

# 江西德兴铜矿田成矿热液演化过程 及其对铼差异性富集的制约

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**内容提要:**铜厂和富家坞矿床是德兴矿田中两个典型的斑岩铜矿床,二者成矿时代、成矿背景和致矿斑岩均较一致,但前者中辉钼矿的 Re 含量明显高于后者。为探究成矿流体演化过程对辉钼矿中 Re 含量差异的影响,本文对铜厂和富家坞不同成矿阶段的石英开展 LA-ICP-MS 微区原位分析以及流体包裹体测温研究。结果显示,二者流体均具有由高温向低温,中低盐度高盐度共存向低盐度演化的趋势,且温度下降、流体沸腾以及 pH 值的变化可能是导致 Cu、Mo 沉淀的主要原因;但就同一成矿阶段而言,铜厂比富家坞成矿温度更低,并且在主成矿阶段,铜厂具有更高的流体盐度;因此,推测温度和盐度可能是导致二者中辉钼矿 Re 含量差异的主导因素。

**关键词:**德兴铜矿田;成矿流体演化;辉钼矿;铼

江西德兴铜矿田是中国东部最大的斑岩型铜矿产地,其矿产资源储量巨大,Cu、Mo 储量分别达超大型、大型。同时还伴生有 Au、Ag、Re 和 Co 等有益组分(朱训等,1983;周清,2011;文鹏,2015),其中 Re 储量可达 1000 t,占全球储量的 10%(龚益彬,2008)。该矿床自发现以来,前人在地质特征(朱训等,1983)、成岩成矿时代(Guo Shuo et al., 2012; Zhou Qing et al., 2012; Li Xiaofeng et al., 2013)、构造背景(Wang Qiang et al., 2006; Wang Guoguang et al., 2015; Li Li et al., 2017; Zhang Chanchan et al., 2017)、成矿物质来源(梁祥济, 1995;钱鹏等,2006)、伴生元素分布状态(王传亮等, 2014;夏瑜等,2017;高知睿等,2018)等方面做了大量研究并取得了众多成果。前人通过辉钼矿 Re-Os 定年以及微量元素方面的研究,发现德兴铜矿田铜厂和富家坞两个矿床的辉钼矿 Re 含量存在显著差异,铜厂辉钼矿平均 Re 含量可达  $1268 \times 10^{-6}$ ,而富家坞矿床平均 Re 含量为  $244 \times 10^{-6}$ (朱训等,

1983;Guo Shuo et al., 2012),但对于差异的原因却少有研究。二者在地质背景、成矿时代、成矿岩体等方面均较一致,这意味着铜厂和富家坞辉钼矿 Re 含量的差异可能与成矿流体性质及演化过程有关。

基于此,本文采用流体包裹体测温以及石英 LA-ICP-MS 微量元素分析等手段,重点对比铜厂和富家坞矿床的流体性质及演化过程,并在此基础上探讨两个矿床辉钼矿 Re 含量差异的原因,深化对 Re 成矿理论的认识。

## 1 区域地质特征

德兴斑岩型铜矿田地处扬子板块东南缘的江南台隆上,江南造山带的东部,江绍断裂带的西侧(金章东等,2002;周清,2011;李利等,2018;Wang Guoguang et al., 2020)。区内出露地层岩性相对简单,全区面积 70% 的地层为新元古界双桥山群浅变质岩(毛景文等,2010)。北东向的赣东北深大断裂、乐安江深大断裂和泗州庙复式向斜组成了区内

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Chen Taoliang, Ren Zhi, Leng Chengbiao, Wang Andong. 2023. The evolution of metallogenic hydrothermal fluid and its effect on the heterogeneous enrichment of rhenium in the Dexing copper ore field, Jiangxi Province. Acta Geologica Sinica, 97(6): 1900~1916.

主要构造框架(图 1)。该区域从晋宁期到喜马拉雅期,共经历了七次较大的构造-岩浆活动,其中以晋宁期及燕山期的岩浆活动最为强烈,前者主要形成火山碎屑岩、角斑岩、玄武岩等,后者以酸性喷出岩及侵入岩为主,岩性主要为火山碎屑岩、花岗斑岩、石英斑岩、花岗闪长斑岩等(朱训等,1983)。矿田资源储量巨大,铜储量超 9 万 t,金 138 t(朱训等,1983)。

2 矿床地质特征

德兴矿田由铜厂、富家坞、朱砂红三个大型斑岩铜矿床组成,三者呈北西向展布(图 2)。在矿田范围内,仅出露新元古界双桥山群的浅变质千枚岩,这

一地层也是矿田的赋矿围岩。矿田内的泗州庙复式向斜及次级褶皱西源岭背斜、官帽山向斜为主要的褶皱构造。矿田主要发育东西向、北东向、北北东向的三组压扭性断裂,同时还存在与之相配套的三组张性断裂组合(朱训等,1983)。三个矿床的成矿与矿田内的 NW 向展布的三个小型花岗闪长斑岩体关系密切,斑岩体呈北西向倾伏,三个斑岩体锆石 U-Pb 年龄集中在 172~170 Ma(王强等,2004;Liu Xuan et al., 2012; Zhou Qing et al., 2012; Li Xiaofeng et al., 2013)。矿体主要赋存于斑岩体浅部的内外接触带,空间分布集中,形态完整,规模巨大,呈现上铜下钼的特征(朱训等,1983)。从朱砂红矿床到富家坞矿床,矿石铜钼品位逐渐增加,矿床剥

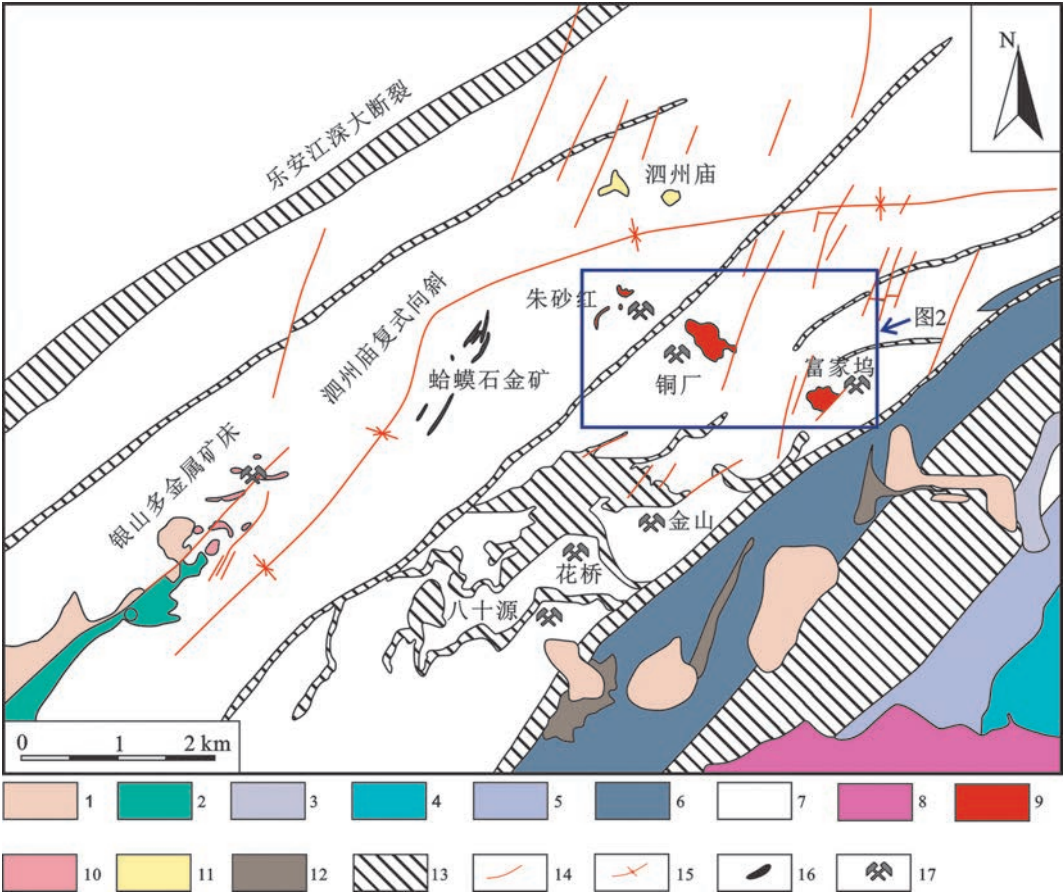


图 1 江西德兴铜矿田区域地质图(据王翠云等,2012 修)

Fig. 1 Regional geological map of the Dexing copper ore field, Jiangxi Province, South China (modified after Wang Cuiyun et al., 2012)

1—白垩系石溪组;2—侏罗系鹅湖岭组;3—侏罗系林山组;4—寒武系河塘组;5—震旦系志堂组;6—新元古界登山群;7—新元古界双桥山群;8—中侏罗世花岗岩;9—中侏罗世花岗闪长斑岩;10—早侏罗世潜火山岩;11—古元古代辉石角闪岩;12—新元古代细碧角斑岩;13—剪切带;14—断裂;15—复式向斜;16—金矿脉;17—矿床

1—Cretaceous Shixi Group; 2—Jurassic Ehuling Group; 3—Jurassic Linshan Group; 4—Cambrian Hetang Group; 5—Sinian System Zhitang Group; 6—Neoproterozoic Dengshan Group; 7—Neoproterozoic Shuangqiaoshan Group; 8—Middle Jurassic granite; 9—Middle Jurassic granodiorite porphyry; 10—Early Jurassic subvolcanic rock; 11—Paleoproterozoic pyroxenite diorite; 12—Neoproterozoic metaspilite keratophyre; 13—shear zone; 14—fault; 15—synclinorium; 16—gold ore bodies; 17—ore deposits

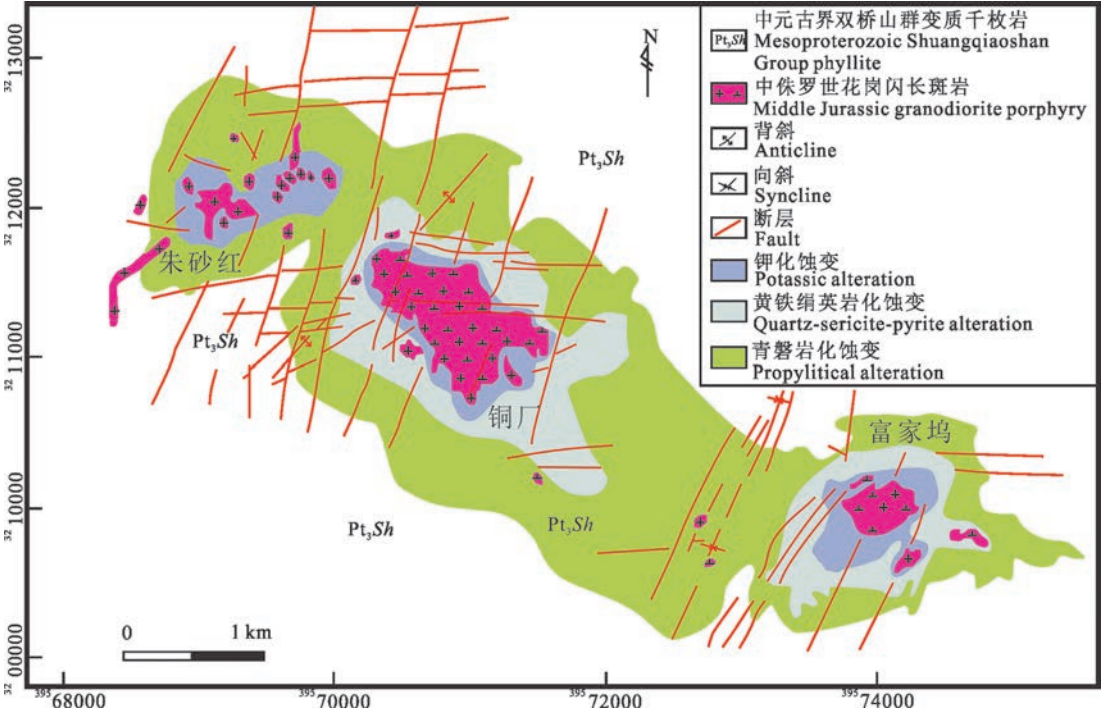


图 2 德兴铜矿田构造分布及蚀变分带简图(据朱训等,1983 修改)

Fig. 2 Simplified structures and alteration zoning map of the Dexing copper ore field (modified after Zhu Xun et al. , 1983)

蚀深度逐渐增大(王国光等,2019)。金属矿物有黄铜矿、辉钼矿、黄铁矿、磁铁矿及赤铁矿,还有少量或微量的方铅矿、磁黄铁矿等。脉石矿物包括钾长石、石英、斜长石、绿泥石、绿帘石和方解石,少量黑云母、白云母、石膏、硬石膏、金红石,以及微量的萤石等。矿石的常见构造主要有块状构造、浸染状构造、脉状构造等。三个矿床围岩蚀变种类、蚀变分带特征也极为相似,主要发育有钾长石化、绢云母化、绿泥石化、白云石化、青磐岩化等蚀变,同时自接触带向外呈现典型的斑岩矿床蚀变分带特征(即,钾化—黄铁绢英岩化—青磐岩化)(图 3;He Wenwu et al. , 1999;Wang Qiang et al. , 2006;Sillitoe, 2010;王翠云等,2012;王国光等,2019)。根据蚀变矿物相互交代以及脉体之间的穿插关系可划分三个蚀变矿化阶段:早期钾长石化阶段、中期的石英-绢云母-绿泥石化阶段以及晚期的碳酸盐-硫酸盐化阶段(朱训等,1983;周清,2013)。

(1)早期钾长石化阶段:该阶段蚀变产物主要为钾长石、石英、黑云母等,偶见电气石、磷灰石,蚀变范围主要集中在岩体内部。此阶段矿化相对微弱,主要为稀疏浸染状产出的磁铁矿、黄铁矿、黄铜矿及少量的辉钼矿。

(2)中期石英-绢云母-绿泥石化阶段:这一阶段主要形成石英、绢云母、绿泥石、伊利石等蚀变矿物,

蚀变范围宽广,发育在岩体内外接触带。矿化强烈,主要为黄铜矿、黄铁矿、辉钼矿等矿物,是 Cu、Mo 矿化的主要阶段。

(3)晚期碳酸盐-硫酸盐化阶段:由于晚期大气降水开始占据主导地位,流体氧逸度上升,温度大幅下降,形成的蚀变矿物主要为方解石、白云石、硬石膏,蚀变范围最广。这一阶段矿化微弱,主要为少量的黄铜矿、黄铁矿,偶见辉钼矿产出。

3 样品及实验方法

3.1 样品采集及特征描述

由于朱砂红矿区尚未开采,难以获得实验所需样品,本次测试样品采自富家坞和铜厂矿区的露天采场,对应标高分别为 133.14 m、204.29 m 以及 -47.20 m、-72.50 m。用于实验的样品主要为弱蚀变花岗闪长斑岩的石英斑晶及含矿石英脉。花岗闪长斑岩表面呈现青灰色,具有斑状结构,块状构造。斑晶总含量约为 30%~60%,成分主要为斜长石(15%~35%)、钾长石(5%~15%)、黑云母(~5%)及少量石英(<2%)。石英斑晶颗粒大小 1~3 mm,常呈自形一半自形粒状,环带不发育,边部被溶蚀呈浑圆状,未见明显次生加大现象,颗粒内部裂隙发育,可见溶蚀坑。根据矿物组合、横切脉关系和蚀变类型,可将富家坞含矿石英脉依据从早到晚、从高温

