 冷秋锋等, 2015; Zheng Wenbao et al., 2016; 林彬等, 2019)、岩石及矿床地球化学特征(郑文宝等, 2010a, 2012; 李永胜等, 2011, 2012; 秦志鹏等, 2011a, 2012; 应立娟等, 2012a)、构造控矿(钟康惠等, 2012; Duan Jilin et

注: 本文为国家重点研发计划-深地专项(编号 2022YFC2905001)、国家自然科学基金科研项目(编号 42272093、41902097)、中国地质科学院矿产资源研究所基本科研业务费(编号 KJ2102、KK2116、KK2017)、西藏自治区科技计划项目(编号 XZ201901-GB-24)和中国地质调查局项目(编号 DD20190167)联合资助的成果。

收稿日期: 2022-06-07; 改回日期: 2022-08-07; 网络发表日期: 2022-09-25; 责任编委: 范宏瑞; 责任编辑: 蔡志慧。

作者简介: 王梦蝶, 女, 1994 年生。硕士研究生, 构造地质学专业。E-mail: 542397420@qq.com。

* 通讯作者: 唐菊兴, 男, 1964 年生。研究员, 主要从事青藏高原矿产勘查与综合研究工作。E-mail: tangjuxing@126.com。

引用本文: 王梦蝶, 唐菊兴, 林彬, 唐攀, 唐晓倩, 孙渺, 李发桥, 祁婧, 傅渊慧, 张忠坤, 崔浩, 杨征坤, 熊妍. 2023. 西藏甲玛 3000 m 科学深钻矽卡岩矿物分带及地质意义. 地质学报, 97(6): 0000~0000, doi: 10.19762/j.cnki.dizhixuebao.2022170.
Wang Mengdie, Tang Juxing, Lin Bin, Tang Pan, Tang Xiaolian, Sun Miao, Li Faqiao, Qi Jing, Fu Yuanhui, Zhang Zhongkun, Cui Hao, Yang Zhengkun, Xiong Yan. 2023. Mineral zoning and geological significance of skarns in the Jiamma 3000 m scientific deep borehole, Tibet. Acta Geologica Sinica, 97(6): 0000~0000.

al., 2014)、成岩成矿年代学(应立娟等, 2009, 2010, 2011; Ying Lijuan et al., 2014; 秦志鹏等, 2011b)、矿物学(王焕, 2011; 应立娟等, 2012b; 冷秋锋, 2016; 冷秋锋等, 2022)等方面对甲玛矿床进行了详细的研究, 并取得了丰硕的研究成果。然而, 对甲玛矿区超大规模矽卡岩的垂向分带及其与金属矿化的耦合关系和矽卡岩中高品位金的富集机制等问题仍不明确。在国家重点研发计划深地专项“青藏高原重要矿产资源基地成矿系统深部探测技术与勘查增储示范”的资助下, 项目组在甲玛矿区开展了 3000 m 的科学深钻(JMKZ-1), 该科学深钻穿透了甲玛斑岩成矿系统中的角岩、矽卡岩及斑岩型矿体, 并进入深部无矿核, 直接揭示甲玛矿区 3000 m 以浅的地质信息, 为矽卡岩矿物学的精细研究提供了关键地质样品(林彬等, 2021)。基于此, 本文以 3000 m 科学深钻为研究对象, 通过详细的地质编录、镜下鉴定和电子探针分析, 结合前人研究资料, 对矽卡岩矿物进行精细分带, 探讨其分带模式与金属矿化的耦合关系, 并基于细致的矿物结构和矿物地球化学证据, 揭示其成矿作用过程和高品位金的富集沉淀机制, 旨在探讨甲玛超大规模矽卡岩矿体的成因、演化过程、形成环境, 为勘查评价提供科学支撑。

1 矿区地质概况

甲玛矿床位于冈底斯成矿带东段。矿区内出露的地层主要为上侏罗统多底沟组(J_3d)灰白色—灰色块状结晶灰岩以及下白垩统林布宗组(K_1l)灰黑色板岩、粉砂岩, 二者为整合接触(图 1)。矿区受甲玛-卡军果推覆构造体系控制明显。矿区局部(铜山)发育滑覆构造(钟康惠等, 2012)。矿区地表岩浆岩出露面积较小, 以中新世中酸性岩脉为主, 包括(石英)闪长玢岩、花岗闪长斑岩、二长花岗斑岩、花岗斑岩以及少量煌斑岩和辉绿岩脉(秦志鹏等, 2011a; Zheng Wenbao et al., 2016)。勘查和研究表明, 甲玛矿区存在典型的“四位一体”矿体结构(图 2), 即浅部为产于斑岩体顶部的角岩型铜钼矿体, 中部为产于上覆角岩与下部大理岩的层间接触带或层间薄弱带的矽卡岩型铜多金属矿体(含 Manto 型矿体), 深部为与隐伏侵入岩脉有关的斑岩型钼铜矿体, 以及局部产于构造破碎带中的脉状金矿体(林彬等, 2012; 郑文宝等, 2012; 唐菊兴等, 2013; 唐攀等, 2017)。此外, 在甲玛主矿区外围的南坑、则古朗北以及象背山等地还发育多个集中矿化段, 它们与主

矿区共同构成了一个完整的斑岩成矿系统(林彬等, 2019; 邹兵等, 2019)。

2 3000 m 科学深钻的基本地质信息

甲玛 3000 m 科学深钻 JMKZ-1 位于甲玛主矿段 16 与 20 号勘探线之间(图 1), 设计方位角 240° , 天顶角 3° 。林彬等(2021)对甲玛 3000 m 科学深钻地质信息进行了详细描述, 0~620.87 m 主要为角岩, 蚀变主要发育硅化、黑云母化以及弱绿泥石化, 矿化以浸染状和脉状黄铁矿、黄铜矿及辉钼矿为主, 局部发育少量的磁铁矿化; 矽卡岩(矽卡岩化大理岩)厚度大于 360.85 m(620.87~981.72 m)且具有明显的分带特征, 从上到下依次为: 石榴子石绿泥石化角岩→绿泥石化石榴子石角岩→透辉石石榴子石矽卡岩→石榴子石矽卡岩→硅灰石石榴子石矽卡岩→石榴子石硅灰石矽卡岩→硅灰石矽卡岩→矽卡岩化大理岩(林彬等, 2019), 整体矿化较好, 以 Cu-Mo 矿化为主。深部(981.72~3003.3 m)主要发育复式斑岩体, 由二长花岗斑岩、花岗闪长斑岩、石英闪长玢岩组成, 并被细粒花岗岩脉穿插。斑岩体矿化相对较弱, 主要为细脉浸染状黄铜矿、石英-辉钼矿脉和少量的石英-黄铁矿-黄铜矿脉, 局部可见星散状黄铜矿, 到深部则无明显矿化。斑岩体浅部的二长花岗斑岩(1021.32~1357.80 m)发育明显的钾长石化、绢云母化以及绿泥石化等热液蚀变, 而中部二长花岗斑岩(1357.80~2116.56 m)蚀变明显减弱, 表现为弱绢云母化和绿泥石化, 深部二长花岗斑岩(2141.16~3003.3 m)仅局部发育弱绿泥石化和绢云母化。

3 样品采集及测试方法

本次研究对甲玛 3000 m 科学深钻从顶部角岩矿体到深部斑岩无矿核进行了典型岩石采样。所采集的样品均进行了详细的岩芯观察描述, 并进行了详细的镜下鉴定, 识别矿物组合与相对含量及矿石组构。本次研究在上述的工作基础上, 重点选取了矽卡岩矿体从浅部透辉石石榴子石矽卡岩至深部内矽卡岩的不同深度不同类型的矽卡岩为样品, 对 167 个点的不同期次不同类型的石榴子石以及部分金属矿物进行了详细的矿物学研究, 旨在通过岩芯地质编录、镜下鉴定和电子探针分析, 揭示矽卡岩矿体的矿物学空间分带及其与金属矿化的耦合关系, 同时, 基于矿物结构和矿物化学证据, 约束其成矿作用过程和高品位金的富集沉淀机制。电子探针实验

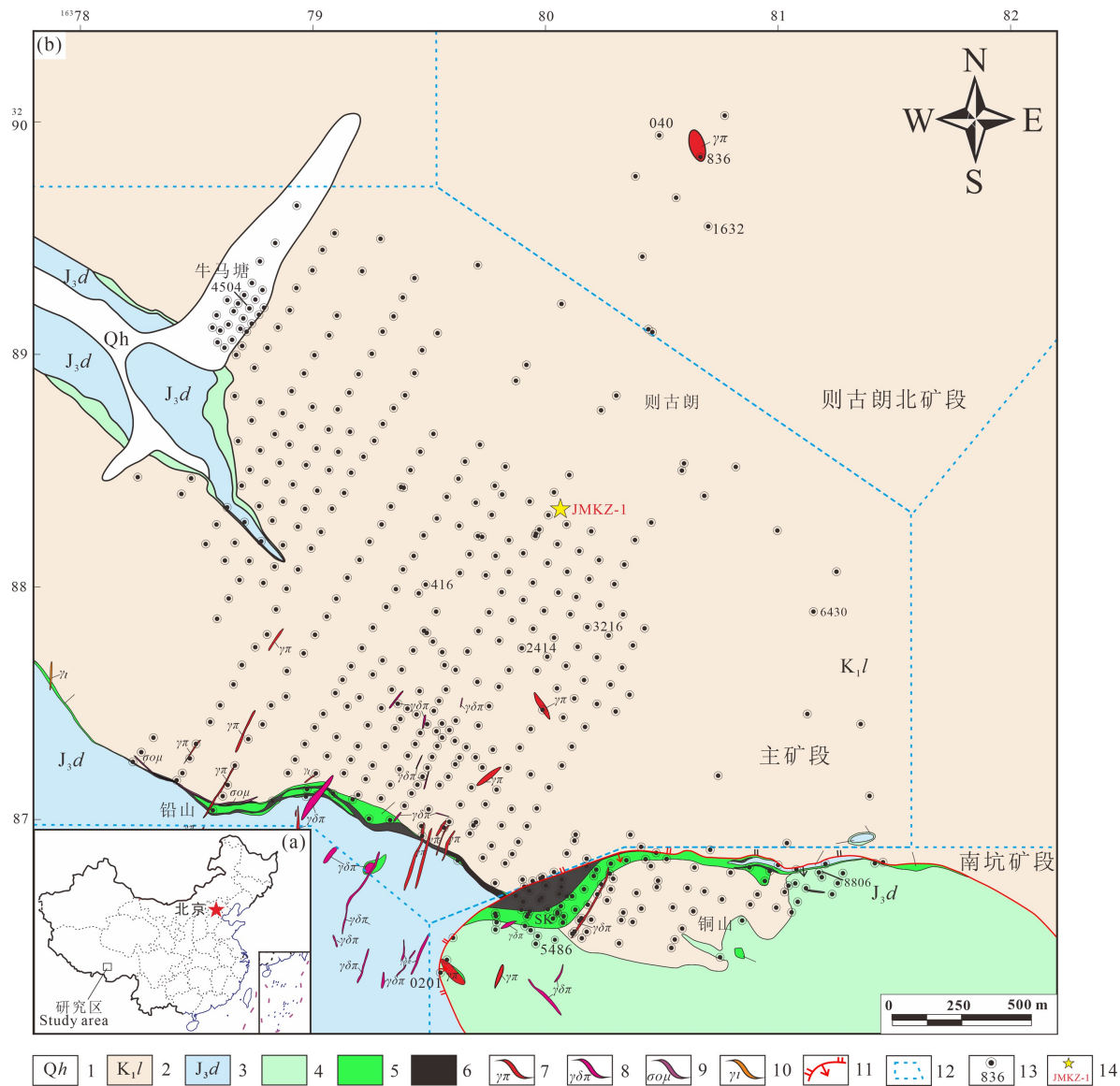


图 1 西藏甲玛矿区地理位置(a)、地质图以及科学深钻 JMKZ-1 位置(b)(据林彬等,2019)

Fig. 1 Geographical location of Jiama mining area, Tibet (a), geological map and scientific deep borehole JMKZ-1 location (b) (after Lin Bin et al. , 2019)

1—第四系沉积物;2—下白垩统林布宗组砂岩、板岩、角岩;3—上侏罗统多底沟组灰岩、大理岩;4—矽卡岩化大理岩;5—矽卡岩;6—矽卡岩型矿体;7—花岗斑岩脉;8—花岗闪长斑岩脉;9—石英闪长玢岩脉;10—细晶岩脉;11—滑覆构造断裂;12—矿段范围;13—钻孔及编号;14—科学深钻及编号

1—Quaternary sediments; 2—sandstone, slate and hornstone of Lower Cretaceous Linbuzong Formation ; 3—limestone and marble of Upper Jurassic Duodigou Formation; 4—skarn marble; 5—skarn; 6—skarn orebody; 7—granite porphyry dikes; 8—granodiorite porphyry dikes; 9—quartz diorite porphyrite dikes; 10—aplite dike; 11—strike slip fault; 12—range of ore block; 13—drill hole and its serial number; 14—scientific deep drilling site and number

在中国地质科学院矿产资源研究所自然资源部成矿作用与资源评价重点实验室完成,仪器型号:JXA-8230,实验条件均为:加速电压 20 kV,束流 20 nA,束斑 5 μm。详细研究结果如下:

3.1 矽卡岩矿物的空间分带

甲玛 3000 m 科学深钻的矽卡岩主要位于钻孔进尺 600~981.72 m。中间有少量的残留大理岩和

中酸性岩脉穿插。其中,根据矿物组合和共生关系,矽卡岩可大致分为透辉石石榴子石矽卡岩、石榴子石矽卡岩、硅灰石石榴子石矽卡岩、石榴子石硅灰石矽卡岩、矽卡岩化大理岩等。

结合详细的岩芯编录、镜下鉴定和电子探针分析结果,甲玛 3000 m 矽卡岩在垂向上具有明显的分带现象。根据矽卡岩矿物组合的变化从上到下依

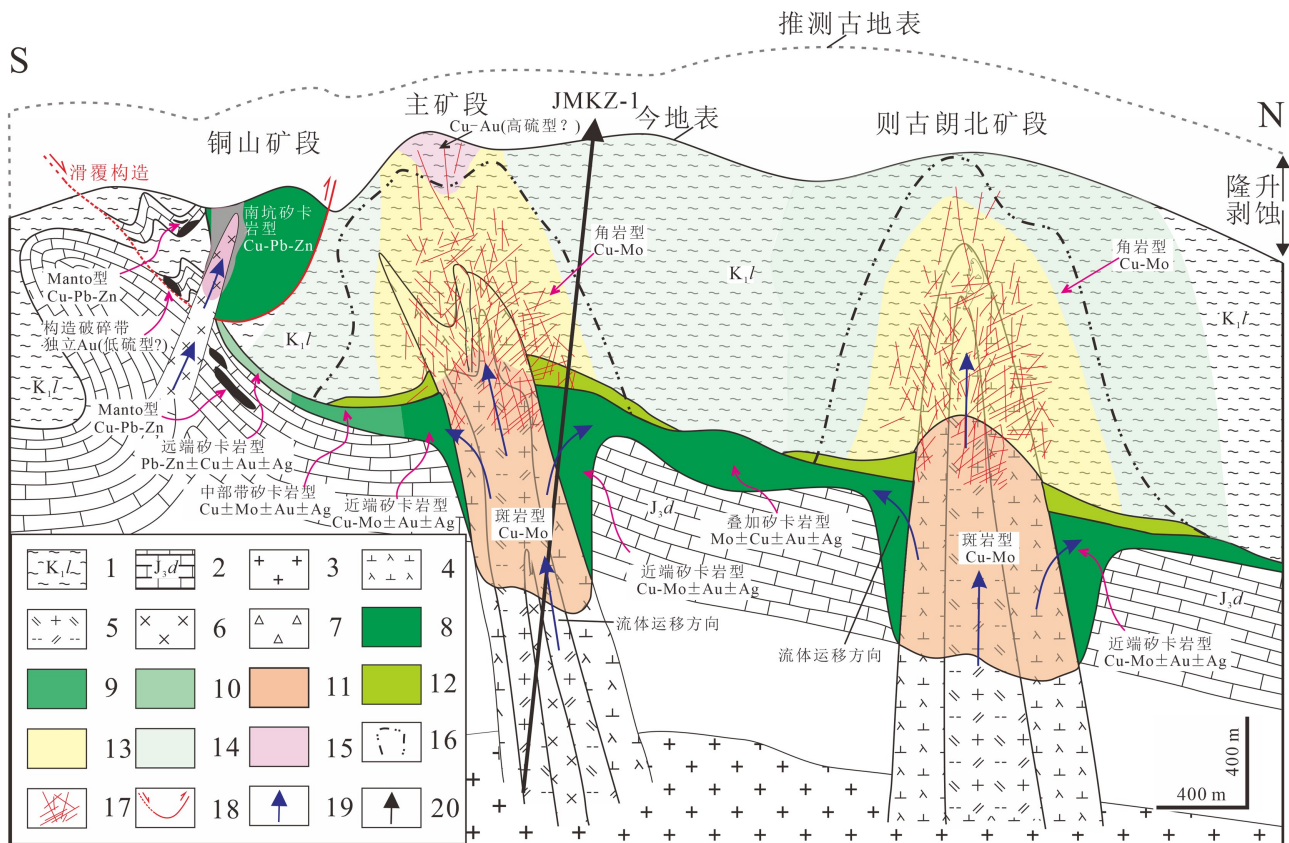


图2 甲玛斑岩成矿系统结构及多中心复合成矿作用模型(据林彬等, 2019)

Fig. 2 Structure of Jiama porphyry metallogenic system and multi center composite metallogenic model

(after Lin Bin et al. , 2019)

1—林布宗组砂、板岩;2—多底沟组灰岩、大理岩;3—浅部岩浆储库;4—二长花岗斑岩;5—花岗闪长斑岩;6—花岗斑岩;7—角砾岩;8—近端矽卡岩;9—中部矽卡岩;10—远端矽卡岩;11—钾硅酸盐岩化;12—绿泥石、绿帘石化;13—绢英岩化、弱泥化;14—角岩化;15—强硅化;16—角岩矿体界限;17—裂隙系统;18—滑覆构造;19—流体运移方向;20—科学深钻

1—sandstone and slate of Linbuzong Formation; 2—limestone and marble of Duodigou Formation; 3—shallow magma reservoir; 4—monzonitic granite porphyry; 5—granodiorite porphyry; 6—granite porphyry; 7—breccia; 8—proximal skarn; 9—intermediate skarn; 10—distal skarn; 11—potassium silicate alteration; 12—chlorite-epidote alteration; 13—phyllitic and weak argillic alteration; 14—hornfels alteration; 15—strong silicic alteration; 16—boundary of hornstone ore-body; 17—fissure system; 18—detachment fault; 19—fluid transport direction; 20—scientific deep borehole

次细分为:矽卡岩化角岩(581.06~600.8 m)→透辉石石榴子石矽卡岩(600.8~609 m)→硅灰石石榴子石矽卡岩(609~615.3 m)→石榴子石硅灰石矽卡岩(615.3~625.9 m)→透辉石石榴子石矽卡岩(625.9~646.67 m)→石榴子石硅灰石矽卡岩(646.67~675.81 m)→矽卡岩化大理岩(675.81~792.91 m)→硅灰石石榴子石矽卡岩(792.91~799.7 m)→透辉石石榴子石矽卡岩(799.7~804.5 m)→硅灰石石榴子石矽卡岩(804.5~812.22 m)→矽卡岩化大理岩(812.22~903.32 m)→硅灰石石榴子石矽卡岩(903.32~911.52 m)→透辉石石榴子石矽卡岩(911.52~920.32 m)→内矽卡岩(即含石榴子石花岗闪长斑岩)(920.32~931.32 m)(图

3),矽卡岩整体上呈现出顶、底板透辉石+石榴子石(图3d,j),中间为硅灰石+石榴子石(图3g)的分带特征。此外,石榴子石类型也随深度的变化呈现出相应的变化,电子探针数据结果显示,石榴子石从浅部至深部钙铝榴石含量逐渐减少,而钙铁榴石含量逐渐增高(图4a,b)。同时,距岩体接触带近端的矽卡岩也表现出相同的分带特征,即逐渐远离岩体时,石榴子石中钙铝榴石的含量逐渐减少,而钙铁榴石含量逐渐增加(图4a,c),透辉石含量也逐渐减少,逐渐过渡为石榴子石+硅灰石的矽卡岩矿物组合(图3c)。中部多为矽卡岩化大理岩,主要表现为石榴子石硅灰石等在大理岩中呈脉状产出(图3h),另可见大理岩中发育矽卡岩夹层(图3b),可观察到透

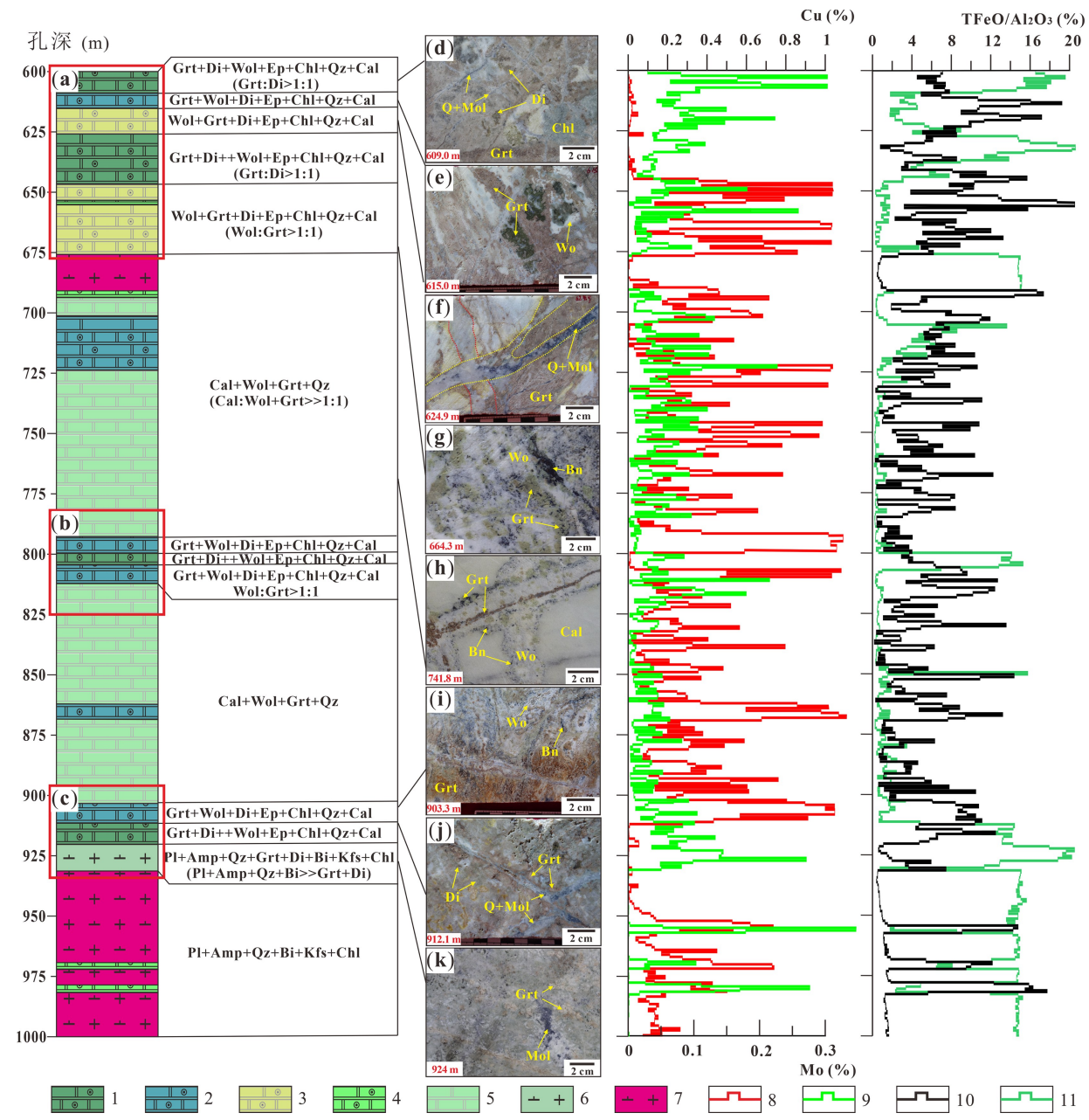


图 3 西藏甲玛 3000 m 科学深钻矽卡岩矿物分带

Fig. 3 Mineral zoning of skarn in Jiama 3000 m scientific deep drill, Tibet

(a)—顶板矽卡岩;(b)—矽卡岩夹层;(c)—底板矽卡岩;(d)—透辉石石榴子石矽卡岩;(e)—硅灰石石榴子石矽卡岩;(f,g)—石榴子石硅灰石矽卡岩;(h)—矽卡岩化大理岩;(i)—硅灰石石榴子石矽卡岩;(j)—透辉石石榴子石矽卡岩;(k)—内矽卡岩;1—透辉石石榴子石矽卡岩;2—硅灰石石榴子石矽卡岩;3—石榴子石硅灰石矽卡岩;4—石榴子石矽卡岩;5—矽卡岩化大理岩;6—内矽卡岩;7—花岗闪长斑岩;8—铜矿化品位;9—钼矿化品位;10—TFeO 含量;11—Al₂O₃ 含量;Grt—石榴子石;Di—透辉石;Wo—硅灰石;Chl—绿泥石;Ep—绿帘石;Pl—斜长石;Qz—石英;Amp—角闪石;Cal—方解石;Bi—黑云母;Kfs—钾长石;Mol—辉钼矿;图中 Cu、Mo、TFeO、Al₂O₃ 含量为甲玛 3000 m 科学深钻矽卡岩样品岩石地球化学分析结果(附表 1)。