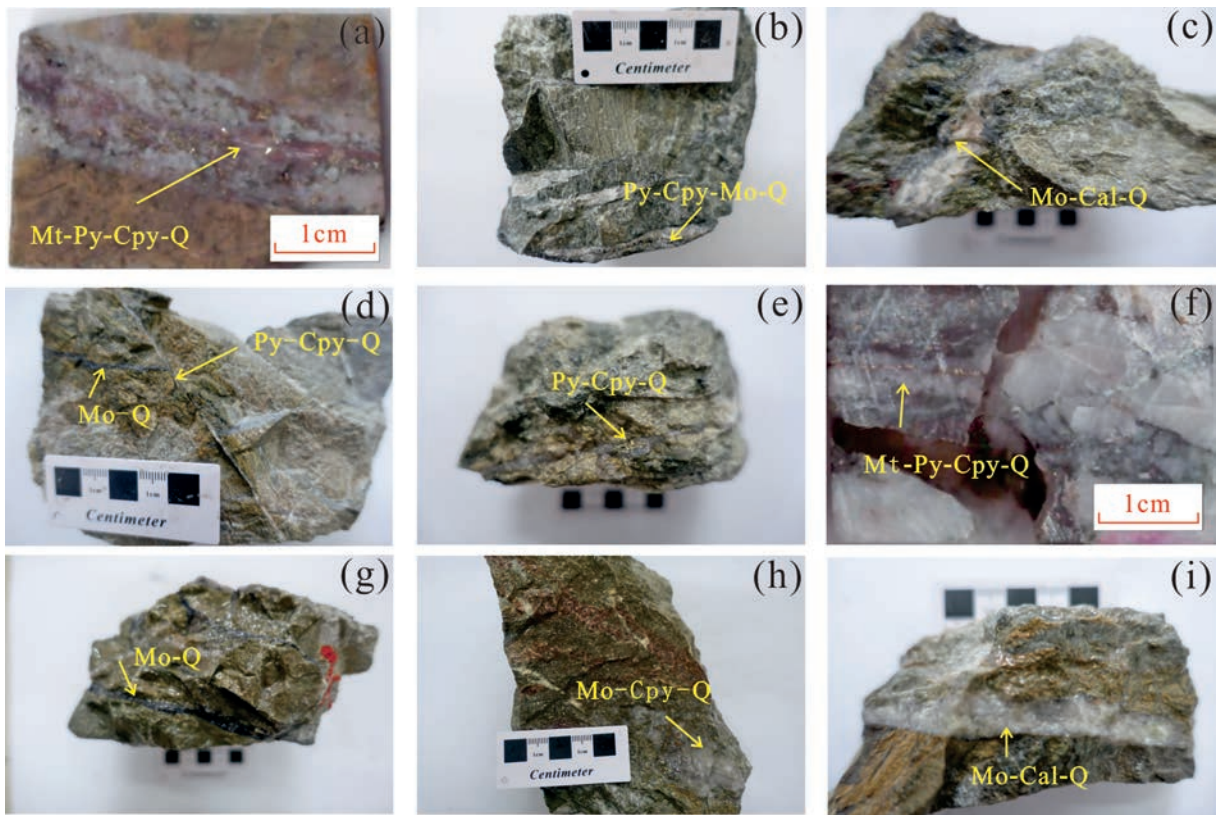


图 3 德兴铜矿田富家坞和铜厂矿床不同成矿阶段脉体特征

Fig. 3 Photos of veins in different metallogenic stages of Fujiawu and Tongchang deposits in the Dexing copper ore field  
(a)—富家坞  $V_1$  脉,可见磁铁矿化;(b)—富家坞  $V_2$  脉,脉内辉钼矿呈脉状产出;(c)—富家坞  $V_3$  脉,脉内可见方解石,辉钼矿呈脉状产出;(d)—富家坞  $V_4$  脉截穿  $V_2$  脉;(e)—富家坞  $V_4$  脉,仅见黄铜矿、黄铁矿化;(f)—铜厂  $V_1$  脉,可见磁铁矿化;(g)—铜厂  $V_2$  脉,辉钼矿呈脉状产出;(h)—铜厂  $V_2$  脉,辉钼矿呈细脉浸染状产出;(i)—铜厂  $V_3$  脉,脉内可见方解石,辉钼矿呈脉状产出;Mt—磁铁矿;Py—黄铁矿;Cpy—黄铜矿;Mo—辉钼矿;Q—石英;Cal—方解石  
(a)—Vein  $V_1$  of Fujiawu, magnetite mineralization; (b)—Vein  $V_2$  of Fujiawu, molybdenite occurs as vein; (c)—Vein  $V_3$  of Fujiawu, molybdenite occurs as vein, calcite can be seen in the vein; (d)—Vein  $V_2$  bearing molybdenite-center-line have been intersected by pyrite-chalcopyrite Vein  $V_4$ ; (e)—Vein  $V_4$  of Fujiawu, with only chalcopyrite and pyrite; (f)—Vein  $V_1$  of Tongchang, magnetite mineralization; (g)—Vein  $V_2$  of Tongchang, molybdenite occurs as veinlet disseminated; (h)—Vein  $V_2$  of Tongchang, molybdenite occurs as veinlet disseminated; (i)—Vein  $V_3$  of Tongchang, molybdenite occurs as vein, calcite can be seen in the vein; Mt—magnetite; Py—pyrite; Cpy—chalcopyrite; Mo—molybdenite; Q—quartz; Cal—calcite

到低温分为四个阶段(图 3)。

(1) $V_1$  脉:即形成于斑岩体尚未完全固结时的 A 脉,石英颗粒较为完整,内部少见裂隙,部分石英发育有次生加大边,与早期钾长石阶段有关。脉内可见磁铁矿以细脉浸染状、脉状形式产出,并伴有黄铁矿化、黄铜矿化,未见辉钼矿产出(图 4a)。

(2) $V_2$  脉:与绿泥石化、绢云母化、伊利石化相关的 B 脉,石英较为完整,内部裂隙较少,可见次生加大现象,未见磁铁矿。脉内主要为辉钼矿、黄铁矿、黄铜矿,其中辉钼矿主要以细脉浸染状(图 4b)、脉状形式(图 4c)产在石英脉中线。

(3) $V_3$  脉:成矿晚阶段  $D_1$  脉,以石英脉为主,石英较为破碎,可见微裂隙穿插。脉内发育方解石、硬

石膏等,同时可见部分辉钼矿以脉状形式产出在石英脉的边缘(图 4d)。

(4) $V_4$  脉:矿化微弱的  $D_2$  脉,石英颗粒极为破碎,可见大量微裂隙穿插。脉内仅发育极少量黄铁矿、黄铜矿(图 4e),可见方解石、硬石膏等。

然而,铜厂矿床中含石英脉仅有  $V_1 \sim V_3$  脉样品(图 4f~i),缺失  $V_4$  脉样品。

### 3.2 分析方法

流体包裹体显微测温实验在东华理工大学核资源与环境国家重点实验室完成,实验仪器为 Linkam 冷热台。该冷热台可观测到  $1 \mu\text{m}$  包裹体,温度精度在  $0.1^\circ\text{C}$  内,实验前利用纯  $\text{H}_2\text{O}$  包裹体冰点温度( $0^\circ\text{C}$ )和纯  $\text{CO}_2$  包裹体熔点温度( $-56.6^\circ\text{C}$ )对冷热

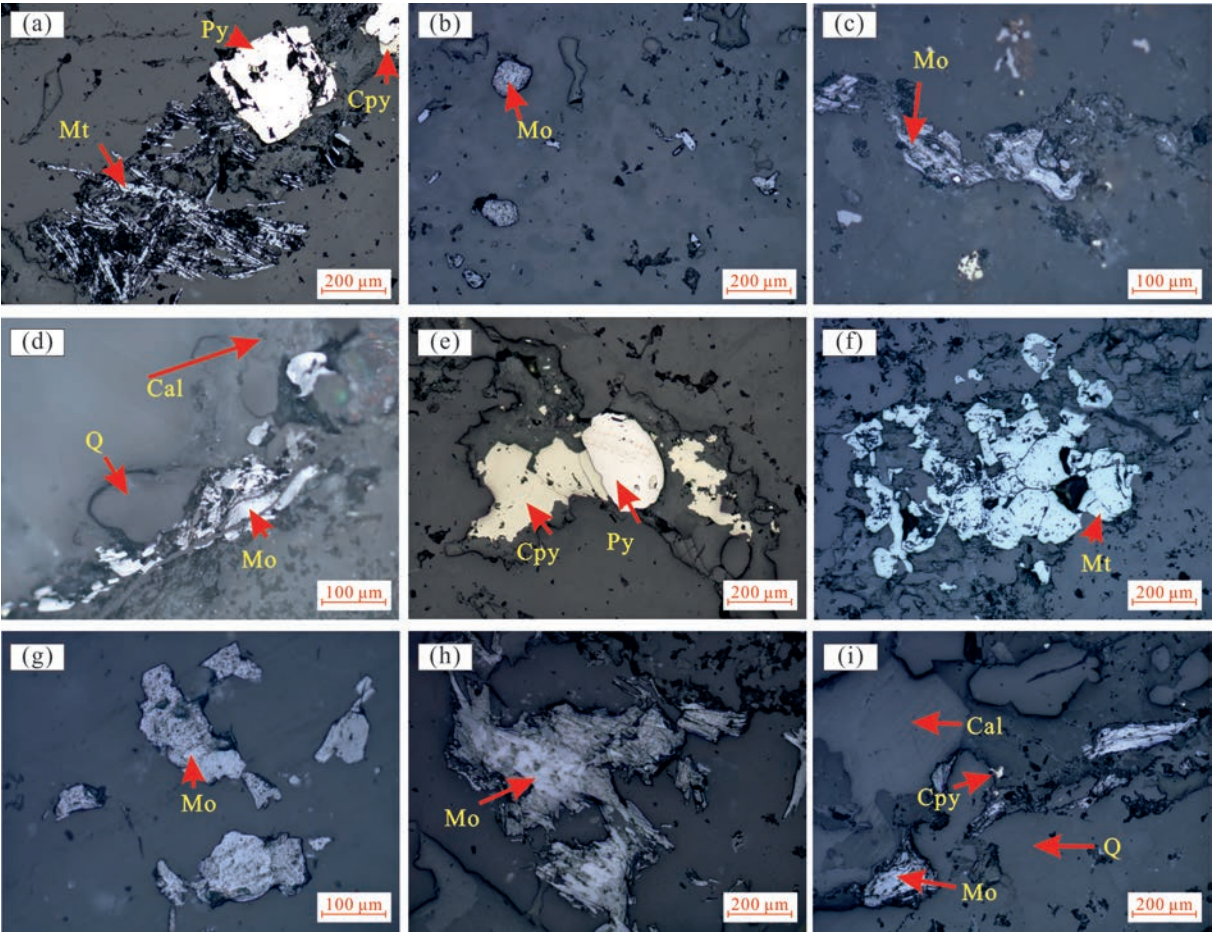


图 4 德兴铜矿田富家坞和铜厂矿床不同成矿阶段镜下照片

Fig. 4 Micrograph of different metallogenic stages of Fujiaiwu and Tongchang deposits in the Dexing copper ore field  
(a)—富家坞  $V_1$  脉, 可见磁铁矿化; (b)—富家坞  $V_2$  脉, 辉钼矿呈细脉浸染状产出; (c)—富家坞  $V_2$  脉, 辉钼矿呈脉状产出; (d)—富家坞  $V_3$  脉, 脉内可见方解石, 辉钼矿呈脉状产出; (e)—富家坞  $V_4$  脉, 仅见黄铜矿、黄铁矿化; (f)—铜厂  $V_1$  脉, 可见磁铁矿化; (g)—铜厂  $V_2$  脉, 辉钼矿呈细脉浸染状产出; (h)—铜厂  $V_2$  脉, 辉钼矿呈脉状产出; (i)—铜厂  $V_3$  脉, 脉内可见方解石, 辉钼矿呈脉状产出; Mt—磁铁矿; Py—黄铁矿; Cpy—黄铜矿; Mo—辉钼矿; Q—石英; Cal—方解石  
(a)—Vein  $V_1$  of Fujiaiwu, magnetite mineralization; (b)—Vein  $V_2$  of Fujiaiwu, molybdenite occurs as veinlet disseminated; (c)— $V_2$  of Fujiaiwu, molybdenite occurs as vein; (d)—Vein  $V_3$  of Fujiaiwu, molybdenite occurs as vein, calcite can be seen in the vein; (e)—Vein  $V_4$  of Fujiaiwu, with only chalcopyrite and pyrite; (f)—Vein  $V_1$  of Tongchang, magnetite mineralization; (g)—Vein  $V_2$  of Tongchang, molybdenite occurs as veinlet disseminated; (h)—Vein  $V_2$  of Tongchang, molybdenite occurs as vein; (i)—Vein  $V_3$  of Tongchang, molybdenite occurs as vein, calcite can be seen in the vein; Mt—magnetite; Py—pyrite; Cpy—chalcopyrite; Mo—molybdenite; Q—quartz; Cal—calcite

台进行温度校正。升温过程的速率在 10~20 ℃/min, 接近相态变化和特征温度点时速率降至 1 ℃/min 以内。流体盐度、密度运用 Hall et al. (1988) 和刘斌等(1999)的计算公式和参数进行计算。

石英 LA-ICP-MS 微量元素分析在东华理工大学核资源与环境国家重点实验室铀-多金属研究中心完成。分析采用 PerkinElmer NexION 1000 四极杆 ICP-MS, 激光剥蚀装置为 NWR femto 257 飞秒激光剥蚀器。激光剥蚀能量密度为 5 J/cm<sup>2</sup>, 脉冲为 4 Hz, 剥蚀直径为 50 μm。激光剥蚀过程中采

用氦气作为剥蚀物质的载气。测试过程中, 分别利用 NIST 610 和 NIST 612、NIST 614 作为元素的外标和监测标样, 每间隔 6 个待测点插入两组 NIST 610 标样, 间隔 6 个待测点插入一组 NIST 612, 并以 <sup>29</sup>Si 为元素内标。石英微量元素数据利用 Iolite 软件处理。

4 分析结果

4.1 流体包裹体类型与测温

通过对不同成矿阶段脉体及斑晶的观察, 发现

铜厂及富家坞包裹体类型多样,存在顺石英生长环带生长或孤立分布的原生包裹体、沿着石英微裂隙生长的次生包裹体、假次生包裹体,其中原生包裹体占主导地位。铜厂和富家坞原生包裹体类型可分为

三类:富气相包裹体(VL 型)、富液相包裹体(LV 型)、含石盐子晶多相包裹体(LVH 型)(图 5)。其中 LV 型包裹体为两个矿床的主要包裹体类型,次为 VL 型包裹体和 LVH 型包裹体。