(a)—roof skarn; (b)—skarn intercalation; (c)—floor skarn; (d)—diopside garnet skarn; (e)—wollastonite garnet skarn; (f, g)—garnet wollastonite skarn; (h)—skarn marble; (i)—wollastonite garnet skarn; (j)—diopside garnet skarn; (k)—endoskarn; 1—diopside garnet skarn; 2—wollastonite garnet skarn; 3—garnet wollastonite skarn; 4—garnet skarn; 5—skarn marble; 6—endoskarn; 7—granodiorite porphyry; 8—copper grade; 9—molybdenum grade; 10—TFeO content; 11—Al₂O₃ content; Grt—garnet; Di—diopside; Wo—wollastonite; Chl—chlorite; Ep—epidote; Pl—plagioclase; Qz—quartz; Amp—amphibole; Cal—calcite; Bi—biotite; Kfs—potassium feldspar; Mol—molybdenite; the contents of Cu, Mo, TFeO and Al₂O₃ (Appendix 1) in the figure are from the petrogeochemical analysis of the skarn sample from the 3000 m scientific deep borehole in Jiama

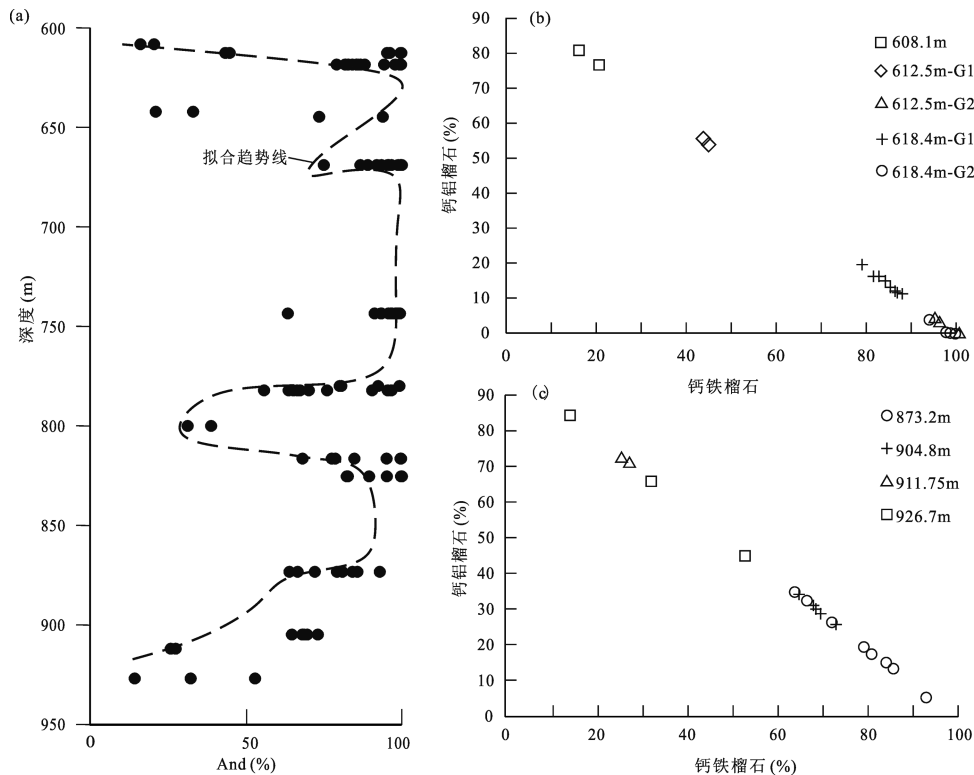


图 4 西藏甲玛 3000 m 科学深钻矽卡岩垂向上石榴子石成分变化图解

Fig. 4 Vertical variation of garnet composition of the skarn in the 3000 m scientific deep borehole skarn in Jiama, Tibet (a)—variation of andradite content of garnet from shallow to deep; (b)—variation of garnet composition in shallow skarn; (c)—variation of garnet composition in deep skarn; the contents of garnet endmembers (Appendix 2) at different depths in the figure are obtained by processing the raw electron probe data through Geokit (Lu Yuanfa, 2004) single-mineral calculation

辉石—石榴子石—硅灰石呈韵律性反复出现,此处矽卡岩矿物的韵律出现可能受构造控制(Einaudi, 1981)。此外,可见不同期次的石榴子石脉体相互穿插(图 6a、b)以及石榴子石的环带结构(图 6c),表明了成矿流体多期次多阶段的活动特征。综上所述,甲玛 3000 m 科学深钻矽卡岩矿物的空间分带不仅与侵入岩和围岩的空间位置密切相关,也受构造环境以及多期次流体叠加改造的影响。

3.2 金属矿化的空间分带

甲玛 3000 m 科学深钻矽卡岩中矿石类型丰富,根据有用矿物组合,主要可以划分为:黄铜矿矿石、斑铜矿矿石、辉钼矿矿石、黄铜矿-辉钼矿矿石、黄铜矿-斑铜矿矿石,矿石主要呈细脉浸染状、网脉状及团斑状产出。甲玛 3000 m 科学深钻矽卡岩金属矿物在空间上也具有明显的分带,从图 5 中可以看出:① 矿石矿物组合总体上从上至下表现出辉钼矿±黄铜矿→斑铜矿+黄铜矿±辉铜矿±硫铋铜矿±辉钼矿→辉钼矿±黄铜矿的过渡趋势;② 成矿元

素表现为 $\text{Mo}\pm\text{Cu}\pm\text{Au}\pm\text{Ag}\rightarrow\text{Cu}(\text{Mo})\pm\text{Au}\pm\text{Ag}\rightarrow\text{Mo}\pm\text{Cu}\pm\text{Au}\pm\text{Ag}$ 的分布规律,这与前人阐述的矽卡岩“上 Mo 下 Cu”的分带特征有所区别(郑文宝等, 2010b; 王焕, 2011; 冷秋锋, 2016; 冷秋锋等, 2022)。

4 讨论

4.1 矽卡岩矿物垂直分带及其与金属矿化的耦合关系

Einaudi(1981)提出控制矽卡岩矿物分带的基本因素主要包括:温度、形成深度、相关侵入岩和围岩的成分、氧化还原状态、pH 值以及所处的构造环境等(于森, 2013)。矽卡岩的形成是一个动态的热液交代演化过程,侵入岩的特征、热液流体的成分以及温度压力条件均可影响矽卡岩矿物组合和化学反应(Titley, 1973; Guilbert et al., 1974; Meinert et al., 2005; 冷秋锋等, 2022)。前人研究表明,随着与岩体热源距离的增加,石榴子石的成分从近端矽

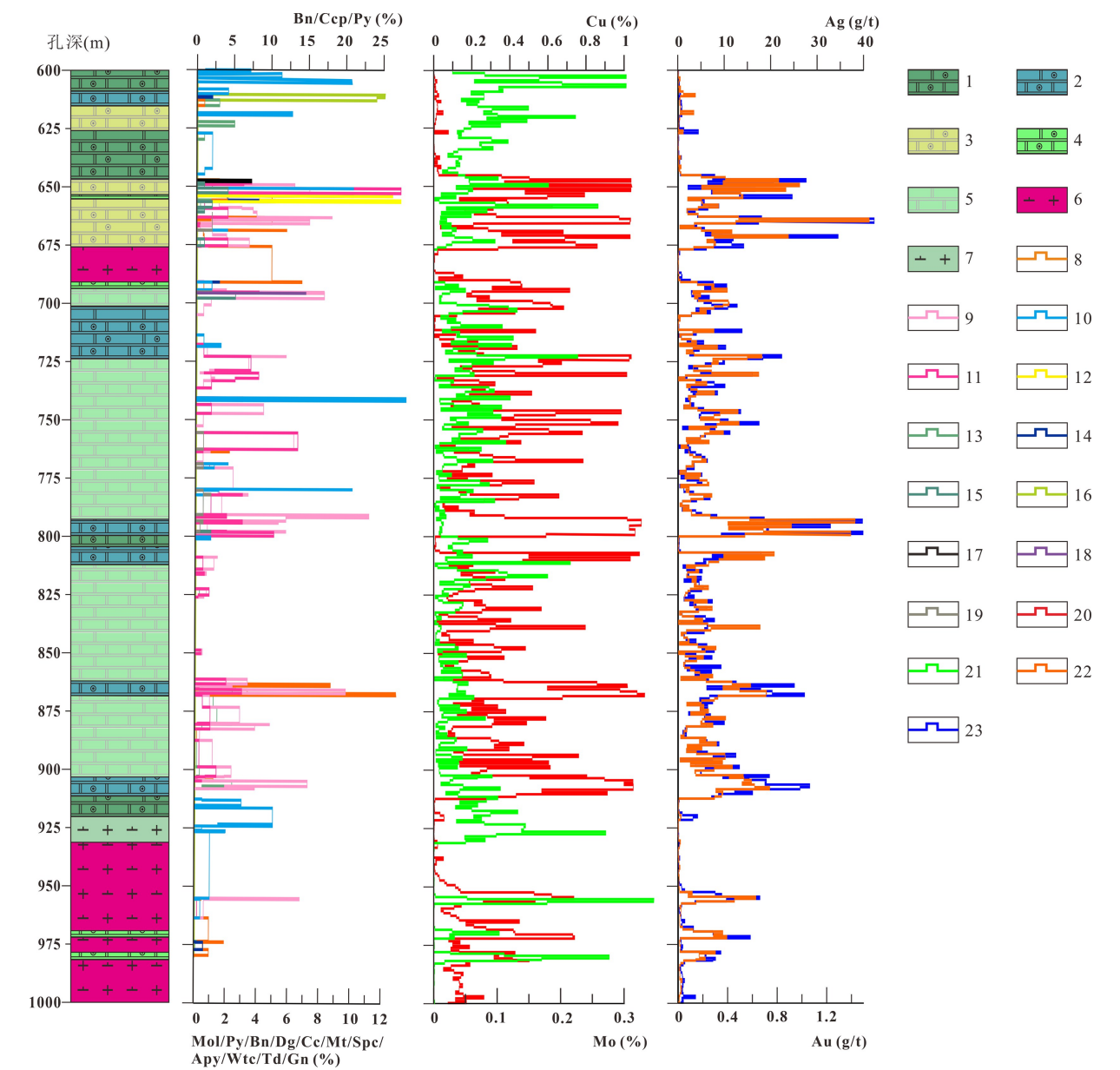


图 5 西藏甲玛 3000 m 科学深钻矽卡岩金属矿物空间分布与元素的对应关系

Fig. 5 Corresponding relationship between spatial distribution of metal minerals and elements of skarn in Jima 3000 m scientific deep borehole, Tibet

1—透辉石石榴子石矽卡岩;2—硅灰石石榴子石矽卡岩;3—石榴子石硅灰石矽卡岩;4—石榴子石矽卡岩;5—矽卡岩化大理岩;6—内矽卡岩;7—花岗闪长斑岩;8—黄铜矿;9—斑铜矿;10—辉钼矿;11—辉铜矿;12—镜铁矿;13—黄铁矿;14—磁铁矿;15—蓝辉铜矿;16—毒砂;17—方铅矿;18—黝铜矿;19—硫铋铜矿;20—铜品位;21—钼品位;22—金品位;23—银品位; Mol—辉钼矿; Py—黄铁矿; Bn—斑铜矿; Ccp—黄铜矿; Dg—蓝辉铜矿; Cc—辉铜矿; Mt—磁铁矿; Spc—镜铁矿; Apy—毒砂; Wtc—硫铋铜矿; Td—黝铜矿; Gn—方铅矿; 图中各金属硫化物含量数据通过镜下目估法所得; 图中 Cu、Mo、Au、Ag 品位数据出自甲玛 3000 m 科学深钻矽卡岩样品岩石地球化学分析(附表 1)

1—diopside garnet skarn; 2—wollastonite garnet skarn; 3—garnet wollastonite skarn; 4—garnet skarn; 5—skarn marble; 6—endoskarn; 7—granodiorite porphyry; 8—chalcophyrite; 9—bornite; 10—molybdenite; 11—chalcocite; 12—specularite; 13—pyrite; 14—magnetite; 15—digenite; 16—arsenopyrite; 17—galena; 18—tetrahedrite; 19—wittichenite; 20—copper grade; 21—molybdenum grade; 22—gold grade; 23—silver grade; Mol—molybdenite; Py—pyrite; Bn—bornite; Ccp—chalcophyrite; Dg—digenite; Cc—chalcocite; Mt—magnetite; Spc—specularite; Apy—arsenopyrite; Wtc—wittichenite; Td—tetrahedrite; Gn—galena; the content data (Appendix 1) of each metal sulfide in the figure is obtained by the visual estimation method under the microscope; the data of Cu, Mo, Au and Ag grades in the picture are from whole rock geochemical analysis of skarn samples from the 3000 m scientific deep borehole in Jima

卡岩到远端矽卡岩,表现为由钙铁榴石向钙铝榴石的转变,且石榴子石多分布在岩体接触带附近,而辉石和硅灰石多分布在距离岩体的远端(王焕,2011;唐晓倩等,2012;冷秋锋,2016;冷秋锋等,2022)。然而,甲玛科学深钻局部区段(850~950 m)垂向上却表现出不同的变化趋势(图 4c),深部靠近花岗闪长斑岩接触带,从深部到浅部石榴子石中钙铁榴石含量逐渐增加,而钙铝榴石的含量逐渐减少。矽卡岩从钙铝榴石向钙铁榴石过渡的原因可能为:① 原岩本身相对富 Al,随着流体的演化,由以钙铝质石榴子石为主转变为钙铁质石榴子石为主(Ghosh et al., 2022)。② 氧逸度的变化导致石榴子石中 Fe 含量的变化(Meinert et al., 2005; Tian Zhendong et al., 2019);③ 矽卡岩顶部有富含 Fe 物质或富 Fe 流体(上部角岩)加入到矽卡岩成岩过程中导致钙铝榴石向钙铁榴石的变化趋势(Ghosh et al., 2022)。④ 以上全部。这也与前人对于矽卡岩的研究一致,即早期的石榴子石相对富铝,晚期石榴子石相对富铁(Einaudi, 1981; Meinert, 1992, 1997; Park et al., 2017)。

石榴子石是广泛存在于矽卡岩矿床中的一种成岩矿物,其成分可以反映矽卡岩形成时的氧逸度(Meinert et al., 2005)。具体而言,当矽卡岩形成时氧化性较强,铁主要以 Fe^{3+} 的形式存在,从而形成钙铁榴石,而在还原条件下,则形成钙铝榴石(朱乔乔等,2014;王伟等,2016)。在甲玛 3000 m 科学深钻中,浅部矽卡岩由透辉石石榴子石矽卡岩向石榴子石硅灰石矽卡岩过渡(图 3a),石榴子石端员则由钙铝榴石向钙铁榴石转变(图 4a、b),这表明成岩流体从早期到晚期由相对还原逐渐向相对氧化的条件转变;在相对还原环境下有利于 Mo 的迁移和沉淀(罗铭玖等,1993;郑文宝等,2011;Seo et al., 2012;王艺云等,2017;),而在相对氧化性的环境下更有利于 Cu 的沉淀(Meinert et al., 2005;王艺云等,2017),而在相对氧化性和偏中性的环境下更有利于 Cu 的沉淀(Meinert et al., 2005;王艺云等,2017),由此对应的金属矿物表现出辉钼矿±黄铜矿→斑铜矿±黄铜矿±辉铜矿±硫铋铜矿±黝铜矿,以及成矿元素表现为“Mo→Cu”的变化趋势。同理,深部靠近花岗闪长斑岩的接触带(图 3c),从深部到浅部石榴子石中钙铁榴石含量逐渐增加,而钙铝榴石的含量逐渐减少(图 4b、c),金属矿化则表现为“上 Cu 下 Mo”的分布特征。从图 5 可以看出,总体上透辉石石榴子石矽卡岩相对于石榴子石硅灰石

矽卡岩、石榴子石矽卡岩,矿化以 Mo 矿化为主,金属矿物为辉钼矿±黄铜矿;而石榴子石硅灰石矽卡岩(硅灰石石榴子石矽卡岩)则主要以 Cu-(Au-Ag)矿化为特征,金属矿物为斑铜矿+黄铜矿±辉铜矿±硫铋铜矿±黝铜矿,表明辉钼矿的分布与透辉石、钙铝质的石榴子石密切相关,而斑铜矿以及黄铜矿等含 Cu 硫化物与硅灰石和钙铁质石榴子石密切相关。

4.2 多期次成岩成矿作用的矿物学和地球化学证据

甲玛矿床矽卡岩分带除与侵入岩与围岩的空间位置以及构造环境有关外,还受到多期次流体叠加改造,具体表现为:① 从浅部到深部,在不同的空间位置均普遍发育石榴子石环带结构(图 6c),环带结构记录了强烈流体流动与流体停滞交替(Meinert et al., 2005),暗示了石榴子石矿物晶体的生长可能存在间断,存在溶液组分与生长晶体表层重新达到热力学平衡的过程(邱瑞龙,1988;应立娟等,2012b);② 常见不同期次的石榴子石脉的相互穿切(图 6a、b),或早期的硅灰石矽卡岩被晚期棕褐色石榴子脉穿切或沿边部交代的现象(图 6d);③ 镜下除常见的斑铜矿与黄铜矿共边结构或固溶体分离结构形成的矿物共生组合外(图 6e~g、i),另常见早期形成的斑铜矿等被晚期形成的蓝辉铜矿沿裂隙交代(图 6h)或早期形成的黄铜矿或硫铋铜矿被晚期形成的斑铜矿交代呈孤岛状(图 6j)。

本文重点选取了同一深度不同期次的石榴子石进行电子探针分析,结果见表 1。环带结构的石榴子石表现为颜色深浅相间变化。石榴子石从核部到边缘,4 件样品中的主要成分 TFeO 、 Al_2O_3 以及石榴子石端元组分钙铁榴石(And)与钙铝榴石(Gro)的变化趋势如图 7a~d。环带结构的石榴子石 TFeO 与 Al_2O_3 含量从核部到边缘呈现出此消彼长的变化趋势,与之对应的钙铁榴石与钙铝榴石含量也呈现出相同的变化趋势(图 7e~h)。通过对比样品 612.5-Grt1 与样品 612.5-Grt2 两个世代的石榴子石,发现早期的石榴子石(样品 612.5-Grt1)以钙铝-钙铁榴石为主(图 7d),而晚期多以钙铁榴石为主(图 7e);此外,可见石榴子石(样品 782-Grt2)发育双环带结构(图 7c),从核部到边缘表现出钙铁榴石与钙铝榴石振荡变化的趋势(图 7f),指示流体温度、pH 值、氧逸度等因素的不断变化,暗示流体的多期多阶段性。多期次热液流体的不断注入,不仅对早期形成的矽卡岩矿物进行了交代叠加改造,还

表 1 西藏甲玛 3000 m 科学深钻矽卡岩中不同期次石榴子石电子探针结果 (%)

Table 1 Electron microprobe analysis results (%) of garnet of different stages in skarn in the 3000 m scientific deep borehole skarn in Jiama, Tibet																		
样品号	612. 5- Grt1	612. 5- Grt1-2	612. 5- Grt1-3	612. 5- Grt1-4	612. 5- Grt1-5	612. 5- Grt2-1	612. 5- Grt2-2	782- Grt1-1	782- Grt1-2	782- Grt1-3	782- Grt1-4	782- Grt1-5	782- Grt1-6	782- Grt1-7	782- Grt1-8	782- Grt2-1	782- Grt2-2	782- Grt2-3
SiO ₂	35. 30	35. 56	35. 55	35. 99	36. 18	37. 85	38. 34	36. 31	37. 50	35. 96	37. 24	36. 12	35. 94	38. 00	37. 21	37. 16	36. 78	37. 21
TiO ₂	0. 00	0. 10	0. 00	0. 00	0. 00	0. 46	0. 34	0. 06	0. 09	0. 10	0. 05	0. 00	0. 02	0. 03	0. 21	0. 05	0. 05	0. 00
Al ₂ O ₃	0. 03	0. 02	0. 08	0. 63	0. 77	10. 53	10. 89	0. 72	6. 69	1. 60	5. 27	0. 58	0. 55	8. 16	5. 70	6. 25	4. 21	6. 12
Cr ₂ O ₃	0. 00	0. 01	0. 00	0. 00	0. 02	0. 01	0. 00	0. 02	0. 00	0. 01	0. 01	0. 00	0. 00	0. 01	0. 00	0. 00	0. 03	0. 00
Fe ₂ O ₃	24. 84	25. 05	25. 19	24. 63	24. 45	13. 41	13. 07	24. 31	18. 36	23. 74	19. 41	24. 41	24. 99	16. 14	18. 43	18. 28	20. 95	18. 92
FeO	4. 49	5. 13	5. 35	5. 12	4. 83	2. 37	2. 80	4. 14	3. 40	4. 82	3. 67	5. 32	5. 49	3. 47	3. 07	2. 92	4. 11	3. 70
MnO	0. 18	0. 23	0. 19	0. 17	0. 26	0. 46	0. 53	0. 03	0. 21	0. 18	0. 19	0. 32	0. 41	0. 37	0. 17	0. 19	0. 10	0. 22
MgO	0. 00	0. 00	0. 00	0. 04	0. 00	0. 08	0. 06	0. 44	0. 36	0. 27	0. 19	0. 05	0. 04	0. 02	0. 11	0. 31	0. 13	0. 13
CaO	33. 99	33. 79	33. 77	34. 11	34. 35	35. 54	35. 32	34. 32	35. 38	34. 10	34. 95	33. 58	33. 87	35. 12	34. 99	35. 16	35. 03	35. 27
Si	3. 05	3. 04	3. 04	3. 04	3. 05	3. 01	3. 03	3. 06	3. 02	3. 02	3. 05	3. 06	3. 03	3. 05	3. 06	3. 04	3. 02	3. 02
Al	0. 00	0. 00	0. 01	0. 07	0. 08	1. 02	1. 05	0. 08	0. 67	0. 17	0. 53	0. 06	0. 06	0. 80	0. 58	0. 63	0. 43	0. 61
Ti	0. 00	0. 01	0. 00	0. 00	0. 00	0. 03	0. 02	0. 00	0. 01	0. 01	0. 00	0. 00	0. 00	0. 00	0. 01	0. 00	0. 00	0. 00
Cr	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00
Fe ³⁺	1. 61	1. 61	1. 62	1. 57	1. 55	0. 80	0. 78	1. 54	1. 11	1. 50	1. 19	1. 56	1. 58	0. 97	1. 14	1. 12	1. 30	1. 16
Fe ²⁺	0. 32	0. 37	0. 38	0. 36	0. 34	0. 16	0. 18	0. 29	0. 23	0. 34	0. 25	0. 38	0. 39	0. 23	0. 21	0. 20	0. 28	0. 25
Mn	0. 01	0. 02	0. 01	0. 01	0. 02	0. 03	0. 04	0. 00	0. 01	0. 01	0. 01	0. 02	0. 03	0. 03	0. 01	0. 01	0. 01	0. 01
Mg	0. 00	0. 00	0. 00	0. 00	0. 00	0. 01	0. 01	0. 06	0. 04	0. 03	0. 02	0. 01	0. 00	0. 00	0. 01	0. 04	0. 02	0. 02
Ca	3. 14	3. 10	3. 09	3. 09	3. 10	3. 03	2. 99	3. 10	3. 05	3. 07	3. 06	3. 05	3. 06	3. 02	3. 08	3. 08	3. 08	3. 07
Andradite	99. 80	99. 80	99. 54	96. 13	95. 22	44. 83	43. 38	95. 46	63. 67	90. 44	70. 12	96. 43	96. 67	55. 81	67. 38	65. 13	75. 97	66. 38
Grossular	0. 00	0. 00	0. 00	3. 18	3. 94	53. 65	55. 04	2. 09	34. 11	7. 62	28. 45	2. 34	1. 93	43. 10	31. 61	32. 93	23. 01	32. 44
Pyrope	0. 00	0. 00	0. 00	0. 20	0. 00	0. 34	0. 24	2. 29	1. 67	1. 38	0. 88	0. 27	0. 19	0. 09	0. 54	1. 45	0. 63	0. 61
Spessartine	0. 20	0. 14	0. 46	0. 49	0. 76	1. 14	1. 33	0. 08	0. 56	0. 51	0. 51	0. 95	1. 20	0. 97	0. 47	0. 49	0. 28	0. 57
Uvarovite	0. 00	0. 06	0. 00	0. 00	0. 08	0. 04	0. 00	0. 09	0. 00	0. 04	0. 04	0. 00	0. 00	0. 03	0. 00	0. 00	0. 11	0. 00