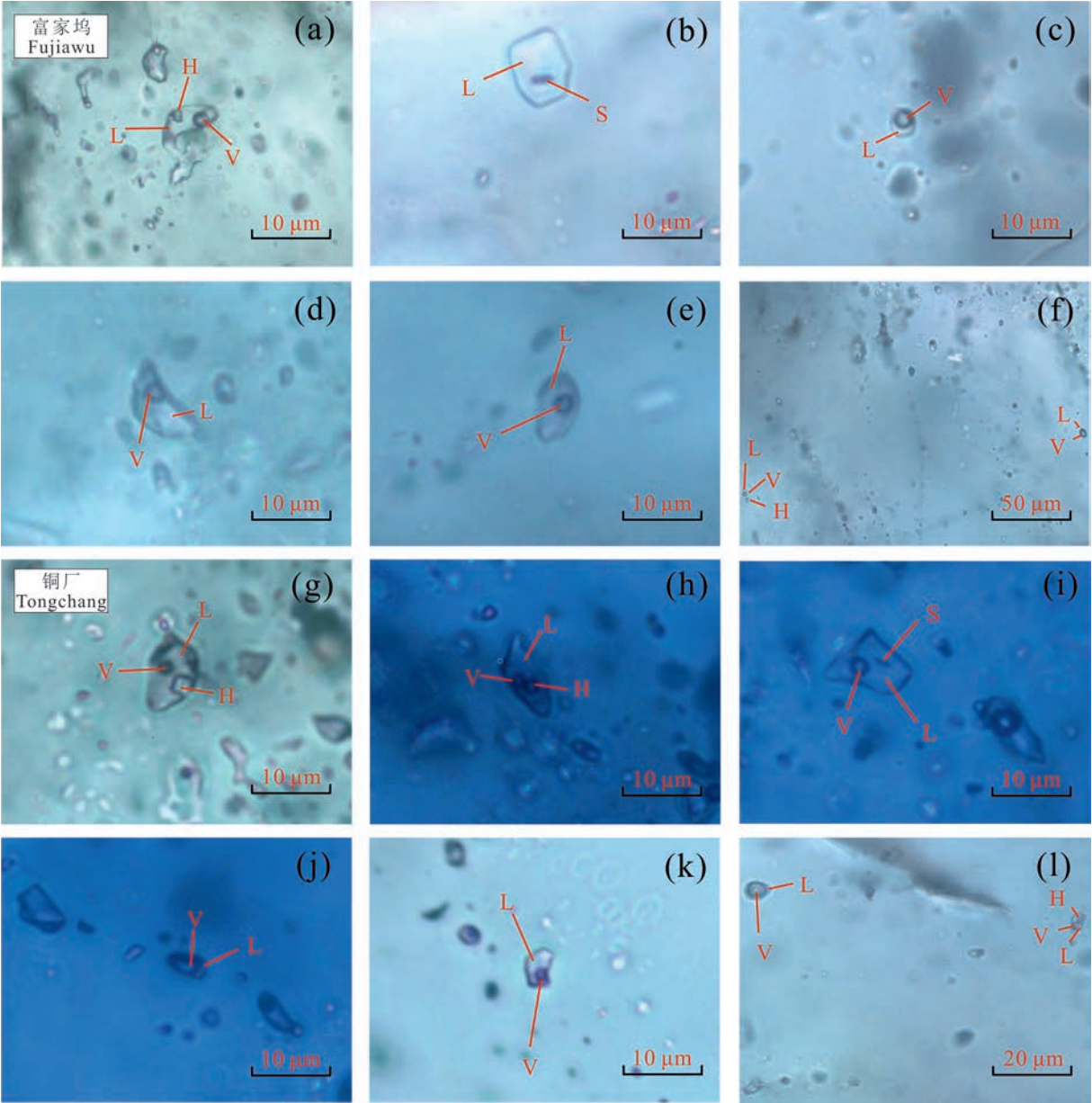


图 5 德兴铜矿田富家坞和铜厂矿床含石英脉中流体包裹体显微照片

Fig. 5 Photomicrographs of fluid inclusions from Fujiawu and Tongchang deposits in the Dexing copper ore field (a)—富家坞  $V_1$  脉 LVH 型包裹体;(b)—富家坞  $V_2$  脉含针状子矿物包裹体;(c)—富家坞  $V_2$  脉 VL 型包裹体;(d)—富家坞  $V_3$  脉 LV 型包裹体;(e)—富家坞  $V_4$  脉 LV 型包裹体;(f)—富家坞  $V_2$  脉流体沸腾的证据;(g)—铜厂  $V_1$  脉 LVH 型包裹体;(h)—铜厂  $V_2$  脉 LVH 型包裹体;(i)—铜厂  $V_2$  脉含针状子矿物包裹体;(j)—铜厂  $V_2$  脉 VL 型包裹体;(k)—铜厂  $V_3$  脉 LV 型包裹体;(l)—铜厂  $V_2$  脉流体沸腾的证据;V—气相;L—液相;H—石盐子晶;S—子矿物 (a)—Vein  $V_1$  of Fujiawu with LVH type inclusions; (b)—Vein  $V_2$  of Fujiawu with acicular mineral inclusions; (c)—Vein  $V_2$  of Fujiawu with VL type inclusions; (d)—Vein  $V_3$  of Fujiawu with LV type inclusions; (e)—Vein  $V_4$  of Fujiawu with LV type inclusions; (f)—boiled fluid inclusions Fujiawu Vein  $V_2$ ; (g)—Vein  $V_1$  of Tongchang with LVH type inclusions; (h)—Vein  $V_2$  of Tongchang with LVH type inclusions; (i)—Vein  $V_2$  of Tongchang with spiculate mineral inclusions; (j)—Vein  $V_2$  of Tongchang with VL type inclusions; (k)—Vein  $V_3$  of Tongchang with LV type inclusions; (l)—Tongchang  $V_2$  boiled fluid inclusions; V—vapor; L—liquid; H—halite; S—daughter mineral

富气相包裹体(VL型):长轴长度为5~12 μm,形态多呈椭圆形,部分呈不规则形,气液比介于50%~90%之间,大多以液相消失达到均一,也有个别以气相消失达到均一。

富液相包裹体(LV型):长轴长3~16 μm,形态呈方形、椭圆形、不规则形,常成环状或孤立分布在石英内,气液比介于2%~40%之间,均以气相消失达到均一。

多相包裹体(LVH型):该类包裹体长轴长8~14 μm,通常呈椭圆形或不规则形孤立分布,子矿物为透明的石盐子晶及针状、他形粒状不透明子矿物。石盐形态多呈方形可能为NaCl子晶,部分呈圆形,可能为KCl子晶,本次多相包裹体测温仅测定NaCl子晶。

铜厂和富家坞矿床在不同成矿阶段所具有的流体包裹体类型基本一致,V<sub>1</sub>石英脉捕获的流体包裹体均为LVH型、VL型及LV型三种类型,VL型包裹体既有液相均一,也存在气相均一,而LVH型均以石盐子晶消失达到均一;V<sub>2</sub>脉相比于V<sub>1</sub>脉,

VL型、LVH型包裹体减少,主要为LV型包裹体;V<sub>3</sub>、V<sub>4</sub>石英脉中主要为LV型包裹体,未见VL型、LVH型包裹体。

两个矿床的不同成矿阶段的流体包裹体测温数据总结于表1,详见附表1,与铜厂矿床相同阶段的流体包裹体相比,富家坞均一温度略高,V<sub>2</sub>脉盐度略低(图6)。

4.2 石英微量元素组成

本文对铜厂和富家坞矿床的石英斑晶和石英脉共分析了14种微量元素,数据汇总结果见表2,详见附表2。除Li、B、Na、Mg、Al、Ca、Ti、Mn、Cl、K元素外,其余元素基本低于检出限。以往研究表明,Ti、Al、Li、Ge是石英中常见的微量元素,并且能够反映石英形成时流体的物理化学性质(Götze et al., 2004; Jacamon and Larsen, 2009; Breiter et al., 2013; Mao Wei et al., 2017)。但本次所测试样品中Ge含量基本低于检出限,因此本文重点关注Ti、Li、Al的含量及变化特征。

富家坞矿床石英斑晶Ti含量为 $48.2 \times 10^{-6} \sim$

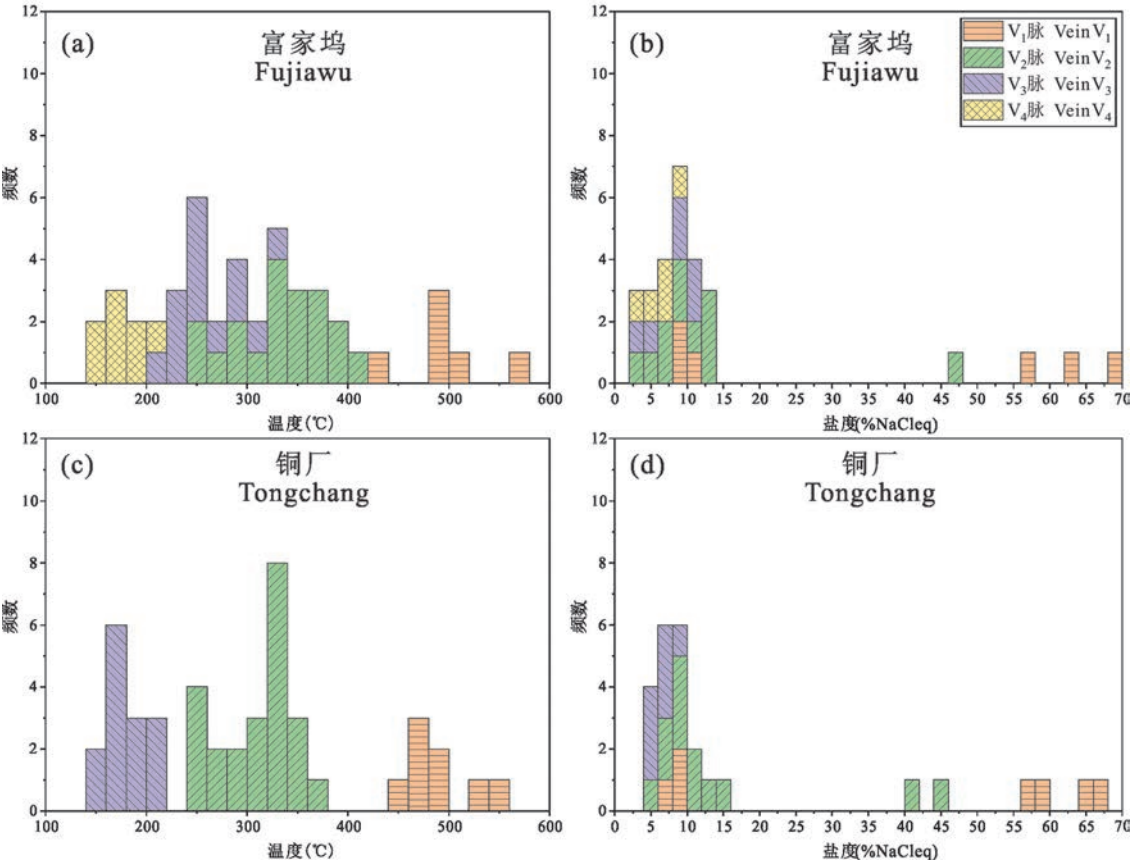


图6 德兴铜矿田富家坞(a)和铜厂(b)矿床不同矿化阶段石英中流体包裹体的温度和盐度直方图  
Fig. 6 Homogenization temperature and salinity histograms for all inclusion types separated into different stages from Fujiaowu (a, b) and Tongchang (c, d) deposits in the Dexing copper ore field

表 1 德兴铜矿田富家坞和铜厂含矿石英脉中流体包裹体测温数据表

Table 1 Temperature data of fluid inclusions from Fujiawu and Tongchang deposits in the Dexing copper ore field

| 矿床  | 成矿阶段  | 温度(℃)   | 脉体             | 包裹体类型 | 长轴长度(μm) | 冰点(℃)      | 子晶融化温度(℃) | 部分均一温度(℃) | 完全均一温度(℃) | 盐度(%NaCleq) |
|-----|-------|---------|----------------|-------|----------|------------|-----------|-----------|-----------|-------------|
| 铜厂  | 高温阶段  | 452~552 | V <sub>1</sub> | VL 型  | 6~12     | -5.4~-4.4  | 477~552   | 287~382   | 461~490   | 7.0~8.5     |
|     |       |         |                | LV 型  | 16       | -5.8       |           |           | 452       | 9.0         |
|     |       |         |                | LVH 型 | 9~14     |            |           |           | 477~552   | 56.7~67.1   |
|     | 中高温阶段 | 242~368 | V <sub>2</sub> | VL 型  | 8~10     | -8.6~-6.3  | 331~368   | 248~273   | 324~341   | 9.6~12.4    |
|     |       |         |                | LV 型  | 4~12     | -10.3~-3.7 |           |           | 242~358   | 5.3~14.2    |
|     |       |         |                | LVH 型 | 11~12    |            |           |           | 331~368   | 40.7~44.1   |
| 富家坞 | 中低温阶段 | 153~216 | V <sub>3</sub> | LV 型  | 2~15     | -5.2~-2.7  |           |           | 153~216   | 4.5~8.2     |
|     | 高温阶段  | 428~563 | V <sub>1</sub> | VL 型  | 5~7      | -5.6~-5.2  | 481~563   | 276~346   | 428~494   | 8.1~8.7     |
|     |       |         |                | LV 型  | 6        | -7.1       |           |           | 487       | 10.6        |
|     |       |         |                | LVH 型 | 8~18     |            |           |           | 481~563   | 57.3~68.6   |
|     | 中高温阶段 | 329~412 | V <sub>2</sub> | VL 型  | 6~9      | -8.3~-3.3  | 388       | 304       | 319~357   | 5.4~12.1    |
|     |       |         |                | LV 型  | 5~12     | -8.7~-2.1  |           |           | 254~412   | 3.5~12.5    |
|     |       |         |                | LVH 型 | 8        |            |           |           | 388       | 46.1        |
|     | 中低温阶段 | 221~321 | V <sub>3</sub> | LV 型  | 3~10     | -7.9~-2.1  |           |           | 221~321   | 3.6~11.5    |
|     | 低温阶段  | 143~208 | V <sub>4</sub> | LV 型  | 5~11     | -5.3~-2.3  |           |           | 143~208   | 3.9~8.3     |

$120 \times 10^{-6}$ ,  $V_1$  脉的 Ti 含量为  $78.0 \times 10^{-6} \sim 188 \times 10^{-6}$ , 石英  $V_2$  脉 Ti 含量为  $88.0 \times 10^{-6} \sim 128 \times 10^{-6}$ ,  $V_3$  脉为  $29.6 \times 10^{-6} \sim 85.1 \times 10^{-6}$ ,  $V_4$  脉含量为  $3.30 \times 10^{-6} \sim 26.6 \times 10^{-6}$ , 从斑晶到  $V_4$  脉 Ti 含量呈现先升高后降低趋势(图 7a)。石英的 Li 含量较为稳定, 不同世代之间无明显差异。Al 是石英中含量最高的微量元素, 斑晶中含量为  $101 \times 10^{-6} \sim 258 \times 10^{-6}$ ,  $V_1$  脉为  $82.5 \times 10^{-6} \sim 315 \times 10^{-6}$ ,

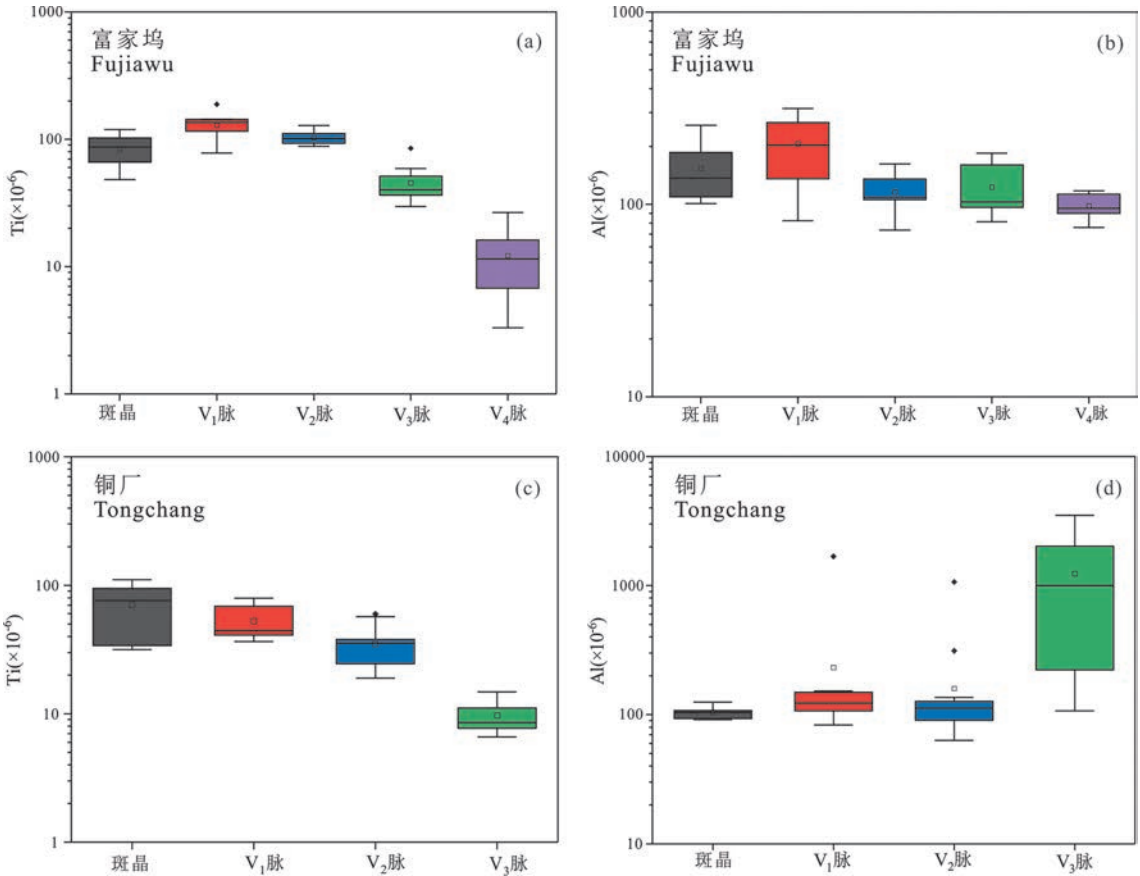


图 7 德兴铜矿田富家坞和铜厂矿床石英中 Ti(a、c)和 Al(b、d)含量变化特征

Fig. 7 Ti (a, c) and Al (b, d) contents in quartz of Fujiawu and Tongchang deposits in the Dexing copper ore field