注: Andradite—钙铁榴石; Grossular—钙铝榴石; Pyrope—镁铝榴石; Spessartine—锰铝榴石; Uvarovite—钙铬榴石。

为后期的成矿提供了大量矿化物质,在原有成矿作用下叠加富集,由此形成了如此厚大的矽卡岩矿体。

4.3 高品位金矿化富集机制

金是典型的亲铜元素,因而在铜矿化强烈的矿石中金也相对富集,富金斑岩-矽卡岩矿床中 Cu 含量与 Au 含量通常具有正相关性(Meinert, 1998; Sillitoe, 2000; 谢桂青等,2020)。根据 3000 m 深钻的岩石地球化学分析数据结果,通过对矽卡岩矿体矿石样品的 Cu、Au 含量的相关系数计算,得出 Cu、Au 的相关系数 R^2 为 0. 9084(图 8),显示极强的相关性(林彬等,2021)。钟裕锋(2011)曾对甲玛矿区伴生元素金的赋存状态进行了详细的研究,矽卡岩矿石的 Au 主要以独立矿物或固溶体形式进入载金矿物中,常见有包裹金、裂隙金、连生金等嵌布于斑铜矿、黄铜矿和黝铜矿等铜硫化物中。深钻矽卡岩金属矿物空间分布与矿化元素的对应关系图显示(图 5),在斑铜矿、黄铜矿和辉铜矿等含 Cu 硫化物富集的空间位置,多有 Au 的富集。甲玛矿床中的含 Cu 硫化物电子探针结果(表 2)显示,如斑铜矿、辉铜矿、硫铋铜矿及黝铜矿中均富含 Au,斑铜矿中 Au 含量高达 0. 16%,进一步说明 Au 可能富集

于斑铜矿等含铜硫化物中。

矽卡岩的空间分带以及多期次石榴子石分布规律揭示多期次热液流体的叠加,而多次流体的叠加导致了流体中氧化电位、pH 值以及硫化物及金属元素的浓度出现反复的变化,有利于金的多次富集和沉淀(Kelser et al. , 2002)。因此,当成矿流体携带大量成矿元素多期次叠加矿化,导致矽卡岩矿石 Au 的富集。

此外,除多期次成矿流体的叠加,成矿岩浆携带了高含量的金(林彬等,2021),也是控制甲玛大规模金富集的重要因素。Chiaradia(2020)对世界上的斑岩 Cu-Au 矿床分析,发现七个最大的富 Au 矿床(Kadjaran、Cadia、Kalmakyr、Oyu Tolgoi、Bingham、Grasberg 和 Pebble)均与高钾钙碱质或碱性岩石有关。部分与正常钙碱性岩浆有关的矿床(如 Panguna、Cerro Casale、Batu Hijau 等大型矿床)也富金。研究表明,甲玛矿床含矿岩浆为富钾或高钾钙碱性系列-钙碱性系列(唐菊兴等,2010),属于富 Au 的岩石类型。同时,林彬等(2021)通过对 3000 m 科学深钻深部岩体结构的详细解剖,揭示深部多处揭露的石英闪长玢岩脉中含有高品位的金

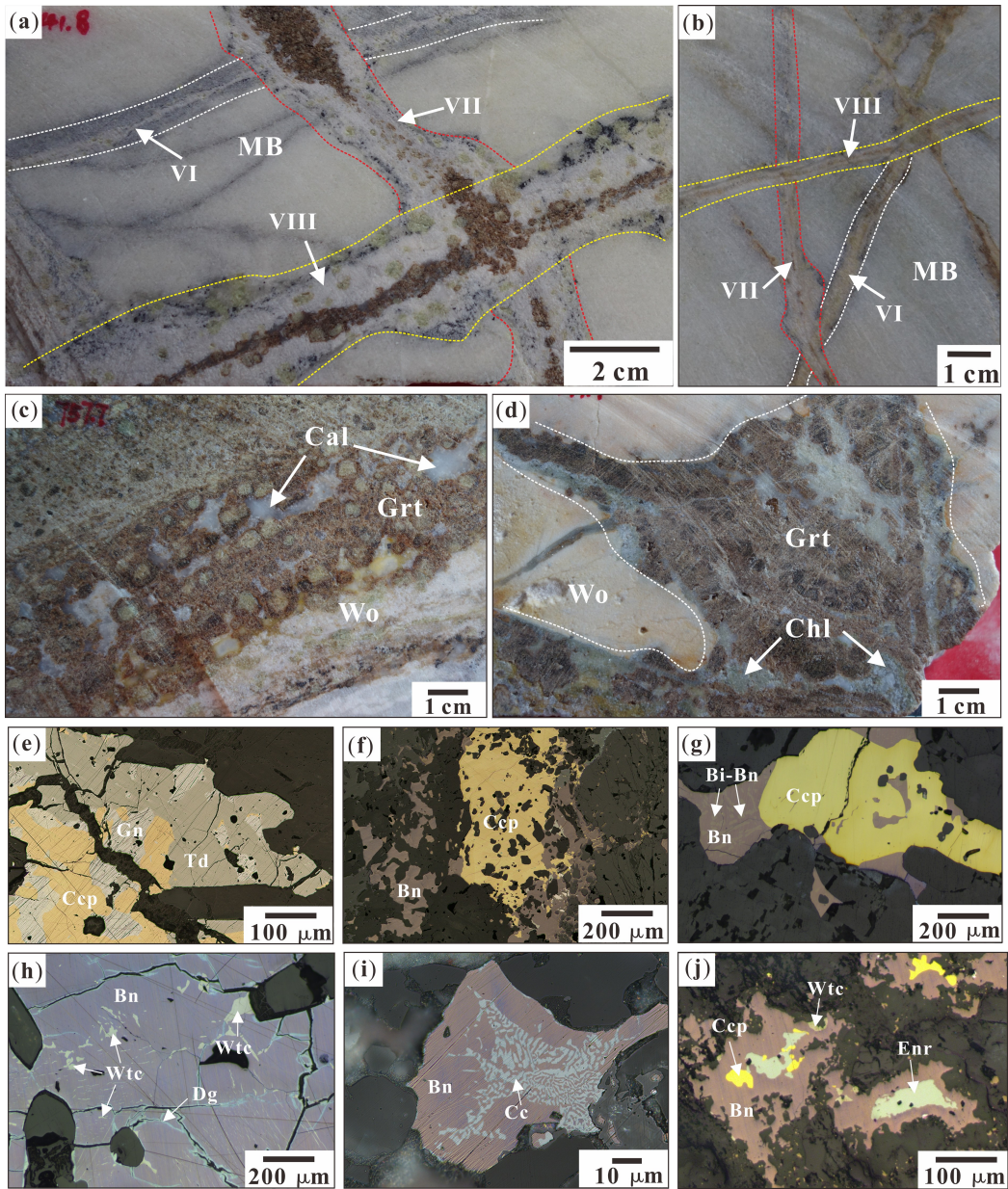


图 6 西藏甲玛 3000 m 科学深钻多期次流体叠加矿物学证据

Fig. 6 Mineralogical evidence of multi-stage fluid superposition in

Jima 3000 m scientific deep borehole, Tibet

(a, b)—多期次(VI~VIII)矽卡岩脉穿插; (c)—石榴子石环带结构; (d)—晚期的棕褐色绿泥石-石榴子石脉穿插早期的硅灰石矽卡岩; (e)—方铅矿-黄铜矿-黝铜矿的共生组合; (f)—斑铜矿与黄铜矿的共生组合; (g)—黄铜矿与斑铜矿的共边结构; (h)—蓝辉铜矿沿裂隙交代早期的斑铜矿以及斑铜矿中出溶出硫铋铜矿; (i)—辉铜矿在斑铜矿中出溶呈蠕虫状文象结构; (j)—早期形成的黄铜矿和硫砷铜矿被斑铜矿交代呈孤岛状; VI—第一期矽卡岩脉; VII—第二期矽卡岩脉; VIII—第三期矽卡岩脉; Grt—石榴子石; Di—透辉石; Wo—硅灰石; Cal—方解石; Bn—斑铜矿; Chl—绿泥石; MB—大理岩; Mt—磁铁矿; Ccp—黄铜矿; Cc—辉铜矿; Dg—蓝辉铜矿; Wtc—硫铋铜矿; Gn—方铅矿; Td—黝铜矿; Enr—硫砷铜矿

(a, b)—multi stage (VI~VIII) skarn vein cutting; (c)—garnet ring structure; (d)—late Brown chlorite garnet vein cuts through the early wollastonite skarn; (e)—galena-chalcopyrite-tetrahedrite symbiotic association; (f)—symbiotic combination of bornite and chalcopyrite; (g)—coplanar structure of chalcopyrite and bornite; (h)—digenite metasomatized the early bornite along the fracture and the dissolved wittichenite in bornite; (i)—exsolution of chalcocite in bornite shows worm like texture; (j)—chalcopyrite and enargite formed in the early stage were metasomatized by bornite in an island shape; VI—first stage skarn vein; VII—second stage skarn vein; VIII—third stage skarn vein; Grt—garnet; Di—diopside; Wo—wollastonite; Cal—calcite; Bn—bornite; Chl—chlorite; MB—marble; Mt—magnetite; Ccp—chalcopyrite; Cc—chalcocite; Dg—digenite; Wtc—wittichenite; Gn—galena; Td—tetrahedrite; Enr—enargite

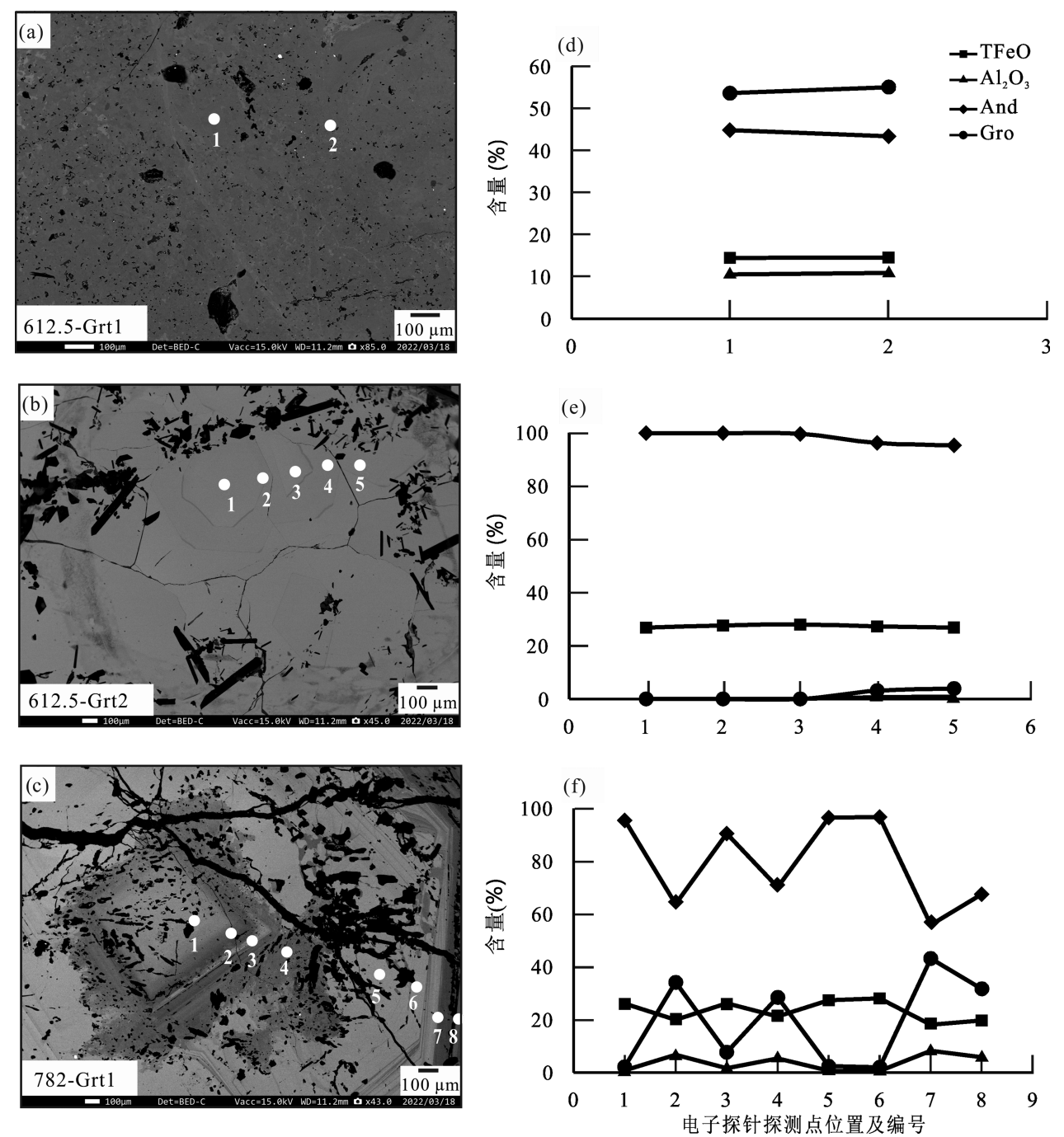


图 7 西藏甲玛 3000 m 科学深钻不同期次石榴子石背散色图像(a~d)及成分变化关系图(e~h)

Fig. 7 Back scattering image (a~d) and composition change diagram (e~h) of garnet in different stages of Jima 3000 m scientific deep borehole, Tibet

图中石榴子石端元组分的含量是通过 Geokit (据路远发, 2004) 单矿物计算对原始电子探针数据进行处理所得; And—钙铁榴石; Gro—钙铝榴石

The contents of garnet endmembers at different depths in the figure are obtained by processing the raw electron probe data through Geokit (Lu Yuanfa, 2004) single-mineral calculation; And—andradite; Gro—grossular

(0.04~0.14 g/t), 由此认为甲玛矿区深部的岩浆源区相对富集 Au, 进而导致岩浆热液流体与碳酸盐岩接触交代形成矽卡岩时, 富集沉淀出高品位的金矿体(林彬等, 2021)。

5 结论

(1) 甲玛 3000 m 科学深钻矽卡岩矿体从浅部至深部具有清晰的蚀变分带结构, 即矽卡岩化角岩

表 2 西藏甲玛科学深钻不同金属矿物电子探针数据(%)

名称	As	Ge	Ga	S	Bi	Sb	Mo	Pb	Au	Se	Zn	Cu	Co	Fe	Ni	Total
Bn ₁	0.00	0.00	0.02	26.07	0.62	0.02	0.37	0.00	0.00	0.00	0.01	62.66	0.01	11.00	0.00	100.77
Bn ₂	0.00	0.08	0.00	26.16	0.36	0.01	0.36	0.00	0.16	0.00	0.08	63.10	0.03	11.04	0.00	101.38
Bn ₃	0.03	0.00	0.00	26.04	0.03	0.01	0.31	0.00	0.02	0.03	0.07	63.15	0.04	11.03	0.00	100.74
Bn ₄	0.08	0.00	0.00	26.26	0.00	0.00	0.35	0.01	0.08	0.00	0.09	63.33	0.01	11.24	0.00	101.45
Bn ₅	0.03	0.02	0.00	25.50	0.08	0.00	0.34	0.06	0.00	0.00	0.08	64.65	0.01	10.47	0.00	101.24
Bn _(Ave)	0.03	0.02	0.00	26.01	0.22	0.01	0.35	0.01	0.05	0.01	0.07	63.38	0.02	10.96	0.00	101.12
Cc ₁	0.00	0.04	0.00	21.25	0.00	0.02	0.30	0.00	0.00	0.00	0.09	78.17	0.00	0.34	0.00	100.20
Cc ₂	0.03	0.00	0.00	26.09	0.75	0.02	0.37	0.00	0.07	0.08	0.26	62.16	0.01	10.82	0.00	100.68
Cc ₃	0.01	0.00	0.00	20.45	0.00	0.00	0.26	0.00	0.03	0.00	0.07	80.60	0.00	0.13	0.00	101.55
Cc ₄	0.00	0.02	0.00	25.74	0.04	0.01	0.30	0.00	0.00	0.00	0.06	64.05	0.03	10.75	0.00	101.00
Cc ₅	0.00	0.00	0.00	20.97	0.00	0.00	0.22	0.00	0.00	0.00	0.03	79.40	0.00	0.29	0.00	100.92
Cc ₆	0.00	0.00	0.02	25.04	0.20	0.01	0.29	0.00	0.00	0.08	0.07	64.08	0.02	11.24	0.00	101.03
Cc _(Ave)	0.01	0.01	0.00	23.26	0.17	0.01	0.29	0.00	0.02	0.03	0.10	71.41	0.01	5.60	0.00	100.90
Wtc ₁	0.02	0.00	0.06	19.03	42.41	0.06	0.10	0.00	0.05	0.00	0.04	38.15	0.00	0.01	0.00	99.93
Wtc ₂	0.03	0.00	0.00	20.03	40.34	0.03	0.24	0.00	0.00	0.00	0.07	40.44	0.00	0.44	0.00	101.63
Wtc ₃	0.01	0.01	0.04	18.49	40.09	0.00	0.23	0.00	0.00	0.00	0.05	40.51	0.01	1.31	0.00	100.74
Wtc ₄	0.00	0.00	0.00	19.75	40.02	0.01	0.16	0.00	0.03	0.01	0.06	40.02	0.02	0.05	0.00	100.13
Wtc _(Ave)	0.02	0.00	0.03	19.33	40.72	0.03	0.18	0.00	0.02	0.00	0.06	39.78	0.01	0.45	0.00	100.61
Td	2.40	0.01	0.00	25.31	6.39	20.16	0.31	0.00	0.01	0.00	5.46	38.79	0.36	0.99	0.01	100.19

注：Bn—斑铜矿；Cc—辉铜矿；Wtc—硫铋铜矿；Td—黝铜矿。

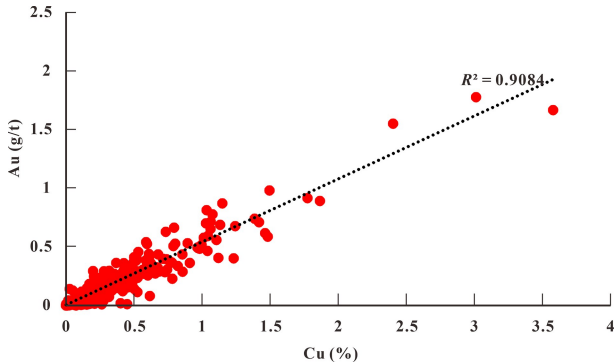


图 8 西藏甲玛 3000 m 科学深钻矽卡岩矿体 Cu-Au 含量关系图

Fig. 8 Cu-Au content relationship of Jiama 3000 m scientific deep drilling skarn ore body

Cu、Au 含量数据来自甲玛 3000 m 科学深钻矽卡岩矿体样品岩石地球化学分析(附表 1)

The data of Cu and Au content come from the petrogeochemical analysis (Appendix 1) of the skarn ore body samples from the 3000 m scientific deep borehole in Jiama, Tibet

→透辉石石榴子石矽卡岩→硅灰石石榴子石矽卡岩
→石榴子石硅灰石矽卡岩→透辉石石榴子石矽卡岩
→石榴子石硅灰石矽卡岩→矽卡岩化大理岩→硅灰石石榴子石矽卡岩→透辉石石榴子石矽卡岩→硅灰石石榴子石矽卡岩→矽卡岩化大理岩→硅灰石石榴子石矽卡岩→透辉石石榴子石矽卡岩→内矽卡岩(含石榴子石花岗闪长斑岩)。

(2)金属矿物组合从浅部至深部明显表现出：辉

钼矿±黄铜矿→斑铜矿+黄铜矿±辉铜矿±硫铋铜矿±辉钼矿→辉钼矿±黄铜矿的过渡趋势；成矿元素表现为 Mo±Cu±Au±Ag→Cu(Mo)±Au±Ag→Mo±Cu±Au±Ag 的分布规律。

(3)甲玛 3000 m 矽卡岩空间分带的原因不仅与侵入岩及围岩的空间位置有关,也是所处的构造环境和多期次热液流体叠加改造的结果。

(4)矽卡岩中高品位金的富集除与斑铜矿等铜硫化物密切相关,也可能是多期次流体叠加和富金岩浆源区共同作用的结果。

致谢:感谢西藏华泰龙矿业开发有限公司为笔者提供的野外支持。感谢中国地质科学院矿产资源研究所电子探针测试实验室陈振宇、刘春花老师对实验分析的指导。感谢匿名审稿专家提出的宝贵修改意见。

附件:本文附件(附表 1~2)详见 http://www.geojournals.cn/dzxb/dzxb/article/abstract/202306095?st=article_issue

References

Chiaradia M. 2020. Gold endowments of porphyry deposits controlled by precipitation efficiency. *Nature Communications*, 11: 1~10.

Duan Jilin, Tang Juxing, Mason, Zheng Wenbao, Ying Lijuan. 2014. Zircon U-Pb age and deformation characteristics of the Jiama porphyry copper Deposit, Tibet: Implications for relationships between mineralization, structure and alteration. *Resource Geology*, 64(4): 316~331.