表 2 德兴铜矿田富家坞和铜厂矿床石英微量元素( $\times 10^{-6}$ )汇总

| Table 2 Summary of trace elements ( $\times 10^{-6}$ ) in quartz from Fujiawu and Tongchang deposits in the Dexing copper ore field |                |     |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|-------------------------------------------------------------------------------------------------------------------------------------|----------------|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 矿床                                                                                                                                  | 石英类型           |     | Li   | B    | Na   | Mg   | Al   | P    | Cl   | K    | Ca   | Ti   | Mn   | Ge   | Rb   | Cs   |
| 富家坞                                                                                                                                 | 斑晶             | 平均值 | 12.0 | 3.42 | 39.0 | 3.84 | 154  | 21.0 | 534  | 21.5 | 121  | 84.4 | 10.7 | —    | 0.43 | 0.09 |
|                                                                                                                                     |                | 标准差 | 7.79 | 0.70 | 48.9 | 1.99 | 48.3 | 1.26 | 23.6 | 19.1 | 33.4 | 21.2 | 5.08 | —    | 0.12 | 0.02 |
|                                                                                                                                     |                | 最小值 | —    | —    | 4.99 | —    | 101  | —    | —    | —    | 66.5 | 48.2 | 7.24 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 26.1 | 4.89 | 158  | 7.34 | 258  | 22.3 | 565  | 60.5 | 170  | 120  | 22.3 | —    | 0.54 | 0.12 |
|                                                                                                                                     |                | 中位数 | 11.0 | 3.51 | 11.2 | 3.16 | 137  | 21.0 | 534  | 13.4 | 123  | 86.9 | 8.53 | —    | 0.43 | 0.09 |
|                                                                                                                                     | V <sub>1</sub> | 平均值 | 13.7 | 4.84 | 11.6 | 3.89 | 207  | 24.3 | 224  | 49.1 | 93.3 | 129  | 6.87 | 1.43 | 0.31 | 0.07 |
|                                                                                                                                     |                | 标准差 | 3.50 | 0.63 | 12.9 | 1.16 | 75.8 | 1.67 | 44.3 | 30.8 | 20.1 | 30.8 | 1.17 | 0.00 | 0.03 | 0.00 |
|                                                                                                                                     |                | 最小值 | 8.43 | 3.70 | 0.74 | 2.20 | 82.5 | —    | —    | —    | 54.8 | 78.0 | 5.65 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 18.9 | 5.71 | 43.1 | 6.34 | 315  | 26.1 | 297  | 114  | 121  | 188  | 9.90 | 1.43 | 0.35 | 0.07 |
|                                                                                                                                     |                | 中位数 | 13.5 | 5.03 | 6.63 | 3.70 | 203  | 24.8 | 213  | 42.3 | 93.5 | 135  | 6.55 | 1.43 | 0.31 | 0.07 |
|                                                                                                                                     | V <sub>2</sub> | 平均值 | 11.3 | 5.06 | 13.1 | 4.03 | 116  | 23.0 | 249  | 10.4 | 111  | 103  | 7.24 | 1.73 | —    | 0.04 |
|                                                                                                                                     |                | 标准差 | 3.09 | 0.71 | 11.1 | 1.10 | 25.7 | 0.99 | 362  | 3.39 | 17.5 | 11.3 | 1.59 | 0.33 | —    | 0.00 |
|                                                                                                                                     |                | 最小值 | 4.53 | 3.65 | 3.40 | 2.49 | 73.6 | —    | —    | —    | 85.0 | 88.0 | 5.81 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 16.0 | 6.10 | 40.5 | 6.50 | 162  | 23.9 | 1204 | 17.4 | 145  | 128  | 10.8 | 2.06 | —    | 0.04 |
|                                                                                                                                     |                | 中位数 | 11.3 | 5.02 | 9.35 | 4.17 | 109  | 23.0 | 107  | 10.5 | 113  | 101  | 6.55 | 1.73 | —    | 0.04 |
|                                                                                                                                     | V <sub>3</sub> | 平均值 | 7.79 | 3.93 | 29.9 | 2.36 | 123  | 19.6 | 247  | 22.3 | 116  | 45.5 | 9.15 | —    | 0.19 | 0.05 |
|                                                                                                                                     |                | 标准差 | 5.71 | 0.59 | 28.8 | 1.15 | 36.5 | 0.00 | 48.5 | 10.7 | 12.8 | 15.6 | 2.27 | —    | 0.00 | 0.01 |
|                                                                                                                                     |                | 最小值 | —    | 2.74 | 2.05 | 1.08 | 81.1 | —    | —    | —    | —    | 29.6 | 5.93 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 16.5 | 5.03 | 86.3 | 5.11 | 184  | 19.6 | 324  | 40.8 | 137  | 85.1 | 12.2 | —    | 0.19 | 0.06 |
|                                                                                                                                     |                | 中位数 | 4.70 | 3.97 | 21.7 | 1.94 | 103  | 19.6 | 244  | 16.2 | 115  | 40.2 | 8.23 | —    | 0.19 | 0.05 |
|                                                                                                                                     | V <sub>4</sub> | 平均值 | 11.8 | 3.55 | 2.61 | 2.76 | 98.3 | 20.0 | 136  | 10.0 | 126  | 12.2 | 7.03 | 1.51 | —    | 0.02 |
|                                                                                                                                     |                | 标准差 | 1.19 | 0.45 | 3.53 | 2.32 | 12.1 | 0.00 | 33.2 | 4.26 | 27.5 | 6.38 | 1.40 | 0.18 | —    | 0.00 |
|                                                                                                                                     |                | 最小值 | 9.51 | 2.70 | 0.53 | —    | 76.0 | —    | —    | —    | 97.0 | 3.30 | 4.90 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 14.0 | 4.20 | 12.8 | 8.80 | 118  | 20.0 | 222  | 16.5 | 194  | 26.6 | 9.70 | 1.73 | —    | 0.02 |
|                                                                                                                                     |                | 中位数 | 11.5 | 3.60 | 1.13 | 1.79 | 95.6 | 20.0 | 127  | 9.35 | 121  | 11.5 | 6.72 | 1.55 | —    | 0.02 |
| 铜厂                                                                                                                                  | 斑晶             | 平均值 | 9.87 | 3.20 | 2.14 | 1.87 | 104  | —    | 415  | —    | 85.1 | 70.7 | 7.60 | —    | —    | —    |
|                                                                                                                                     |                | 标准差 | 1.11 | 0.51 | 2.31 | 0.13 | 10.1 | —    | 93.4 | —    | 17.5 | 28.2 | 0.73 | —    | —    | —    |
|                                                                                                                                     |                | 最小值 | 8.09 | —    | 0.39 | —    | 91.8 | —    | 260  | —    | 73.0 | 31.6 | 6.19 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 11.7 | 3.70 | 7.40 | 2.00 | 125  | —    | 510  | —    | 126  | 110  | 8.30 | —    | —    | —    |
|                                                                                                                                     |                | 中位数 | 9.85 | 3.40 | 1.06 | 1.87 | 104  | —    | 445  | —    | 77.0 | 76.0 | 7.90 | —    | —    | —    |
|                                                                                                                                     | V <sub>1</sub> | 平均值 | 24.2 | 4.28 | 18.8 | 1.80 | 232  | 21.0 | 270  | 13.6 | 106  | 52.9 | 8.33 | 5.44 | 0.21 | 0.05 |
|                                                                                                                                     |                | 标准差 | 50.6 | 0.86 | 13.7 | 0.72 | 403  | 2.72 | 80.3 | 8.43 | 16.8 | 14.5 | 2.12 | 5.53 | 0.07 | 0.02 |
|                                                                                                                                     |                | 最小值 | 6.08 | —    | 0.96 | —    | 83.4 | —    | —    | —    | 73.1 | —    | 6.00 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 206  | 5.60 | 47.7 | 3.60 | 1682 | 24.7 | 412  | 33.1 | 141  | 79.3 | 13.6 | 13.3 | 0.31 | 0.07 |
|                                                                                                                                     |                | 中位数 | 10.7 | 4.10 | 18.6 | 1.52 | 123  | 19.9 | 242  | 8.59 | 106  | 44.2 | 7.80 | 1.71 | 0.16 | 0.05 |
|                                                                                                                                     | V <sub>2</sub> | 平均值 | 11.2 | 4.09 | 5.91 | 1.84 | 160  | 19.5 | 318  | 107  | 98.4 | 34.9 | 6.98 | 2.56 | 0.27 | 0.21 |
|                                                                                                                                     |                | 标准差 | 6.58 | 0.82 | 15.2 | 0.88 | 209  | 1.42 | 68.3 | 105  | 15.5 | 12.7 | 0.84 | 1.16 | 0.12 | 0.14 |
|                                                                                                                                     |                | 最小值 | 1.26 | —    | 0.37 | —    | 63.2 | —    | —    | —    | 74.0 | 18.9 | 5.00 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 34.7 | 5.70 | 72.4 | 3.70 | 1067 | 21.0 | 440  | 251  | 131  | 59.7 | 8.66 | 3.98 | 0.36 | 0.35 |
|                                                                                                                                     |                | 中位数 | 11.5 | 3.80 | 1.22 | 1.52 | 112  | 19.8 | 325  | 62.3 | 95.0 | 35.5 | 7.12 | 2.56 | 0.35 | 0.21 |
|                                                                                                                                     | V <sub>3</sub> | 平均值 | 117  | 7.04 | 24.8 | 2.85 | 1237 | 28.1 | 281  | 49.6 | 115  | 9.75 | 7.85 | 10.1 | 0.40 | 0.15 |
|                                                                                                                                     |                | 标准差 | 121  | 3.08 | 16.3 | 2.41 | 1166 | 9.37 | 60.4 | 29.0 | 37.6 | 2.93 | 1.87 | 6.07 | 0.13 | 0.14 |
|                                                                                                                                     |                | 最小值 | 4.10 | 4.42 | 3.16 | —    | 107  | —    | —    | —    | 89.2 | —    | 6.48 | —    | —    | —    |
|                                                                                                                                     |                | 最大值 | 373  | 13.2 | 50.2 | 6.26 | 3498 | 46.6 | 345  | 99.1 | 224  | 14.8 | 13.5 | 21.8 | 0.53 | 0.50 |
|                                                                                                                                     |                | 中位数 | 79.8 | 5.32 | 24.5 | 1.27 | 1001 | 24.3 | 294  | 47.5 | 98.1 | 8.55 | 7.36 | 10.5 | 0.40 | 0.09 |

注:— 表示低于检出限。

V<sub>2</sub> 脉为  $73.6 \times 10^{-6} \sim 162 \times 10^{-6}$ , V<sub>3</sub> 脉为  $81.1 \times 10^{-6} \sim 184 \times 10^{-6}$ , V<sub>4</sub> 脉为  $76.0 \times 10^{-6} \sim 117 \times 10^{-6}$ , 总体呈现先升后降, 再升再降的波动趋势(图 7b)。

不同于富家坞矿床 Ti 含量的变化趋势, 铜厂

Ti 含量从斑晶到 V<sub>3</sub> 脉持续降低(图 7c), 且与富家坞矿床石英相比, 铜厂同一成矿阶段石英具有更低的 Ti 含量。Li 总体具有相似的变化范围及平均含量, 但在石英 V<sub>3</sub> 脉内, Li 呈现“双峰”特点, 变化范围为  $4.10 \times 10^{-6} \sim 16.0 \times 10^{-6}$  及  $49.9 \times 10^{-6} \sim$

$373 \times 10^{-6}$ 。与 Li 的变化相似,Al 在  $V_3$  脉内同样具有“双峰”特点,变化范围  $107 \times 10^{-6} \sim 301 \times 10^{-6}$  及  $680 \times 10^{-6} \sim 3498 \times 10^{-6}$ ,石英斑晶到  $V_3$  脉中 Al 含量的变化趋势与富家坞矿床一致(图 7d)。

仅考虑单个石英脉体的数据,可以发现在富家坞矿床中 Ti 与 Al、Li 在  $V_1 \sim V_3$  脉内呈现正相关,  $V_4$  脉内呈负相关(图 8a、b);而铜厂矿床  $V_1 \sim V_2$  脉内 Ti 与 Al、Li 呈现正相关,  $V_3$  脉内呈负相关(图 8g、h)。Li 和 Al 在两个矿床的单个脉体内普遍具

有正相关关系(图 8c、i)。整体而言,两个矿床石英中 Al 与 Li、K 含量均具有明显正相关关系,Al 和 P 之间呈微弱的正相关(图 8c~e、i~k)。

5 讨论

5.1 石英中微量元素的赋存形式

LA-ICP-MS 分析不仅能够得到精确的元素含量,还能获取元素随激光剥蚀深度的空间变化趋势,进而为我们探讨元素在矿物中的赋存形式提供可靠的信息(冷成彪和齐有强,2017)。大多数样品中