- Einaudi M T. 1981. Skarn deposits. *Economic Geology*, (75): 317~391.
- Einaudi M T, Burt D M. 1982. Introduction, terminology, classification, and composition of skarn deposits. *Economic Geology*, 77(4): 745~754.
- Guilbert J M, D Lowell J. 1974. Variations in zoning patterns in porphyry copper deposits. *Canadian Institute of Mining and Metallurgy Bulletin*, (67): 99~109.
- Ghosh U, Upadhyay D. 2022. The retrograde evolution of F-rich skarns: Clues from major and trace element chemistry of garnet, scheelite, and vesuvianite from the Belka Pahar wollastonite deposit, India. *Lithos*, 422-423: 106750.
- Kesler S E, Chrysosoulis S L, Simon G. 2002. Gold in porphyry copper deposits: Its abundance and fate. *Ore Geology Reviews*, 21: 103~124.
- Leng Qiufeng, Tang Juxing, Zheng Wenbao, Lin Bin, Wang Yiyun, Tang Pan, Lin Xin. 2015. A study of ore-controlling factors of thick and large skarn orebodies in Jiama porphyry metallogenic system, Tibet. *Mineral Deposits*, 34(2): 273~288 (in Chinese with English abstract).
- Leng Qiufeng. 2016. Skarn diagenesis and metallogenesis in Jiama copper-polymetallic deposit, Tibet. PhD degree dissertation of Chengdu University of Technology (in Chinese with English abstract).
- Leng Qiufeng, Tang Juxing, Zheng Wenbao, Tang Pan, Lin Bin. 2022. Skarn mineral assemblage and zonation pattern in the Jiama superlarge deposit, Tibet. *Acta Geologica Sinica*, 96(2): 574~591 (in Chinese with English abstract).
- Li Yongsheng, Zhao Caisheng, Lü Zhicheng, Yan Guangsheng, Zhen Shimin. 2011. Characteristics of fluid inclusions in Jiama copper-polymetallic ore deposit, Tibet and its geological significance. *Journal of Jilin University (Earth Science Edition)*, 41(1): 122~136 (in Chinese with English abstract).
- Li Yongsheng, Lü Zhicheng, Yan Guangsheng, Zhen Shimin, Du Zezhong. 2012. Isotopic characteristics of S, Pb, H and O of Jiama copper-polymetallic ore deposit, Tibet and their significance. *Earth Science Frontiers (China University of Geosciences (Beijing): Peiking University)*, 19(4): 72~81 (in Chinese with English abstract).
- Lin Bin, Tang Juxing, Zang Zhi, Zheng Wenbao, Leng Qiufeng, Zhong Wanting, Ying Lijuan. 2012. Preliminary study of fissure system in Jiama porphyry deposit of Tibet and its significance. *Mineral Deposits*, 31(3): 579~589 (in Chinese with English abstract).
- Lin Bin, Tang Juxing, Tang Pan, Zheng Wenbao, Greg Hall, Chen Guoliang, Zhang Zhongkun. 2019. Polycentric complex mineralization model of porphyry system: A case study of Jiama superlarge deposit in Tibet. *Mineral Deposits*, 38(6): 1204~1222 (in Chinese with English abstract).
- Lin Bin, Tang Juxing, Tang Pan, Zhou Aorigele, Sun Miao, Qi Jing, Chen Guoliang, Zhang Zhongkun, Zhang Zebin, Wu Chunheng, Tian Zhichao, Dai Jingjing, Yang Zhengkun, Yao Xiaofeng. 2021. Preliminary study of first 3000 m scientific drilling in Jiama porphyry metallogenic system, Tibet. *Mineral Deposits*, 40(6): 1119~1134 (in Chinese with English abstract).
- Lu Yuanfa. 2004. GeoKit—A geochemical toolkit for Microsoft Excel. *Geochimica*, (5): 459~464 (in Chinese with English abstract).
- Luo Mingjiu, Lin Qianlong, Lu Xinxiang, Chen tiehua. 1993. Geological characteristics of molybdenum-bearing granites in the East Qinling Mountains. *Henan Geology*, (1): 2~8 (in Chinese with English abstract).
- Meinert L D. 1987. Skarn zonation and fluid evolution in the Groundhog Mine, Central mining district, New Mexico. *Economic Geology*, 82(3): 523~545.
- Meinert L D. 1992. Skarns and skarn deposits. *Geoscience Canada*, 19(4): 145~162.
- Meinert L D. 1997. Geology, zonation, and fluid evolution of the big gossan Cu-Au skarn deposit, Ertsberg district, Irian Jaya. *Economic Geology*, 92(5): 509~534.
- Meinert L D. 1998. A review of skarns that contain gold. *Mineralized Intrusions-Related Skarns Systems: Mineralogical Association of Canada, Short course*, 26: 359~414.
- Meinert L D, Dipple G M, Nicolescu S. 2005. World skarn deposits. *Economic Geology 100th Anniversary Volume*, 299~336.
- Park C, Choi W, Kim H, Park M H, Kang I M, Lee H S, Song Y. 2017. Oscillatory zoning in skarn garnet: Implications for tungsten ore exploration. *Ore Geology Reviews*, 89: 1006~1018.
- Qin Zhipeng, Wang Xiongwu, Tang Juxing, Tang Xiaoqian, Zhou Yun, Peng Lijuan. 2011a. Geochemical characteristics and their implications of peraluminous granite in the Jiama deposit, Tibet. *Journal of Chengdu University of Technology (Science and Technology Edition)*, 38(1): 76~84 (in Chinese with English abstract).
- Qin Zhipeng, Wang Xiongwu, Duo Ji, Tang Xiaoqian, Zhou Yun, Peng Huijuan. 2011b. LA-ICP-MS U-Pb zircon age of intermediate-acidic intrusive rocks in Jiama of Tibet and its metallogenic significance. *Mineral Deposits*, 30(2): 339~348 (in Chinese with English abstract).
- Qin Zhipeng, Wang Xiongwu, Tang Juxing, Zhou Yun, Tang Xiaoqian. 2012. Geochemical characteristics and significance of the Jiama Adakitic porphyry, Tibet. *Journal of Jilin University: Earth Science Edition*, 42(S1): 267~280 (in Chinese with English abstract).
- Qiu Ruilong. 1988. Study on garnets and their rings of skarn copper ore in Tongshan, Guichi, Anhui. *Acta Petrologica et Mineralogica*, (3): 244~252+288 (in Chinese with English abstract).
- Seo J H, Guillong M, Heinrich C A. 2012. Separation of molybdenum and copper in porphyry deposits: The roles of sulfur, redox, and pH in ore mineral deposition at Bingham Canyon. *Economic Geology*, 107(2): 333~356.
- Sillitoe R H. 2000. Gold-rich porphyry deposits: descriptive and genetic models and their role in exploration and discovery. *Reviews in Economic Geology*, 13: 315~345.
- Tang Juxing, Wang Denghong, Wang Xiongwu, Zhong Kanghui, Ying Lijuan, Zheng Wenbao, Li Fengji, Guo Na, Qin Zhipeng, Yao Xiaofeng, Li Lei, Wang You, Tang Xiaoqian. 2010. Geological features and metallogenic model of the Jiama copper-polymetallic deposit in Tibet. *Acta Geoscientia Sinica*, 31(4): 495~506 (in Chinese with English abstract).
- Tang Juxing, Deng Shilin, Zheng Wenbao, Ying Lijuan, Wang Xiongwu, Zhong Kanghui, Qin Zhipeng, Ding Feng, Li Fengji, Tang Xiaoqian, Zhong Yufeng, Peng Huijuan. 2011. An exploration model for Jiama copper polymetallic deposit in Maizhokunggar County, Tibet. *Mineral Deposits*, 30(2): 179~196 (in Chinese with English abstract).
- Tang Juxing, Zheng Wenbao, Chen YuChuan, Wang Denghong, Yin Lijuan, Qin Zhipeng. 2013. Prospecting breakthrough of the deep porphyry ore body and its significance in Jiama copper polymetallic deposit, Tibet, China. *Journal of Jilin University: Earth Science Edition*, 43(4): 1100~1110 (in Chinese with English abstract).
- Tang Pan, Tang Juxing, Zheng Wenbao, Leng Qiufeng, Lin Bin, Tang Xiaoqian, Wang Hao, Gao Xin, Zhang Zebin, Zhou Hongbing. 2017. Is Tongshan orebody in the Jiama copper-polymetallic deposit Manto-type ore? *Acta Geoscientia Sinica*, 38(5): 829~838 (in Chinese with English abstract).
- Tang Xiaoqian, Wang Guozhi, Qin Zhipeng, Yao Xiaofeng, Zhou Yuxiong. 2012. Mineralogical characteristics and genesis of garnet in the Jiama (Gyama) copper-polymetallic deposit of Tibet. *Acta Geoscientia Sinica*, 33(4): 633~640 (in Chinese with English abstract).
- Tian Zhendong, Leng Chengbiao, Zhang Xingchun, Zafar T, Zhang Lejun, Hong Wei, Lai Chun-kit. 2019. Chemical composition,

- genesis and exploration implication of garnet from the Hongshan Cu-Mo skarn deposit, SW China. *Ore Geology Reviews*, 112: 103016.
- Titley S. R. 1973. Pyrometasomatism-an alteration type. *Economic Geology*, 68: 1326~1328.
- Wang Huan. 2011. The study on mineralogical characteristics and its genetic significance of Jiama copper polymetallic deposit, Tibet. Master degree dissertation of Chinese Academy of Geological Sciences (in Chinese with English abstract).
- Wang Wei, Wang Minfang, Liu Kun, Guo Xiaonan. 2016. The current status and prospects of the study of garnet in skarn for hydrothermal fluid evolution tracing and mineralization zoning. *Acta Petrologica et Mineralogica*, 35(1): 147~161 (in Chinese with English abstract).
- Wang Yiyun, Zheng Wenbao, Chen Yuchuan, Tang Juxing, Leng Qiufeng, Tang Pan, Ding Shuai, Zhou Yun. 2017. Discussion on the mechanism of separation of copper and molybdenum in Jiama porphyry deposit system, Tibet. *Acta Petrologica Sinica*, 33(2): 495~514 (in Chinese with English abstract).
- Xie Guiqing, Li Xinhao, Han Yingxiao, Zhu Qiaoqiao, Li Wei, Ye Hui, Song Shiwei. 2020. Recent progress in study of enrichment mechanism of tellurium, selenium and thallium from oxidized gold-rich porphyry-skarn deposits. *Mineral Deposits*, 39(4): 559~567 (in Chinese with English abstract).
- Ying Lijuan, Tang Juxing, Wang Denghong, Chang Zhesheng, Qu Wenjun, Zheng Wenbao. 2009. Re-Os isotopic dating of molybdenite in skarn from the Jiama copper polymetallic deposit of Tibet and its metallogenic significance. *Rock and Mineral Analysis*, 28(3): 265~268 (in Chinese with English abstract).
- Ying Lijuan, Wang Denghong, Tang Juxing, Chang Zhesheng, Qu Wenjun, Zheng Wenbao, Wang Huan. 2010. Re-Os dating of molybdenite from the Jiama copper polymetallic deposit in Tibet and its metallogenic significance. *Acta Geologica Sinica*, 84(8): 1165~1174 (in Chinese with English abstract).
- Ying Lijuan, Tang Juxing, Wang Denghong, Zheng Wenbao, Qin Zhipeng Zhang Li. 2011. Zircon SHRIMP U-Pb dating of porphyry vein from the Jiama copper polymetallic deposit in Tibet and its significance. *Acta Petrologica Sinica*, 27(7): 2095~2102 (in Chinese with English abstract).
- Ying Lijuan, Zheng Wenbao, Wang Weipin, Leng Qiufeng, Ding Shuai. 2012a. Stable isotopes geochemistry of the Jiama copper polymetallic deposit in Tibet. *Acta Geoscientia Sinica*, 33(4): 519~527 (in Chinese with English abstract).
- Yin Lijuan, Tang Juxing, Wang Denghong. 2012b. Features of garnet in the Jiama super-large Cu polymetallic deposit and its genetic significance. *Acta Geologica Sinica*, 86(11): 1735~1747 (in Chinese with English abstract).
- Ying Lijuan, Wang Chenghui, Tang Juxing, Wang Denghong, Qu Wenjun, Li Chao. 2014. Re-Os systematics of sulfides (chalcopyrite, bornite, pyrite and pyrrhotite) from the Jiama Cu-Mo deposit of Tibet, China. *Journal of Asian Earth Sciences*, 79(2): 497~506.
- Yu Miao. 2013. Study on Mineralogy and mineralization alteration band characteristics of silica rock of Galinger iron ore in Qinghai. MD degree dissertation of China University of Geosciences, Beijing (in Chinese with English abstract).
- Zhao Yiming, Tan Huijing, Sunjinghua. 1982. Characteristics of the skarn zoning of the Makeng and Vengshan iron ore deposits in Fujian and the relationship with the mineralization zoning. *Rock and Mineral Analysis*, (1): 11~22 (in Chinese with English abstract).
- Zheng Wenbao, Tang Juxing, Chang Zhesheng, Li Fengji, Yao Xiaofeng. 2010a. Geological and geochemical characteristics and genesis of the Jiama polymetallic copper deposit in Tibet geology and exploration. *Geology and Prospecting*, 46(6): 985~994 (in Chinese with English abstract).
- Zheng Wenbao, Chen Yuchuan, Song Xin, Tang Juxing, Ying Lijuan, Li Fengji, Tang Xiaoqian. 2010b. Element distribution of Jiama copper-polymetallic deposit in Tibet and its geological significance. *Mineral Deposits*, 29(5): 775~784 (in Chinese with English abstract).
- Zheng Wenbao, Leng Qiufeng, Chang Zhesheng, Ying Lijuan, Lin Bin. 2011. Molybdenum metallogenesis and prospecting direction of the Jiama deposit in Tibet. *Journal of Chengdu University of Technology (Science & Technology Edition)*, 38(1): 59~66 (in Chinese with English abstract).
- Zheng Wenbao, Tang Juxing, Wang Xiongwu, Wang Huan, Ying Lijuan, Zhong Yufeng, Zhong Wanting. 2012. Analysis on gold metallization in Jiama copper polymetallic deposit, Tibet. *Journal of Jilin University (Earth Science Edition)*, 42(S1): 181~196 (in Chinese with English abstract).
- Zheng Wenbao, Tang Juxing, Zhong Kanghui, Ying Lijuan, Leng Qiufeng, Ding Shuai, Lin Bin. 2016. Geology of the Jiama porphyry copper-polymetallic system, Lhasa Region, China. *Ore Geology Reviews*, 74: 151~169.
- Zhong Kanghui, Li Lei, Zhou Huiwen, Bai Jingguo, Li Wei, Zhong Wanting, Zhang Yongqiang, Lin Jiqing, Zheng Fanshi, Huang Xiaoyu, Lu Biao, Lei Bo. 2012. Features of Jiama-Kajunguo thrust-gliding nappe tectonic system in Tibet. *Acta Geoscientia Sinica*, 33(4): 411~423 (in Chinese with English abstract).
- Zhong Yufeng. 2011. Study on the Occurrence State of Associated Au in Jiama copper-polymetallic deposit, Tibet. Master degree dissertation of Chengdu University of Technology (in Chinese with English abstract).
- Zhu Qiaoqiao, Xie Guiqing, Li Wei, Zhang Fan, Wang Jian, Zhang Ping. 2014. In situ analysis of garnets from the Jingshandian iron skarn deposit, Hubei Province, and its geological implications. *Geology in China*, 41(6): 1944~1963 (in Chinese with English abstract).
- Zou Bing, Lin Bin, Zheng Wenbao, Song Yang, Tang Pan, Zhang Zebin, Gao Xin. 2019. The characteristics of alteration and mineralization and geochronology of ore-bearing porphyry in south pit of Jiama copper-polymetallic deposit, Tibet. *Acta Petrologica Sinica*, 35(3): 953~967 (in Chinese with English abstract).

参 考 文 献

- 冷秋锋. 2016. 西藏甲玛铜多金属矿床矽卡岩成岩与成矿作用. 成都理工大学博士学位论文.
- 冷秋锋, 唐菊兴, 郑文宝, 林彬, 王艺云, 唐攀, 林鑫. 2015. 西藏甲玛斑岩成矿系统中厚大矽卡岩矿体控矿因素研究. *矿床地质*, 34(2): 273~288.
- 冷秋锋, 唐菊兴, 郑文宝, 唐攀, 林彬. 2022. 西藏甲玛超大型矿床矽卡岩矿物组合及其分带模式. *地质学报*, 96(2): 574~591.
- 李永胜, 赵财胜, 吕志成, 严光生, 甄世民. 2011. 西藏甲玛铜多金属矿床流体包裹体特征及地质意义. *吉林大学学报(地球科学版)*, 41(1): 122~136.
- 李永胜, 吕志成, 严光生, 甄世民, 杜泽忠. 2012. 西藏甲玛铜多金属矿床 S、Pb、H、O 同位素特征及其指示意义. *地学前缘*, 19(4): 72~81.
- 林彬, 唐菊兴, 张志, 郑文宝, 冷秋锋, 钟婉婷, 应立娟. 2012. 西藏甲玛斑岩矿床裂隙系统的初步研究及意义. *矿床地质*, 31(3): 579~589.
- 林彬, 唐菊兴, 唐攀, 郑文宝, Greg Hall, 陈国良, 张忠坤. 2019. 斑岩成矿系统多中心复合成矿作用模型——以西藏甲玛超大型矿床为例. *矿床地质*, 38(6): 1204~1222.
- 林彬, 唐菊兴, 唐攀, 周放日格勒, 孙渺, 祁婧, 陈国良, 张忠坤, 张泽斌, 吴纯能, 田志超, 代晶晶, 杨征坤, 姚晓峰. 2021. 青藏高原甲玛斑岩成矿系统首例 3000 m 科学深钻的初步认识. *矿床地质*, 40(6): 1119~1134.
- 路远发. 2004. GeoKit: 一个用 VBA 构建的地球化学工具软件包. *地球化学*, (5): 459~464.
- 罗铭玖, 林潜龙, 卢欣祥, 陈铁华. 1993. 东秦岭含铜花岗岩的地质特征. *河南地质*, (1): 2~8.
- 秦志鹏, 汪雄武, 唐菊兴, 唐晓倩, 周云, 彭慧娟. 2011a. 西藏甲玛过铝质花岗岩的地球化学特征及成因意义. *成都理工大学学报*

(自然科学版), 38(1): 76~84.

秦志鹏, 汪雄武, 多吉, 唐晓倩, 周云, 彭惠娟. 2011b. 西藏甲玛中酸性侵入岩 LA-ICP-MS 锆石 U-Pb 定年及成矿意义. 矿床地质, 30(2): 339~348.

秦志鹏, 汪雄武, 唐菊兴, 周云, 唐晓倩. 2012. 西藏甲玛埃达克质斑岩的地球化学特征及意义. 吉林大学学报(地球科学版), 42(S1): 267~280.

邱瑞龙. 1988. 安徽贵池铜山矽卡岩铜矿石榴石及其环带研究. 岩石矿物学杂志, (3): 244~252+288.

唐菊兴, 王登红, 汪雄武, 钟康惠, 应立娟, 郑文宝, 黎枫估, 郭娜, 秦志鹏, 姚晓峰, 李磊, 王友, 唐晓倩. 2010. 西藏甲玛铜多金属矿床地质特征及其矿床模型. 地球学报, 31(4): 495~506.

唐菊兴, 邓世林, 郑文宝, 应立娟, 汪雄武, 钟康惠, 秦志鹏, 丁枫, 黎枫估, 唐晓倩, 钟裕锋, 彭慧娟. 2011. 西藏墨竹工卡县甲玛铜多金属矿床勘查模型. 矿床地质, 30(2): 179~196.

唐菊兴, 郑文宝, 陈毓川, 王登红, 应立娟, 秦志鹏. 2013. 西藏甲玛铜多金属矿床深部斑岩矿体找矿突破及其意义. 吉林大学学报(地球科学版), 43(4): 1100~1110.

唐攀, 唐菊兴, 郑文宝, 冷秋锋, 林彬, 唐晓倩, 王豪, 高昕, 张泽斌, 周洪兵. 2017. 西藏甲玛铜多金属矿床铜山矿体为 manto 型矿体? 地球学报, 38(5): 829~838.

唐晓倩, 王国芝, 秦志鹏, 姚晓峰, 周宇雄. 2012. 西藏甲玛铜多金属矿石石榴子石矿物学特征及成因意义. 地球学报, 33(4): 633~640.

王焕. 2011. 西藏甲玛铜多金属矿床矿物学特征及其成因意义研究. 中国地质科学院硕士学位论文.

王伟, 王敏芳, 刘坤, 郭晓南. 2016. 矽卡岩中石榴子石在示踪热液流体演化和矿化分带中的研究现状及其展望. 岩石矿物学杂志, 35(1): 147~161.

王艺云, 郑文宝, 陈毓川, 唐菊兴, 冷秋锋, 唐攀, 丁帅, 周云. 2017. 西藏甲玛斑岩成矿系统铜铅元素分离机制探讨. 岩石学报, 33(2): 495~514.

谢桂青, 李新昊, 韩颖霄, 朱乔乔, 李伟, 叶晖, 宋世伟. 2020. 氧化性富金斑岩-矽卡岩矿床中碲、硒、铊富集机制的研究进展. 矿床地质, 39(4): 559~567.

应立娟, 唐菊兴, 王登红, 畅哲生, 屈文俊, 郑文宝. 2009. 西藏甲玛铜多金属矿床矽卡岩中辉钼矿铼-钨同位素定年及其成矿意义. 岩矿测试, 28(3): 265~268.

应立娟, 王登红, 唐菊兴, 畅哲生, 屈文俊, 郑文宝, 王焕. 2010. 西藏甲玛铜多金属矿辉钼矿 Re-Os 定年及其成矿意义. 地质学报, 84(8): 1165~1174.

应立娟, 唐菊兴, 王登红, 郑文宝, 秦志鹏, 张丽. 2011. 西藏甲玛超大型铜矿区斑岩脉成岩时代及其与成矿的关系. 岩石学报, 27(7): 2095~2102.

应立娟, 郑文宝, 王崴平, 冷秋锋, 丁帅. 2012a. 西藏甲玛铜多金属矿硫同位素地球化学研究. 地球学报, 33(4): 519~527.

应立娟, 唐菊兴, 王登红, 王崴平. 2012b. 西藏甲玛超大型铜矿石石榴子石特征及成因意义. 地质学报, 86(11): 1735~1747.

于森. 2013. 青海杂林格铁矿矽卡岩矿物学及矿化蚀变分带特征研究. 中国地质大学(北京)硕士学位论文.

赵一鸣, 谭惠静, 孙静华. 1982. 福建马坑、阳山铁矿床的矽卡岩分带特征及其与矿化分带的关系. 岩矿测试, (1): 11~22.

郑文宝, 唐菊兴, 畅哲生, 黎枫估, 姚晓峰. 2010a. 西藏甲玛铜多金属矿床地质地球化学特征及成因浅析. 地质与勘探, 46(6): 985~994.

郑文宝, 陈毓川, 宋鑫, 唐菊兴, 应立娟, 黎枫估, 唐晓倩. 2010b. 西藏甲玛铜多金属矿元素分布规律及地质意义. 矿床地质, 29(5): 775~784.

郑文宝, 冷秋锋, 畅哲生, 应立娟, 林彬. 2011. 西藏甲玛矿区钨成矿作用与找矿方向. 成都理工大学学报(自然科学版), 38(1): 59~66.

郑文宝, 唐菊兴, 汪雄武, 王焕, 应立娟, 钟裕锋, 钟婉婷. 2012. 西藏甲玛铜多金属矿床金矿地质特征及成矿作用. 吉林大学学报(地球科学版), 42(S1): 181~196.

钟康惠, 李磊, 周慧文, 白景国, 李伟, 钟婉婷, 张勇强, 蔺吉庆, 郑凡石, 黄小雨, 陆彪, 雷波. 2012. 西藏甲玛-卡果果推-滑覆构造系特征. 地球学报, 33(4): 411~423.

钟裕锋. 2011. 西藏甲玛铜多金属矿伴生元素金的赋存状态研究. 成都理工大学硕士学位论文.

朱乔乔, 谢桂青, 李伟, 张帆, 王建, 张平, 于炳飞. 2014. 湖北金山店大型矽卡岩型铁矿石石榴子石原位微区分析及其地质意义. 中国地质, 41(6): 1944~1963.

邹兵, 林彬, 郑文宝, 宋扬, 唐攀, 张泽斌, 高昕. 2019. 西藏甲玛矿床南坑矿段蚀变、矿化及含矿斑岩年代学. 岩石学报, 35(3): 953~967.

Mineral zoning and geological significance of skarns in the Jiama 3000 m scientific deep borehole, Tibet

WANG Mengdie¹⁾, TANG Juxing^{*2)}, LIN Bin²⁾, TANG Pan³⁾, TANG Xiaoqian⁴⁾,
SUN Miao⁵⁾, LI Faqiao⁵⁾, QI Jing⁵⁾, FU Yuanhui⁶⁾, ZHANG Zhongkun⁶⁾,
CUI Hao¹⁾, YANG Zhengkun⁶⁾, XIONG Yan¹⁾

1) College of Earth Sciences, Chengdu University of Technology, Chengdu, Sichuan 610059, China;

2) MNR Key Laboratory of Metallogeny and Mineral Resource Assessment, Institute of Mineral Resources, CAGS, Beijing 100037, China;

3) The Key Laboratory of the Ministry of Education on Solid Waste Treatment and Recycling, School of Environment and Resource, Southwest University of Science and Technology, Mianyang, Sichuan 621010, China;

4) Beijing China Mining Federation Consulting Center, Beijing 100044, China;

5) China University of Geosciences, Beijing 100083, China;

6) Tibet Huatailong Ming Corp. Ltd., Lhasa, Tibet 850200, China;

* Corresponding author: tangjuxing@126.com

Abstract

The Jiama copper polymetallic deposit is a super large porphyry skarn deposit of great economic value and scientific research significance in the eastern part of the Gangdise metallogenic belt, which completely preserves important information on the formation and evolution of skarn deposits. Previous studies mostly focused on the horizontal zoning of skarn, but the vertical zoning of skarn minerals and its coupling relationship with metal mineralization is less understood. This paper focuses on the detailed mineralogical study of skarn ore body in the Jiama 3000 m scientific deep borehole, and systematically reveals the mineralogical spatial zoning characteristics of skarn ore body and its coupling relationship with metal mineralization. The results show that the skarn has clear zoning from shallow to deep, i. e. skarn hornfeld → diopside garnet skarn → wollastonite garnet skarn → garnet wollastonite skarn → diopside garnet skarn → garnet wollastonite skarn → Skarn marble → wollastonite garnet skarn → diopside garnet skarn → diopside garnet skarn → wollastonite garnet skarn → skarn marble → wollastonite garnet skarn → wollastonite garnet skarn → skarn marble → wollastonite garnet skarn → diopside garnet skarn → endoskarn (containing garnet granodiorite porphyry). The metal mineral assemblage changes from shallow to deep, molybdenite ± chalcopyrite → bornite + chalcopyrite ± chalcocite ± wittichenite ± (molybdenite) → molybdenite ± chalcopyrite. The corresponding metallogenic elements are $\text{Mo} \pm \text{Cu} \pm \text{Au} \pm \text{Ag} \rightarrow \text{Cu}(\text{Mo}) \pm \text{Au} \pm \text{Ag} \rightarrow \text{Mo} \pm \text{Cu} \pm \text{Au} \pm \text{Ag}$. The research shows that the spatial location of intrusive and surrounding rocks, tectonic settings and the superposition of multi-stage hydrothermal fluids are important factors controlling the zoning of skarn minerals. At the same time, the mineralogical characteristics show that the enrichment of high-grade gold in skarn is closely related to copper sulfides such as bornite, and may also be related to the superposition of multi-stage fluids and the source area of gold-rich magma.

Key words: skarn zoning; porphyry skarn deposit; skarn mineralogy; Jiama; Tibet