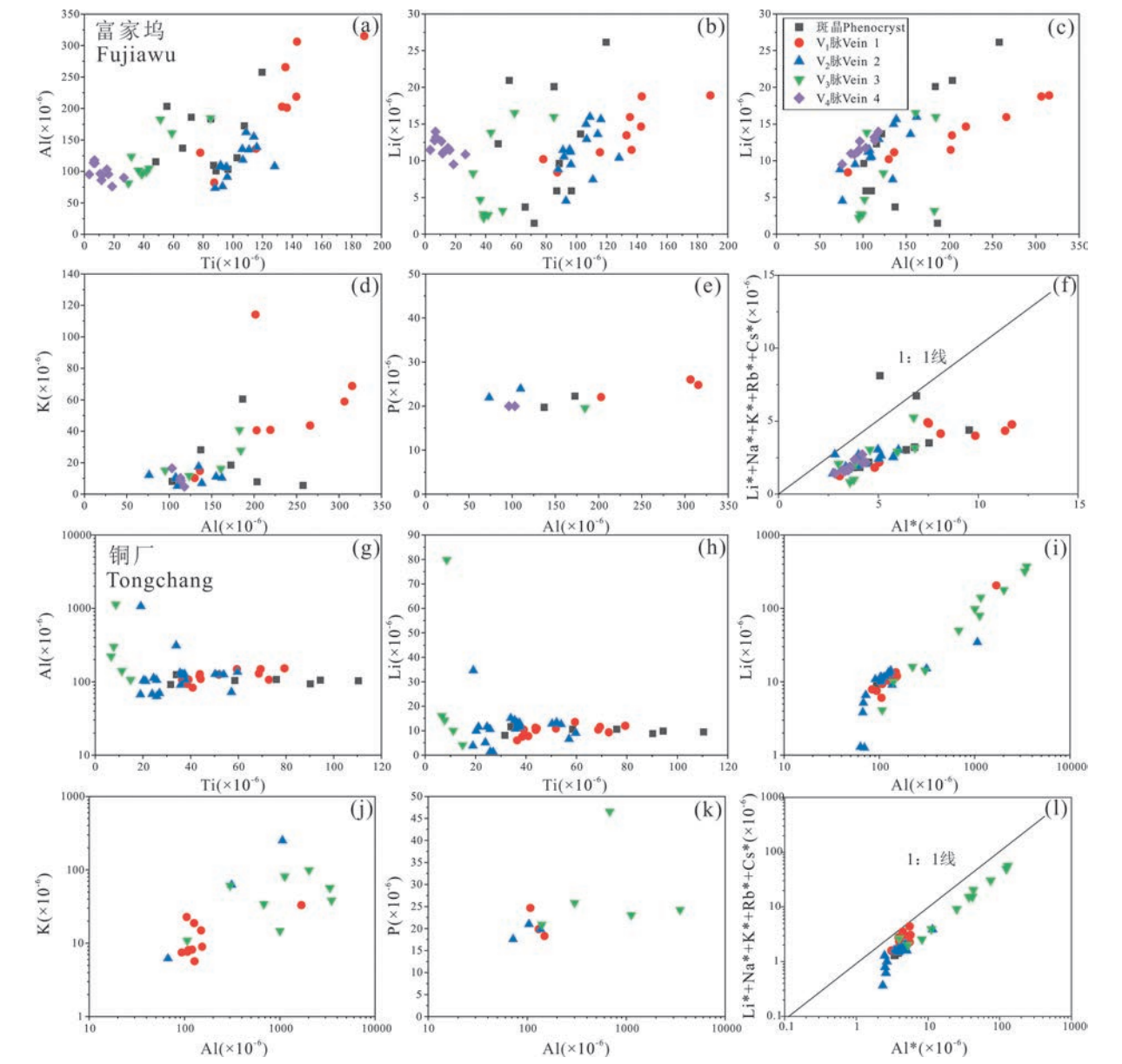


图 8 德兴铜矿田富家坞及铜厂矿床石英微量元素图解

Fig. 8 Diagrams of trace elements in quartz from Fujiawu and Tongchang deposits in the Dexing copper ore field  
(a)~(f)—富家坞;(g)~(l)—铜厂;其中\*为元素的摩尔含量  
(a)~(f)—Fujiawu; (g)~(l)—Tongchang; \* represents molecular weight

Li、B、Na、Mg、Al、P、Cl、K、Ca、Ti、Mn、Rb、Cs 等元素在 LA-ICP-MS 时间分辨率剖面图中均呈现较为平缓的直线(图 9a),表明这些元素主要以类质同象的形式赋存在石英晶格中。尽管我们在测试过程中已尽可能避开流体包裹体,但部分样品中 Na、Ca、Al、K 等元素时间-分辨信号图呈现为波动起伏的不规则曲线,表明仍然存在含 Na、Ca、Al、K 的包裹体赋存在石英颗粒内(图 9b~d)。Al 作为石英中含量最高的微量元素,其进入石英晶格主要有两种形式:①离子团替换:与  $P^{5+}$  结合替代  $Si^{4+}$ ,形成  $[AlPO_4]$ ;②电价补偿替换:与碱金属等一价阳离子进行电荷补偿替换石英中的  $Si^{4+}$  (Götze et al., 2004; Jacamon and Larsen, 2009; 陈剑锋和张辉, 2011)。铜厂和富家坞矿床的绝大多数石英中的 P 含量低于检出限,且 P 与 Al 之间的相关性微弱(图 8e,i),表明在铜厂和富家坞矿床中, $[AlPO_4]$  不是 Al 在石英中的主要存在形式,而两个矿床石英中

Al 含量与碱金属含量之间均具有良好的相关性(图 8f,l),表明 Al 主要以与碱金属电荷补偿的形式进入石英晶格当中。假设 Al 全部以与一价阳离子配位的形式赋存,碱金属与 Al 的含量比应该为 1 : 1,而图 8f 中,富家坞斑晶中二者比值大于 1,表明测试结果可能受到了斑晶中上述含碱金属的流体包裹体影响。这可能也是富家坞与铜厂矿床斑晶至  $V_1$  脉中 Ti 含量未呈现一致变化趋势的原因。

5.2 流体特征及演化过程

5.2.1 流体性质

(1)压力:两个矿床  $V_1$  脉中 LVH 相包裹体全部以石盐子晶的消失达到均一,表明  $V_1$  脉形成于较高的压力条件(潘小菲等,2009)。假设所测定  $V_1$  脉中的 LVH 相包裹体均为高压环境下石英捕获石盐的不饱和溶液,依据 Cline and Bodnar(1994)给出的压力估算图(图 10),可以得出富家坞  $V_1$  脉的压力介于 115~200 MPa 之间,铜厂  $V_1$  脉的介于 100

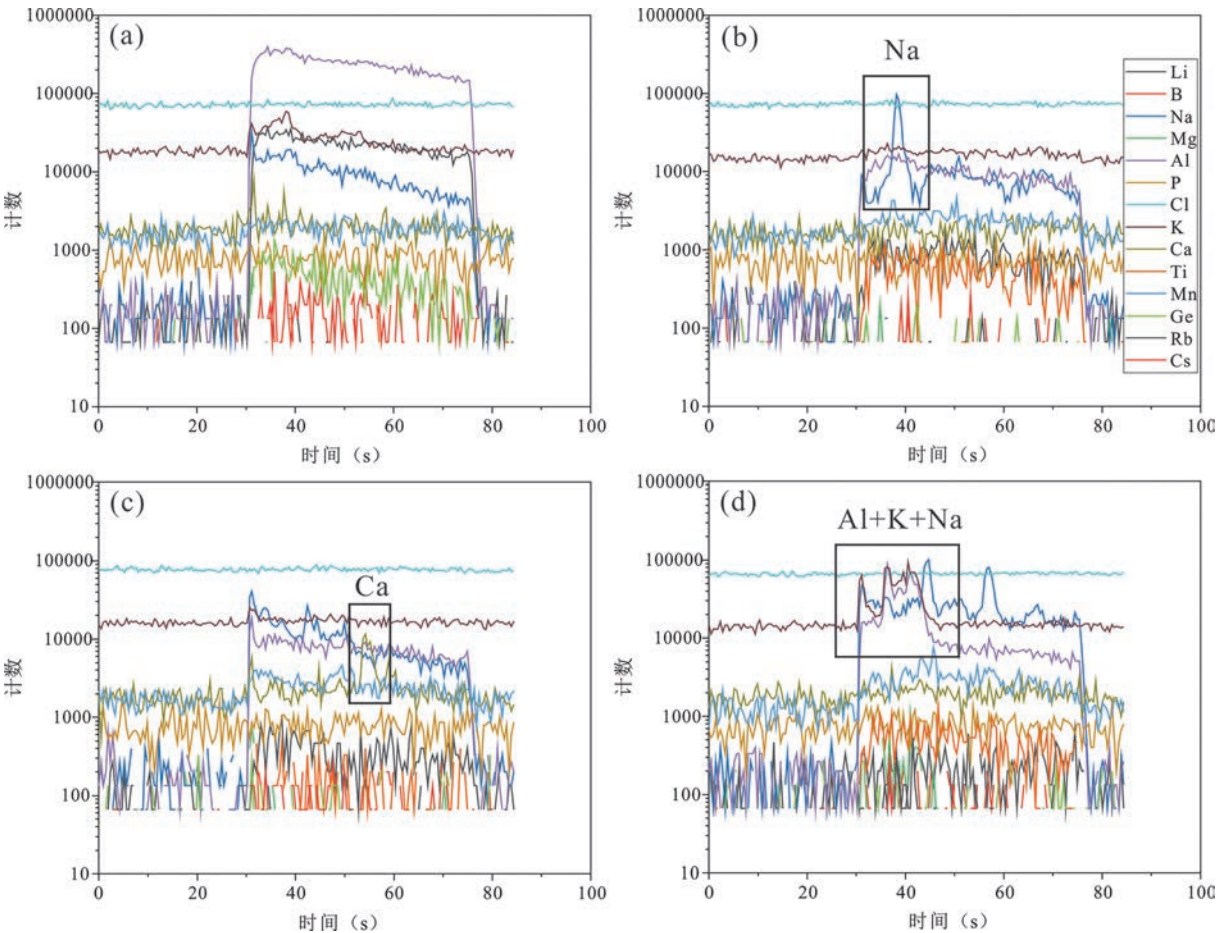


图 9 德兴铜矿田富家坞及铜厂矿床石英 LA-ICP-MS 时间分辨率剖面图  
Fig. 9 Representative single-spot LA-ICP-MS spectra for selected elements in quartz from Fujiawu and Tongchang deposits in the Dexing copper ore field

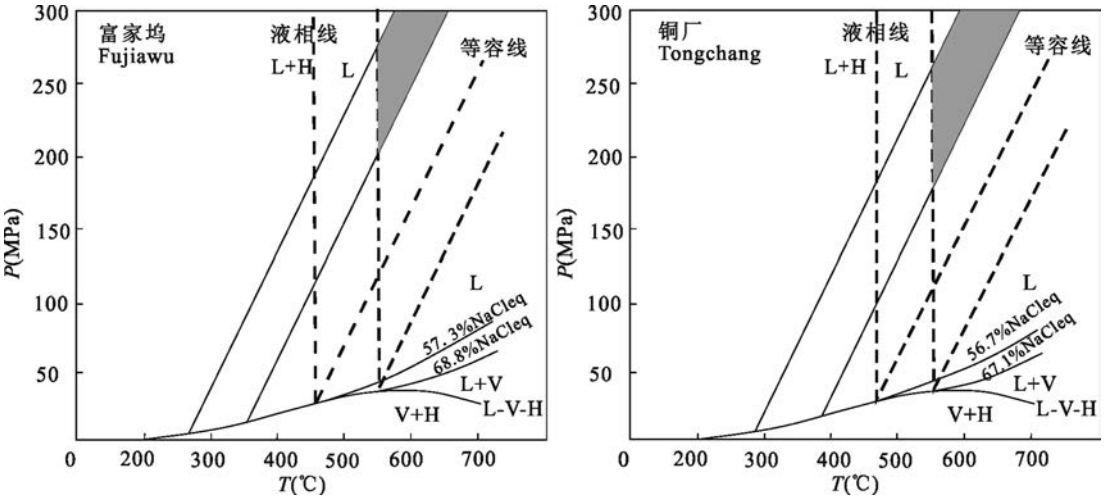


图 10 德兴铜矿田富家坞、铜厂矿床早期  $V_1$  脉中 LVH 相包裹体的均一温度-形成压力相图(含阴影区域为德兴铜厂  
斑岩矿床  $V_1$  脉石英中 LVH 相包裹体的最小  $P$ - $T$  区域)(据 Cline and Bodnar, 1994)

Fig. 10 Diagrams for pressure with temperature (the shadow district represents the smallest  
range of  $P$ - $T$  condition of LVH fluid inclusions hosted in quartz of  $V_1$  from Fujiawu and Tongchang  
deposits in the Dexing copper ore field) (after Cline and Bodnar, 1994)

L—液相稳定区;V—气相稳定区;H—固相稳定区  
L—stable liquid area; V—stable vapor area; H—stable halite area

~175 MPa 之间,而自地表每增加 1 km,岩压增大 27 MPa(金章东,1999),富家坞  $V_1$  脉形成的深度 4.26~7.41 km,铜厂为 3.70~6.48 km。 $V_2 \sim V_4$  脉压力的估算依据 Bodnar et al. (1985) 的 NaCl- $H_2O$  体系  $P$ - $X$  图解(图 11)。可以得出富家坞  $V_2$  脉形成的压力约为 15~30 MPa,铜厂  $V_2$  脉介于 10~22 MPa,而富家坞  $V_3$  脉、 $V_4$  脉形成压力普遍低于 16 MPa,铜厂  $V_3$  脉低于 12 MPa。

(2)密度:铜厂高温阶段  $V_1$  脉相分离形成的低盐度流体和高盐度流体密度范围分别为 0.403~0.504 g/cm<sup>3</sup> 和 1.135~1.260 g/cm<sup>3</sup>,中高温阶段  $V_2$  脉相分离形成的低盐度流体和高盐度流体密度范围分别为 0.700~0.888 g/cm<sup>3</sup> 和 1.064~1.072 g/cm<sup>3</sup>;中低温阶段  $V_3$  脉密度范围为 0.894~0.965 g/cm<sup>3</sup>;富家坞高温阶段  $V_1$  脉相分离产生的低盐度和高盐度流体密度范围分别为 0.439~0.568 g/cm<sup>3</sup> 和 1.138~1.256 g/cm<sup>3</sup>,中高温阶段  $V_2$  脉相分离形成的低盐度和高盐度流体密度范围分别为 0.657~0.901 g/cm<sup>3</sup> 和 1.076 g/cm<sup>3</sup>;中低温阶段  $V_3$  脉密度范围为 0.717~0.929 g/cm<sup>3</sup>;中低温阶段  $V_4$  脉密度为 0.918~0.968 g/cm<sup>3</sup>。

(3)pH 值:Al 在石英中含量反映了 Al 在热液中的溶解度,而 Al 的溶解度受成矿流体 pH 值的影响(Rusk et al., 2008),pH 值越高,Al 的溶解度越低,石英中 Al 含量也就越低。铜厂矿床  $V_1 \sim V_3$  石

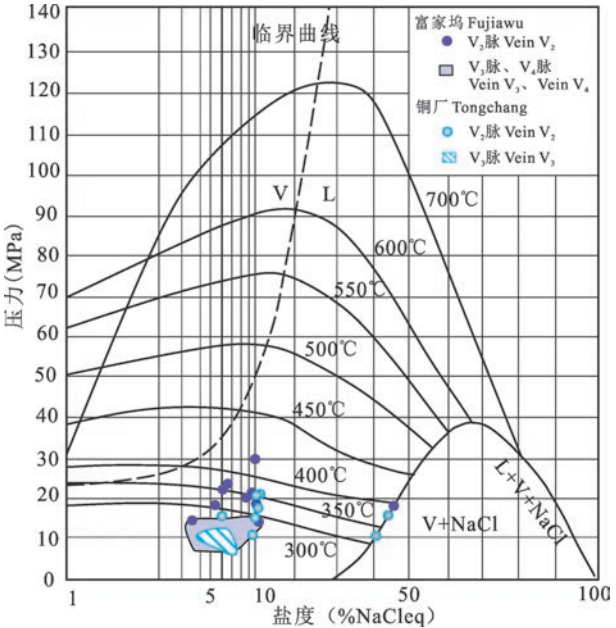


图 11 德兴铜矿田富家坞  $V_3$  脉、 $V_4$  脉,铜厂矿床  $V_3$  脉包裹体 NaCl- $H_2O$  体系  $P$ - $X$  相图(据 Bodnar et al., 1985 修改)

Fig. 11 Pressure-composition phase diagram for NaCl- $H_2O$  system inclusions of Vein  $V_3$ , Vein  $V_4$  from Fujiawu and Vein  $V_3$  from Tongchang deposits in the Dexing copper ore field (modified after Bodnar et al., 1985)

L—液相稳定区;V—气相稳定区  
L—stable liquid area; V—stable vapor area

英脉,石英中 Al 含量呈先降低后升高的趋势,表明铜厂矿床自高温阶段转变为中低温阶段过程中,pH

值先升高后降低。富家坞矿床  $V_1 \sim V_3$  脉(高温阶段—中低温阶段)的 pH 值变化趋势与铜厂矿床一致,而  $V_4$  脉 Al 含量下降,表明在成矿晚期流体 pH 值再次升高。

### 5.2.2 流体演化过程浅析

根据上述不同类型石英脉流体包裹体的温度-盐度数据及石英 LA-ICP-MS 数据,铜厂和富家坞矿床不同成矿阶段的温度、盐度及成分略有差异,但变化趋势基本一致。铜厂高温阶段流体温度集中在  $452 \sim 552^\circ\text{C}$ ,压力  $100 \sim 175\text{ MPa}$ ;富家坞高温阶段流体温度集中在  $428 \sim 563^\circ\text{C}$ ,压力  $115 \sim 200\text{ MPa}$ 。两个矿床均存在均一温度相近的富气相低盐度包裹体与含石盐子晶高盐度包裹体共存的现象,表明该阶段流体发生了沸腾(金章东,1999;潘小菲等,2009;姚静等,2012)。这使得早期中低盐度(9%)的初始出溶流体(潘小菲等,2009)分离成低盐度的富气相流体以及与残余熔体相平衡的高温高盐度流体,两矿床 LVH 型石盐子晶溶解温度远大于气相消失温度,表明捕获的流体是过饱和的(冷成彪等,2008),此阶段铜厂和富家坞流体密度分别为  $0.403 \sim 0.536\text{ g/cm}^3$  和  $1.135 \sim 1.260\text{ g/cm}^3$  以及  $0.439 \sim 0.568\text{ g/cm}^3$  和  $1.140 \sim 1.256\text{ g/cm}^3$ 。这一阶段蚀变类型以钾长石化为主,并形成钾长石、磁铁矿、黑云母等高温蚀变矿物组合。

高温阶段矿物组合的生成以及富气相低盐度流体持续向上运移,使得流体温度压力持续降低。铜厂中高温阶段时流体温度集中在  $242 \sim 368^\circ\text{C}$ ,压力为  $10 \sim 22\text{ MPa}$ ,富家坞中高温阶段时流体温度集中在  $329 \sim 412^\circ\text{C}$ ,压力为  $14 \sim 30\text{ MPa}$ ,该阶段同样存在均一温度相近的低盐度富气相包裹体与石盐包裹体共存现象,表明该阶段发生了流体的二次沸腾,流体再次发生相分离,铜厂和富家坞矿床发生沸腾作用的温度分别在  $320 \sim 380^\circ\text{C}$  和  $320 \sim 400^\circ\text{C}$ 。该阶段铜厂成矿流体的密度经过计算为  $0.700 \sim 0.888\text{ g/cm}^3$  和  $1.064 \sim 1.072\text{ g/cm}^3$ ,富家坞流体密度为  $0.657 \sim 0.901\text{ g/cm}^3$  和  $1.076\text{ g/cm}^3$ ,相比高温阶段成矿流体密度均略有上升,这可能是由于流体二次沸腾使得挥发分逸出导致的。该阶段发育的绢云母化蚀变以及高温阶段的钾长石化,使得流体中  $\text{H}^+$  被消耗,Al 在流体中的溶解度下降,相比于高温阶段流体 pH 值升高,Al 含量下降。

之后中低温中低盐度流体继续向上运移,温度压力再次降低。铜厂温度集中在  $153 \sim 216^\circ\text{C}$ ,压力小于  $12\text{ MPa}$ ,富家坞温度集中在  $221 \sim 321^\circ\text{C}$ ,压力

小于  $15\text{ MPa}$ ,包裹体类型为富液相包裹体。脉体可见方解石、硬石膏等,主要发育碳酸盐化及硫酸盐化。高温阶段及中高温阶段对流体中金属元素及硅酸盐类物质的消耗,使得这一阶段相比于中高温阶段,矿化相对微弱,流体黏度降低,渗透性更强,蚀变范围更广。而大面积的硫酸盐化,致使成矿流体 pH 值降低。铜厂这一阶段成矿流体密度为  $0.894 \sim 0.965\text{ g/cm}^3$ ,富家坞密度为  $0.717 \sim 0.929\text{ g/cm}^3$ ,相比上一阶段略有升高,表明挥发分持续逸出或大气降水已开始加入成矿流体。

最后,大气降水开始在成矿流体中占主导地位,流体演化成低温低盐度流体,流体包裹体类型为富液相包裹体。富家坞流体密度经过计算为  $0.918 \sim 0.968\text{ g/cm}^3$ ,接近于大气降水密度。由于成矿流体被大幅度稀释,相比于中低温阶段  $\text{H}^+$  浓度下降, pH 值升高。此后,温度继续降低直至流体完全凝结成贫矿、无矿的石英脉、方解石脉,最终结束整个流体演化。

### 5.3 金属沉淀机制

以往研究表明,Cu 在富 S 岩浆热液中优先进入蒸汽相,以硫氢络合物的形式运移,在富 Cl 贫 S 的热液中优先进入卤水相,主要以铜氯络合物的形式运移,而 Mo 主要以羟基络合物的形式迁移(Klemm et al., 2008; 冷成彪等,2008,2009; Ren Zhi et al., 2018)。当温度降低、pH 值变化、大气降水的混入或流体沸腾时,流体中络合物的稳定性会被破坏并使得成矿物质发生沉淀(Hemley and Hunt, 1992; Gruen et al., 2010; 孙嘉等,2012; 康永建等,2016)。

上文提到高温阶段 LVH 型包裹体捕获的流体盐度是过饱和的,且在该类包裹体中曾发现硫化物的存在(潘小菲等,2012),因此,在铜厂和富家坞矿床,Cu 可能主要是在卤水相中以铜氯络合物的形式运移。铜氯络合物的活度受 pH 值影响很大,在黄铜矿与黄铁矿平衡时,pH 值每升高 1 个单位,活度下降 100 倍。此外,pH 值的上升还会促进铜氯络合物、Mo 羟基络合物解离(朱训等,1983; 黄朋等,2000; 周雄,2017),这意味着 pH 值相对更高的中高温阶段流体有利于黄铜矿与辉钼矿的沉淀。

温度下降是金属沉淀的最重要机制(Ulrich et al., 2002; Redmond et al., 2004)。温度下降能导致铜氯络合物的活度和稳定性的急剧下降,促进黄铜矿的沉淀(朱训等,1983; 朱金初等,2002)。对于辉钼矿而言,流体中 99% 的辉钼矿会在相分离后温

度下降 100℃ 内沉淀出来(Klemm et al. , 2008),这意味着绝大部分辉钼矿会在中高温阶段沉淀。相比于无辉钼矿 V<sub>1</sub> 脉所处的高温阶段,两个矿床流体温度下降幅度均<110℃,表明温度对辉钼矿沉淀也有很大影响。

流体沸腾作用是矿床成矿物质沉淀的常见原因(金章东,1999;康永建等,2016)。铜厂和富家坞流体包裹体测温结果及镜下特征已经表明德兴矿田存在流体沸腾现象(图 5f、l)。在流体沸腾过程中,流体中挥发分会快速散失,致使流体中金属元素浓度升高,造成流体中大量 Cu、Mo 的过饱和进而沉淀。

上文已表明黄铜矿与辉钼矿主要在中高温阶段沉淀,而 H-O 同位素分析(潘小菲等,2012;刘德伟,2018)结果表明,在主成矿阶段(中高温阶段)晚期两矿床中仅有少量大气水的加入,故认为大气降水的混入对 Cu、Mo 沉淀影响较小。因此流体温度下降、流体沸腾作用、pH 值的变化是导致 Cu、Mo 沉淀的主要原因

### 5.4 Re 的差异性富集与流体演化过程的关系

德兴矿田不同矿床之间辉钼矿 Re 平均含量的差异可能与质量平衡效应有关(Stein et al. , 2001),即当矿田中伴生 Re 总量一定时,若辉钼矿的体量越大,则辉钼矿中铼的相对含量越低。由于铜厂矿区辉钼矿的体量小于富家坞矿区(朱训等,1983),因此铜厂矿区的辉钼矿相对更富 Re。除此之外两个矿床的 Re 含量差异还可能与成矿流体性质及其演化过程相关。尽管铜厂与富家坞属于同一矿田,但其成矿热液演化过程仍然略有差异。石英的 LA-ICP-MS 的分析结果显示,同一成矿阶段铜厂的石英具有更低的 Ti 含量,而石英中 Ti 含量与温度呈正相关(Rusk et al. , 2008),这意味着在同一成矿阶段,铜厂矿床的成矿温度略低于富家坞矿床,这与上述流体包裹体测温结果一致。ReS<sub>2</sub> 在 400~500℃,随温度升高,溶解度略微升高,意味着在较高温度时会有更多的 ReS<sub>2</sub> 溶解(Xiong and Wood, 2002),这表明在较低温度下形成的辉钼矿具有较高的 Re 含量。此外,流体包裹体测温结果还显示中高温辉钼矿主成矿阶段铜厂矿床具有相对更高的盐度。Re 在流体中主要以含 Cl 络合物的形式迁移(Xiong and Wood, 2002),这意味着流体盐度越高,在成矿过程中能够提供更多的 Cl<sup>-</sup>,越有利于 Re 的运移;且流体中较高的 Cl 含量降低了流体中的羟基含量,这可能减少了以羟基络合物形式输送的 Mo 含量,从而使得流体中的 Re/Mo 比值升

高,有利于高 Re 辉钼矿的形成(Selby and Creaser, 2001)。因此具有更高成矿流体盐度、更低成矿温度的铜厂辉钼矿便具有更高的 Re 含量。

## 6 结论

(1)铜厂和富家坞矿床中,Al 主要以与碱金属电荷补偿的形式进入石英晶格中。

(2)温度下降、流体沸腾以及 pH 值的变化是导致成矿流体中 Cu、Mo 沉淀的主要原因。

(3)温度和盐度差异可能是导致铜厂和富家坞辉钼矿 Re 含量显著不同的控制因素。

附件:本文附件(附表 1~2)详见 [http://www.geojournals.cn/dzxb/dzxb/article/abstract/202306098?st=article\\_issue](http://www.geojournals.cn/dzxb/dzxb/article/abstract/202306098?st=article_issue)

## References

Bodnar R J. 1983. A method of calculating fluid inclusion volumes based on vapor bubble diameters and P-V-T-X properties of inclusion fluids. *Economic Geology*, 78: 535~542.

Bodnar R J, Burnham C W, Sterner S M. 1985. Synthetic fluid inclusions in natural quartz. III. Determination of phase equilibrium properties in the system H<sub>2</sub>O-NaCl to 1000℃ and 1500 bars. *Geochimica et Cosmochimica Acta*, 49 (9): 1861~1873.

Breiter K, Ackerman L, Svojtka M, Müller A. 2013. Behavior of trace elements in quartz from plutons of different geochemical signature; A case study from the Bohemian Massif, Czech Republic. *Lithos*, 175-176: 54~67.

Chen Jianfeng, Zhang Hui. 2011. Trace elements in quartz lattice and their implications for petrogenesis and mineralization. *Geological Journal of China Universities*, 17(1): 125~135 (in Chinese with English abstract).

Chen Taoliang, Ren Zhi, Li Kaixuan, Liu Fei, Duan Fenghao, Leng Chengbiao. 2021. Distribution characteristics and influencing factors of rhenium concentrations in molybdenite from the porphyry Cu-systems: A review. *Acta Petrologica Sinica*, 37 (9): 2677~2690 (in Chinese with English abstract).

Cline J S, Bodnar R J. 1994. Direct evolution of brine from a crystallizing silicic melt at the Questa, New Mexico, molybdenum deposit. *Economic Geology*, 89: 1780~1802.

Gao Zhirui, Chang Yuhu, Zhao Yuanyi, Wang Yuxian, Sun Yiwei. 2018. Process mineralogy in ore flotation of the Dexing copper deposit. *Bulletin of Mineralogy, Petrology and Geochemistry*, 37(3): 539~554 (in Chinese with English abstract).

Gong Yibin. 2008. Description of Mo concentrate production and developing strategy of JCC Dexing new technology company. *Copper Engineering*, (4): 18~20 (in Chinese with English abstract).

Götze J, Plötze M, Graupner T, Hallbauer D K, Bray C J. 2004. Trace element incorporation into quartz: A combined study by ICP-MS, electron spin resonance, cathodoluminescence, capillary ion analysis, and gas chromatography. *Geochimica et Cosmochimica Acta*, 68(18): 3741~3759.

Gruen G, Heinrich C A, Schroeder K. 2010. The Bingham canyon porphyry Cu-Mo-Au deposit. II. Vein geometry and ore shell formation by pressure-driven rock extension. *Economic Geology*, 105(1): 69~90.

Guo Shuo, Zhao Yuanyi, Qu Huanchun, Wu Dexin, Xu Hong, Li Chao, Liu Yan, Zhu Xiaoyun, Wang Zengke. 2012. Geological characteristics and ore-forming time of Dexing porphyry copper

- ore mine in Jiangxi Province. *Acta Geologica Sinica* (English Edition), 86(3): 691~699.
- Hall D L, Sterner S M, Bodnar R J. 1988. Freezing point depression of NaCl-KCl-H<sub>2</sub>O solutions. *Economic Geology*, 83: 197~202.
- He Wenwu, Bao Zhengyu, Li Tieping. 1999. One-dimensional reactive transport models of alteration in the Tongchang porphyry copper deposit, Dexing district, Jiangxi Province, China. *Economic Geology*, 94(3): 307~323.
- Hemley J J, Hunt J P. 1992. Hydrothermal ore-forming processes in the light of studies in rock-buffered systems: II. Some general geologic applications. *Economic Geology*, 87(1): 23~43.
- Huang Peng, Gu Xuexiang, Tang Juxing. 2000. A study on Cu, Mo migration and precipitation mechanism in the Yulong porphyry Cu-Mo deposit, Xizang. *Acta Geologica Sichuan*, 20(1): 57~61 (in Chinese with English abstract).
- Jacamon F, Larsen R B. 2009. Trace element evolution of quartz in the charnockitic Kleivan granite, SW-Norway: The Ge/Ti ratio of quartz as an index of igneous differentiation. *Lithos*, 107(3-4): 281~291.
- Jin Zhangdong. 1999. Geochemistry and evolution of ore-forming fluids at Tongchang porphyry copper deposit, Dexing County, Jiangxi Province. Doctoral dissertation of Nanjing University, 1~124 (in Chinese with English abstract).
- Jin Zhangdong, Zhu Jinchu, Li Fuchun. 2002. O, Sr and Nd isotopic tracing of ore-forming process in Dexing porphyry copper deposit, Jiangxi Province. *Mineral Deposit*, 21(4): 341~349 (in Chinese with English abstract).
- Kang Yongjian, Xiang Anping, She Hongquan, Sun Yuliang, Yang Wensheng. 2016. The characteristics of ore-forming fluids and mineralization mechanism in the Badaguan porphyry Cu-Mo deposit, Inner Mongolia, NE China. *Acta Geologica Sinica*, 90(8): 1778~1797 (in Chinese with English abstract).
- Klemm L M, Pettke T, Heinrich C A. 2008. Fluid and source magma evolution of the Questa porphyry Mo deposit, New Mexico, USA. *Mineralium Deposita*, 43(5): 533~552.
- Leng Chengbiao, Zhang Xingchun, Qin Chaojian, Wang Shouxu, Ren Tao, Wang Waiquan. 2008. Study of fluid inclusions in quartz veinlets in the Xuejiping porphyry copper deposit, Northwest Yunnan, China. *Acta Petrologica Sinica*, 24(9): 2017~2028 (in Chinese with English abstract).
- Leng Chengbiao, Zhang Xingchun, Wang Shouxu, Qin Chaojian, Wu Kongwen, Ren Tao. 2009. Advances of researches on the evolution of ore-forming fluids and the vapor transport of metals in magmatic-hydrothermal systems. *Geological Review*, 55(1): 100~112 (in Chinese with English abstract).
- Leng Chengbiao, Qi Youqiang. 2017. Genesis of lengshuikeng Ag-Pb-Zn orefield in Jiangxi: Constraint from *in-situ* LA-ICP-MS analyses of minor and trace elements in sphalerite and galena. *Acta Geologica Sinica*, 91(10): 2256~2272 (in Chinese with English abstract).
- Li Li, Ni Pei, Wang Guoguang, Zhu Andong, Pan Junyi, Chen Hui, Huang Bao, Yuan Huixiang, Wang Zengke, Fang Minghui. 2017. Multi-stage fluid boiling and formation of the giant Fujiawu porphyry Cu-Mo deposit in South China. *Ore Geology Reviews*, 81: 898~911.
- Li Li, Ni Pei, Wang Guoguang, Zhu Andong. 2018. Re-Os isotopic dating of pyrite from Dexing porphyry copper orefield and its geological significance. *Mineral Deposit*, 37(6): 1168~1178 (in Chinese with English abstract).
- Li Xiaofeng, Hu Ruizhong, Rusk Brian, Xiao Rong, Wang Cuiyun, Yang Feng. 2013. U-Pb and Ar-Ar geochronology of the Fujiawu porphyry Cu-Mo deposit, Dexing district, Southeast China: Implications for magmatism, hydrothermal alteration, and mineralization. *Journal of Asian Earth Sciences*, 74: 330~342.
- Liang Xiangji. 1995. The experimental study on the source of the ore-forming materials for the Dexing porphyry copper deposit, Jiangxi Province. *Geological Review*, 41(5): 463~471 (in Chinese with English abstract).
- Liu Dewei. 2018. Study on the fluid inclusions of the Fujiawu porphyry Cu deposit, Dexing, Jiangxi Province. Master thesis of China University of Geosciences (Beijing) (in Chinese with English abstract).
- Liu Xuan, Fan Hongrui, Santosh M, Hu Fangfang, Yang Kuifeng, Li Qiuli, Yang Yueheng, Liu Yongsheng. 2012. Remelting of Neoproterozoic relict volcanic arcs in the Middle Jurassic: Implication for the formation of the Dexing porphyry copper deposit, Southeastern China. *Lithos*, 150: 85~100.
- Mao Jingwen, Zhang Jiandong, Guo Chunli. 2010. Porphyry Cu, epithermal Ag-Pb-Zn, distal hydrothermal Au deposits: A new model of mineral deposit-taking the Dexing area as an example. *Journal of Earth Sciences and Environment*, 32(1): 1~14 (in Chinese with English abstract).
- Mao Wei, Rusk B, Yang Fuchu, Zhang Mingji. 2017. Physical and chemical evolution of the Dabaoshan porphyry Mo deposit, South China: Insights from fluid inclusions, cathodoluminescence, and trace elements in quartz. *Economic Geology*, 112(4): 889~918.
- Pan Xiaofei, Song Yucai, Wang Shuxian, Li Zhenqing, Yang Zhiming, Hou Zengqian. 2009. Evolution of hydrothermal fluid of Dexing Tongchang copper-gold porphyry deposit. *Acta Geologica Sinica*, 83(12): 1929~1950 (in Chinese with English abstract).
- Pan Xiaofei, Song Yucai, Li Zhenqing, Hu Baogen, Zhu Xiaoyun, Wang Zengke, Yang Dan, Zhang Tianfu, Li Yan. 2012. Restriction of H-O isotopes for alteration and mineralization system of Tongchang Cu (-Mo-Au) porphyritic deposit, Jiangxi Province. *Mineral Deposit*, 31(4): 850~860 (in Chinese with English abstract).
- Qian Peng, Lu Jianjun, Liu Fengxiang. 2006. Isotopic tracing of ore-forming source materials in the porphyry copper deposit of Dexing, Jiangxi Province. *Global Geology*, 25(2): 135~140 (in Chinese with English abstract).
- Redmond P B, Einaudi M T, Inan E E, Landtwing M R, Heinrich C A. 2004. Copper deposition by fluid cooling in intrusion-centered systems: New insights from the Bingham porphyry ore deposit, Utah. *Geology*, 32(3): 217~220.
- Ren Zhi, Zhou Taofa, Hollings Pete, White Noel C, Wang Fangyue, Yuan Feng. 2018. Trace element geochemistry of molybdenite from the Shapinggou super-large porphyry Mo deposit, China. *Ore Geology Reviews*, 95: 1049~1065.
- Rusk B G, Lowers H A, Reed Mark H. 2008. Trace elements in hydrothermal quartz: Relationships to cathodoluminescent textures and insights into vein formation. *Geology*, 36(7): 547~550.
- Selby D, Creaser R A. 2001. Re-Os geochronology and systematics in molybdenite from the Endako porphyry molybdenum deposit, British Columbia, Canada. *Economic Geology*, 96(1): 197~204.
- Sillitoe R H. 2010. Porphyry copper systems. *Economic Geology*, 105(1): 3~41.
- Steele M M, Lecumberri S P, Bodnar R J. 2012. HokieFlincs\_H<sub>2</sub>O-NaCl: A Microsoft Excel spreadsheet for interpreting microthermometric data from fluid inclusions based on the PVTX properties of H<sub>2</sub>O-NaCl. *Computers and Geosciences*, 49: 334~337.
- Stein H J, Markey R J, Morgan J W, Hannah J L, Scherstén A. 2001. The remarkable Re ± Os chronometer in molybdenite: How and why it works. *Terra Nova*, 13(6): 479~486.
- Sun Jia, Mao Jingwen, Xie Guiqing, Zen Zailin, Su Huimin, Liu Yong. 2012. Characteristics of ore-forming fluid and metallogenesis of the Tongkengzhang porphyry molybdenum deposit. *Acta Petrologica Sinica*, 28(1): 91~104 (in Chinese with English abstract).
- Ulrich T, Günther D, Heinrich C A. 2002. The evolution of a porphyry Cu-Au deposit, based on LA-ICP-MS analysis of fluid inclusions: Bajo de la Alumbrera, Argentina. *Economic*

Geology, 97(8): 1889~1920.

Wang Cuiyun, Li Xiaofeng, Xiao Rong, Yang Feng, Wang Zengke, Zhu Xiaoyun. 2012. Types and distribution of veins in Tongchang porphyry copper deposit, Dexing, Jiangxi Province. Mineral Deposit, 31(1): 94~110 (in Chinese with English abstract).

Wang Guoguang, Ni Pei, Yao Jing, Wang Xiaolei, Zhao Kuidong, Zhu Renzhi, Xu Yingfeng, Pan Junyi, Li Li, Zhang Yinghong. 2015. The link between subduction-modified lithosphere and the giant Dexing porphyry copper deposit, South China: Constraints from high-Mg adakitic rocks. Ore Geology Reviews, 67: 109~126.

Wang Guoguang, Ni Pei, Zhao Chao, Yao Jing, Li Li, Zhao Danlei, Zhu Andong, Hu Jinshan. 2019. The research advances and genetic model of the giant Dexing Cu-Au ore cluster. Acta Petrologica Sinica, 35(12): 3644~3658 (in Chinese with English abstract).

Wang Guoguang, Ni Pei, Li Li, Wang Xiaolei, Zhu Andong, Zhang Yinghong, Zhang Xin, Liu Zheng, Li Bing. 2020. Petrogenesis of the Middle Jurassic andesitic dikes in the giant Dexing porphyry copper ore field, South China: Implications for mineralization. Journal of Asian Earth Sciences, 196: 104~375.

Wang Qiang, Zhao Zhenhua, Jian Ping, Xu Jifeng, Bao Zhiwei, Ma Jinlong. 2004. SHRIMP zircon geochronology and Nd-Sr isotopic geochemistry of the Dexing granodiorite porphyries. Acta Petrologica Sinica, 20(2): 315~324 (in Chinese with English abstract).

Wang Qiang, Xu Jifeng, Jian Ping, Bao Zhiwei, Zhao Zhenhua, Li Chaofeng, Xiong Xiaolin, Ma Jinlong. 2006. Petrogenesis of adakitic porphyries in an extensional tectonic setting, Dexing, South China: Implications for the genesis of porphyry copper mineralization. Journal of Petrology, 47(1): 119~144.

Wen Peng. 2015. Research of distribution law between the Cu and its associated Au-Ag-Re-Co elements in Fujiawu Dexing copper (molybdenum) deposit. Master thesis of China University of Geosciences, Beijing (in Chinese with English abstract).

Xia Yu, Peng Guangju, Zhou Weining, Zhang Xinhai, Ma Rongkai. 2017. Study on occurrence state of rhenium copper-molybdeum ore from the Fujiawu deposit, Jiangxi Province and factors affecting Re recovery. Rock and Mineral Analysis, 36(6): 659~665 (in Chinese with English abstract).

Xiong Yongliang, Wood Scott A. 2002. Experimental determination of the hydrothermal solubility of ReS<sub>2</sub> and the Re-ReO<sub>2</sub> buffer assemblage and transport of rhenium under supercritical conditions. Geochemical Transactions, 3(1): 1~10.

Yao Jing, Ni Pei, Zhao Kuidong, Wang Hongtao. 2012. Evolution of ore-forming fluids in the Tongchang porphyry copper deposit Dexing, northeast Jiangxi Province. Bulletin of Mineralogy, Petrology and Geochemistry, 31(2): 97~104(in Chinese with English abstract).

Zhang Chanchan, Sun Weidong, Wang Jintuan, Zhang Lipeng, Sun Saijun, Wu Kai. 2017. Oxygen fugacity and porphyry mineralization: A zircon perspective of Dexing porphyry Cu deposit, China. Geochimica et Cosmochimica Acta, 206: 343~363.

Zhou Qing. 2011. Petrogenesis and metallogeny for the Dexing porphyry copper deposits. Doctoral dissertation of Nanjing University, 1~109 (in Chinese with English abstract).

Zhou Qing, Jiang Yaohui, Zhao Peng, Liao Shiyong, Jin Guodong. 2012. Origin of the Dexing Cu-bearing porphyries, SE China: elemental and Sr-Nd-Pb-Hf isotopic constraints. International Geology Review, 54(5): 572~592.

Zhou Qing, Jiang Yaohui, Liao Shiyong, Jin Guodong, Zhao Peng, Liu Zheng, Jia Ruya. 2013. New research progress of Dexing porphyry copper deposit. Geological Review, 59(5): 933~940 (in Chinese with English abstract).

Zhou Xiong. 2017. Study on the fluid inclusions of Bangpu molybdenum copper polymetallic deposit, Tibet. Master thesis of Chengdu University of Technology (in Chinese with English abstract).

Zhu Jinchu, Jin Zhangdong, Rao Bing, Li Fuchun. 2002. Ore-forming fluid process in the Dexing porphyry copper deposit, Jiangxi Province: Evidence from claymineralogy, fluid inclusion and isotope tracing. Journal of Nanjing University (Natural Science), 38(3): 418~434 (in Chinese with English abstract).

Zhu Xun, Huang Chongke, Rui Zongyao, Zhou Yaohua, Zhu Xianjia, Hu Congsheng, Mei Zhankui. 1983. The Geology of Dexing Porphyry Copper Ore Field. Beijing: Geology Publishing House, 1~336 (in Chinese).

参 考 文 献

- 31(1): 94~110.
- 王国光, 倪培, 赵超, 姚静, 李利, 赵丹蕾, 朱安东, 胡金山. 2019. 德兴大型铜金矿集区的研究进展和成矿模式. 岩石学报, 35(12): 3644~3658.
- 王强, 赵振华, 简平, 许继峰, 包志伟, 马金龙. 2004. 德兴花岗闪长斑岩 SHRIMP 锆石 U-Pb 年代学和 Nd-Sr 同位素地球化学. 岩石学报, 20(2): 315~324.
- 文鹏. 2015. 德兴富家坞铜(钼)矿床地质特征及其共(伴)生铼钴金银的分布规律. 中国地质大学(北京)硕士学位论文.
- 夏瑜, 彭光菊, 周卫宁, 张新海, 马荣锴. 2017. 江西富家坞矿床铜钼矿石中铼元素的赋存状态及其回收影响因素分析. 岩矿测试, 36(6): 659~665.
- 姚静, 倪培, 赵葵东, 王洪涛. 2012. 德兴铜厂斑岩铜矿成矿流体演化特征. 矿物岩石地球化学通报, 31(2): 97~104.
- 周清. 2011. 德兴斑岩铜矿含矿斑岩成岩及成矿机制. 南京大学博士学位论文.
- 周清, 姜耀辉, 廖世勇, 靳国栋, 赵鹏, 刘铮, 贾儒雅. 2013. 德兴斑岩铜矿床研究新进展. 地质论评, 59(5): 933~940.
- 周雄. 2017. 西藏邦铺铜多金属矿床流体包裹体研究. 成都理工大学硕士学位论文.
- 朱金初, 金章东, 饶冰, 李福春. 2002. 德兴铜厂斑岩铜矿流体过程. 南京大学学报(自然科学), 38(3): 418~434.
- 朱训, 黄崇珂, 芮宗瑶, 周耀华, 朱贤甲, 胡淙声, 梅占魁. 1983. 德兴斑岩矿床. 北京: 地质出版社, 1~336.

## The evolution of metallogenic hydrothermal fluid and its effect on the heterogeneous enrichment of rhenium in the Dexing copper ore field, Jiangxi Province

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### Abstract

Tongchang and Fujiawu are two typical porphyry copper deposits in the Dexing ore field. Their metallogenic ages, metallogenic backgrounds and ore-forming porphyries are relatively consistent, but the Re contents of molybdenite in Tongchang are significantly higher than that in Fujiawu. In order to explore the effect of ore-forming fluid evolution on the heterogeneous enrichment of rhenium, LA-ICP-MS analysis on quartz and fluid inclusions in quartz in different metallogenic stages of Tongchang and Fujiawu were carried out in this paper. The results show that they have similar fluid evolution processes. The decrease of temperature, fluid boiling and the change of pH may be the main reasons for the precipitation of Cu and Mo. However, the temperature for the same metallogenic stage in Tongchang is lower than that in Fujiawu, and the fluid in Tongchang has higher salinity in the main metallogenic stage. Therefore, it is proposed that the temperature and salinity are the dominant factors leading to the heterogeneous enrichment of rhenium in molybdenite in the Dexing copper ore field.

**Key words:** Dexing copper ore field; evolution of ore-forming fluid; molybdenite; rhenium

附表 1 德兴铜矿田富家坞和铜厂矿床流体包裹体测温数据

| Appendix 1 Temperature data of fluid inclusions in Fujiawu and Tongchang deposits in the Dexing copper ore field |                |           |     |            |            |           |                   |                   |             |     |                 |                            |
|------------------------------------------------------------------------------------------------------------------|----------------|-----------|-----|------------|------------|-----------|-------------------|-------------------|-------------|-----|-----------------|----------------------------|
| 矿床                                                                                                               | 脉体             | 样品号       | 类型  | 大小<br>(μm) | 气液比<br>(%) | 冰点<br>(℃) | 子晶融<br>化温度<br>(℃) | 部分均<br>一温度<br>(℃) | 均一温<br>度(℃) | 均一相 | 盐度<br>(%NaCleq) | 密度<br>(g/cm <sup>3</sup> ) |
| 富家坞                                                                                                              | V <sub>1</sub> | FW-B2-1   | VL  | 5          | 65         | −5.2      |                   |                   | 428         | 气相  | 8.1             | 0.568                      |
|                                                                                                                  |                | FW-B2-2   | LVH | 3          |            |           | 563               | 276               | 563         |     | 68.6            | 1.268                      |
|                                                                                                                  |                | FW-B2-3   | LV  | 6          | 30         | −7.1      |                   |                   | 487         |     | 10.6            | 0.499                      |
|                                                                                                                  |                | FW-B2-4   | LVH | 18         |            |           | 517               | 346               | 517         |     | 62.1            | 1.256                      |
|                                                                                                                  |                | FW-B2-5   | VL  | 7          | 70         | −5.6      |                   |                   | 494         | 气相  | 8.7             | 0.439                      |
|                                                                                                                  |                | FW-B2-6   | LVH | 9          |            |           | 481               | 313               | 481         |     | 57.3            | 1.140                      |
|                                                                                                                  | V <sub>2</sub> | FW-B3-1   | LV  | 8          | 20         |           |                   |                   | 338         |     |                 |                            |
|                                                                                                                  |                | FW-B3-2   | LV  | 7          | 40         |           |                   |                   | 392         |     |                 |                            |
|                                                                                                                  |                | FW-B3-3   | LV  | 8          | 20         | −5.4      |                   |                   | 341         |     | 8.4             | 0.733                      |
|                                                                                                                  |                | FW-B3-4   | LV  | 8          | 15         | −3.7      |                   |                   | 348         |     | 6.0             | 0.689                      |
|                                                                                                                  |                | FW-B3-5   | LV  | 12         | 10         |           |                   |                   | 367         |     |                 |                            |
|                                                                                                                  |                | FW-B3-6   | VL  | 6          | 60         | −6.3      |                   |                   | 357         |     | 9.5             | 0.723                      |
|                                                                                                                  |                | FW-B3-7   | LV  | 7          | 90         |           |                   |                   | 363         |     |                 |                            |
|                                                                                                                  |                | FW-B3-8   | LVH | 8          |            |           | 388               | 304               | 388         |     | 46.1            | 1.076                      |
|                                                                                                                  |                | FW-B3-9   | VL  | 6          | 60         | −3.3      |                   |                   | 319         | 气相  | 5.4             | 0.731                      |
|                                                                                                                  |                | FW-B3-10  | LV  | 10         | 12         | −8.6      |                   |                   | 254         |     | 12.4            | 0.901                      |
|                                                                                                                  |                | FW-B3-11  | LV  | 7          | 5          | −4.1      |                   |                   | 369         |     | 6.6             | 0.657                      |
|                                                                                                                  |                | FW-B3-12  | LV  | 9          | 20         |           |                   |                   | 337         |     |                 |                            |
|                                                                                                                  |                | FW-B3-13  | LV  | 7          | 40         | −8.7      |                   |                   | 412         |     | 12.5            | 0.677                      |
|                                                                                                                  |                | FW-B3-14  | LV  | 6          | 10         |           |                   |                   | 278         |     |                 |                            |
|                                                                                                                  |                | FW-B3-15  | LV  | 5          | 12         |           |                   |                   | 295         |     |                 |                            |
|                                                                                                                  |                | FW-B3-16  | LV  | 10         | 55         |           |                   |                   | 327         |     |                 |                            |
|                                                                                                                  |                | FW-B3-17  | VL  | 9          | 65         | −8.3      |                   |                   | 328         | 气相  | 12.1            | 0.800                      |
|                                                                                                                  |                | FW-B3-18  | LV  | 6          | 20         | −2.1      |                   |                   | 254         |     | 3.5             | 0.818                      |
|                                                                                                                  |                | FW-B3-19  | LV  | 7          | 20         | −6.7      |                   |                   | 282         |     | 10.1            | 0.842                      |
|                                                                                                                  | V <sub>3</sub> | FW-B25-1  | LV  | 3          | 10         |           |                   |                   | 271         |     |                 |                            |
|                                                                                                                  |                | FW-B25-2  | LV  | 7          | 15         |           |                   |                   | 214         |     |                 |                            |
|                                                                                                                  |                | FW-B25-3  | LV  | 4          | 8          |           |                   |                   | 242         |     |                 |                            |
|                                                                                                                  |                | FW-B25-4  | LV  | 10         | 8          | −6.8      |                   |                   | 221         |     | 10.2            | 0.918                      |
|                                                                                                                  |                | FW-B25-5  | LV  | 3          | 30         | −7.9      |                   |                   | 222         |     | 11.5            | 0.929                      |
|                                                                                                                  |                | FW-B25-6  | LV  | 5          | 30         | −2.4      |                   |                   | 317         |     | 4.0             | 0.717                      |
|                                                                                                                  |                | FW-B25-7  | LV  | 6          | 40         | −2.1      |                   |                   | 226         |     | 3.6             | 0.859                      |
|                                                                                                                  |                | FW-B25-8  | LV  | 7          | 35         |           |                   |                   | 321         |     |                 |                            |
|                                                                                                                  |                | FW-B25-9  | LV  | 4          | 15         | −5.3      |                   |                   | 242         |     | 8.2             | 0.877                      |
|                                                                                                                  |                | FW-B25-10 | LV  | 5          | 7          | −6.0      |                   |                   | 240         |     | 9.2             | 0.888                      |
|                                                                                                                  |                | FW-B25-11 | LV  | 8          | 20         |           |                   |                   | 295         |     |                 |                            |
|                                                                                                                  |                | FW-B25-12 | LV  | 5          | 30         |           |                   |                   | 290         |     |                 |                            |
|                                                                                                                  |                | FW-B25-13 | LV  | 7          | 15         |           |                   |                   | 242         |     |                 |                            |
|                                                                                                                  | V <sub>4</sub> | FW-B24-1  | LV  | 11         | 15         |           |                   |                   | 184         |     |                 |                            |
|                                                                                                                  |                | FW-B24-2  | LV  | 7          | 15         | −3.4      |                   |                   | 185         |     | 5.6             | 0.924                      |
|                                                                                                                  |                | FW-B24-3  | LV  | 7          | 10         | −5.3      |                   |                   | 208         |     | 8.3             | 0.918                      |
|                                                                                                                  |                | FW-B24-4  | LV  | 6          | 10         | −2.3      |                   |                   | 147         |     | 3.9             | 0.951                      |
|                                                                                                                  |                | FW-B24-5  | LV  | 5          | 2          | −3.7      |                   |                   | 143         |     | 6.1             | 0.968                      |
|                                                                                                                  |                | FW-B24-6  | LV  | 6          | 5          |           |                   |                   | 168         |     |                 |                            |
|                                                                                                                  |                | FW-B24-7  | LV  | 6          | 25         | −4.6      |                   |                   | 171         |     | 7.3             | 0.950                      |
|                                                                                                                  |                | FW-B24-8  | LV  | 7          | 15         |           |                   |                   | 168         |     |                 |                            |

续附表 1

| 矿床 | 脉体             | 样品号       | 类型  | 大小<br>(μm) | 气液比<br>(%) | 冰点<br>(℃) | 子晶融<br>化温度<br>(℃) | 部分均<br>一温度<br>(℃) | 均一温<br>度(℃) | 均一相 | 盐度<br>(%NaCleq) | 密度<br>(g/cm <sup>3</sup> ) |
|----|----------------|-----------|-----|------------|------------|-----------|-------------------|-------------------|-------------|-----|-----------------|----------------------------|
| 铜厂 | V <sub>1</sub> | TC-B14-1  | LVH | 9          |            |           | 492               | 342               | 492         |     | 58.7            | 1.153                      |
|    |                | TC-B14-2  | LVH | 13         |            |           | 552               | 287               | 552         |     | 67.1            | 1.260                      |
|    |                | TC-B14-3  | LVH | 11         |            |           | 477               | 382               | 477         |     | 56.7            | 1.135                      |
|    |                | TC-B14-4  | LVH | 14         |            |           | 536               | 402               | 536         |     | 64.8            | 1.253                      |
|    |                | TC-B14-5  | VL  | 6          | 70         | − 5.4     |                   |                   | 461         |     | 8.5             | 0.504                      |
|    |                | TC-B14-6  | LV  | 16         | 35         | − 5.8     |                   |                   | 452         |     | 9.0             | 0.536                      |
|    |                | TC-B14-7  | VL  | 12         | 60         |           |                   |                   | 472         | 气相  |                 |                            |
|    |                | TC-B14-8  | VL  | 12         | 55         | − 4.4     |                   |                   | 490         | 气相  | 7.0             | 0.403                      |
|    | V <sub>2</sub> | TC-B21-1  | LV  | 12         | 20         |           | 368               | 248               | 266         |     | 44.1            | 1.072                      |
|    |                | TC-B21-2  | LVH | 11         |            |           |                   |                   | 368         |     |                 |                            |
|    |                | TC-B21-3  | LV  | 6          | 15         |           |                   |                   | 267         |     |                 |                            |
|    |                | TC-B21-4  | LV  | 12         | 40         |           |                   |                   | 339         |     |                 |                            |
|    |                | TC-B21-5  | LV  | 10         | 15         | − 7.7     |                   |                   | 352         |     | 11.4            | 0.755                      |
|    |                | TC-B21-6  | LV  | 8          | 20         |           |                   |                   | 320         | 气相  |                 |                            |
|    |                | TC-B21-7  | LV  | 12         | 20         | − 10.3    |                   |                   | 358         |     | 14.2            | 0.785                      |
|    |                | TC-B21-8  | VL  | 8          | 65         | − 8.6     |                   |                   | 341         |     | 12.4            | 0.785                      |
|    |                | TC-B21-9  | LV  | 7          | 8          | − 3.2     |                   |                   | 336         |     | 5.3             | 0.700                      |
|    |                | TC-B21-10 | LV  | 4          | 20         |           |                   |                   | 327         |     |                 |                            |
|    |                | TC-B21-11 | LV  | 4          | 15         |           |                   |                   | 317         |     |                 |                            |
|    |                | TC-B21-12 | LV  | 8          | 30         | − 8.2     |                   |                   | 328         | 气相  | 11.9            | 0.798                      |
|    |                | TC-B21-13 | LV  | 7          | 20         |           |                   |                   | 252         |     |                 |                            |
|    |                | TC-B21-14 | LV  | 8          | 30         | − 4.9     |                   |                   | 247         |     | 7.7             | 0.866                      |
|    |                | TC-B21-15 | LV  | 9          | 40         |           |                   |                   | 332         |     |                 |                            |
|    |                | TC-B21-16 | LV  | 6          | 15         | − 5.8     |                   |                   | 291         |     | 9.0             | 0.817                      |
|    |                | TC-B21-17 | VL  | 10         | 60         | − 6.3     |                   |                   | 324         |     | 9.6             | 0.777                      |
|    |                | TC-B21-18 | LVH | 12         |            |           | 331               | 273               | 331         |     | 40.7            | 1.064                      |
|    |                | TC-B21-19 | LV  | 5          | 25         |           |                   |                   | 245         |     |                 |                            |
|    |                | TC-B21-20 | LV  | 7          | 25         | − 6.2     |                   |                   | 242         |     | 9.5             | 0.888                      |
|    |                | TC-B21-21 | LV  | 9          | 25         |           |                   |                   | 311         |     |                 |                            |
|    |                | TC-B21-22 | LV  | 7          | 30         | − 3.7     |                   |                   | 287         |     | 6.1             | 0.793                      |
|    |                | TC-B21-23 | LV  | 5          | 40         |           |                   |                   | 307         |     |                 |                            |
|    | V <sub>3</sub> | TC-B22-1  | LV  | 12         | 2          | − 4.4     |                   |                   | 153         |     | 7.0             | 0.965                      |
|    |                | TC-B22-2  | LV  | 6          | 2          |           |                   |                   | 158         |     |                 |                            |
|    |                | TC-B22-3  | LV  | 12         | 10         |           |                   |                   | 175         |     |                 |                            |
|    |                | TC-B22-4  | LV  | 4          | 7          |           |                   |                   | 185         |     |                 |                            |
|    |                | TC-B22-5  | LV  | 5          | 8          |           |                   |                   | 203         |     |                 |                            |
|    |                | TC-B22-6  | LV  | 6          | 6          |           |                   |                   | 174         |     |                 |                            |
|    |                | TC-B22-7  | LV  | 6          | 5          |           |                   |                   | 162         |     |                 |                            |
|    |                | TC-B22-8  | LV  | 8          | 15         | − 4.0     |                   |                   | 163         |     | 6.4             | 0.952                      |
|    |                | TC-B22-9  | LV  | 11         | 9          | − 3.5     |                   |                   | 188         |     | 5.8             | 0.922                      |
|    |                | TC-B22-10 | LV  | 10         | 15         |           |                   |                   | 169         |     |                 |                            |
|    |                | TC-B22-11 | LV  | 5          | 7          | − 3.7     |                   |                   | 195         |     | 6.0             | 0.915                      |
|    |                | TC-B22-12 | LV  | 10         | 8          | − 2.7     |                   |                   | 179         |     | 4.5             | 0.923                      |
|    |                | TC-B22-13 | LV  | 9          | 12         | − 5.2     |                   |                   | 204         |     | 8.2             | 0.921                      |
|    |                | TC-B22-14 | LV  | 10         | 11         | − 4.0     |                   |                   | 216         |     | 6.4             | 0.894                      |

注:未作特别说明,均一相均为液相。

附表 2 德兴铜矿田富家坞和铜厂矿床石英微量元素数据(×10<sup>-6</sup>)

| Appendix 2 Trace elements data (×10 <sup>-6</sup> ) in quartz of Tongchang and Fujiawu deposits in the Dexing copper ore field |                  |              |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|--------------------------------------------------------------------------------------------------------------------------------|------------------|--------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 矿床                                                                                                                             | 类型               | 样品号          | Li   | B    | Na   | Mg   | Al   | P    | Cl   | K    | Ca   | Ti   | Mn   | Ge   | Rb   | Cs   |
| 富家坞                                                                                                                            | 斑晶               | FW-13-1-BJ1  | —    | 4.89 | 58.9 | 3.18 | 173  | 22.3 | 520  | 18.5 | 160  | 108  | 9.83 | —    | —    | 0.12 |
|                                                                                                                                |                  | FW-13-1-BJ2  | 9.63 | 3.52 | 10.3 | —    | 101  | —    | 504  | —    | 111  | 88.7 | 8.53 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-1-BJ3  | 13.7 | 3.51 | 4.99 | 2.57 | 122  | —    | 565  | —    | 66.5 | 103  | 9.19 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-1-BJ4  | 26.1 | 2.62 | 11.2 | 7.18 | 258  | —    | 548  | 5.56 | 80.3 | 120  | 7.74 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-1-BJ5  | 20.9 | 2.90 | 6.73 | 2.99 | 203  | —    | —    | 7.88 | 123  | 55.5 | 7.53 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-1-BJ6  | 20.1 | 3.65 | 7.47 | 4.59 | 184  | —    | —    | —    | 75.1 | 85.1 | 7.68 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-1-BJ7  | 12.3 | —    | 9.16 | 1.69 | 116  | —    | —    | —    | 123  | 48.2 | 7.24 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-1-BJ8  | 1.49 | 4.09 | 114  | 7.34 | 186  | —    | —    | 60.5 | 146  | 72.0 | 22.3 | —    | 0.54 | 0.09 |
|                                                                                                                                |                  | FW-13-1-BJ9  | 3.70 | 2.72 | 158  | 3.16 | 137  | 19.7 | —    | 28.1 | 170  | 66.1 | 20.3 | —    | 0.31 | 0.06 |
|                                                                                                                                |                  | FW-13-1-BJ10 | 5.91 | 2.87 | 25.7 | 1.84 | 103  | —    | —    | 8.18 | 132  | 96.6 | 8.46 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-1-BJ11 | 5.91 | —    | 22.9 | —    | 110  | —    | —    | —    | 148  | 86.9 | 8.72 | —    | —    | 0.09 |
|                                                                                                                                | V <sub>1</sub> 脉 | FW-2-1       | 11.5 | 5.01 | 7.96 | 2.94 | 201  | —    | 191  | 114  | 99.0 | 136  | 6.42 | 1.43 | —    | —    |
|                                                                                                                                |                  | FW-2-2       | 11.2 | 5.50 | 4.44 | 2.20 | 136  | —    | 207  | 14.8 | 93.5 | 115  | 6.55 | —    | —    | —    |
|                                                                                                                                |                  | FW-2-3       | 10.2 | 5.15 | 2.09 | 3.61 | 130  | —    | —    | 10.4 | 82.5 | 78.0 | 6.29 | —    | —    | —    |
|                                                                                                                                |                  | FW-2-4       | 8.43 | 4.30 | 0.74 | 2.85 | 82.5 | —    | 155  | —    | 117  | 87.4 | 5.96 | —    | —    | —    |
|                                                                                                                                |                  | FW-2-5       | 13.5 | 5.71 | 43.1 | 4.15 | 203  | 22.1 | 268  | 40.7 | 55   | 133  | 9.90 | —    | —    | 0.07 |
|                                                                                                                                |                  | FW-2-6       | 14.7 | 3.70 | 22.8 | 6.34 | 219  | —    | 240  | 40.9 | 85.5 | 143  | 5.65 | —    | —    | —    |
|                                                                                                                                |                  | FW-2-7       | 16.0 | 4.06 | 13.4 | 4.69 | 266  | —    | 213  | 43.7 | 76.0 | 135  | 6.78 | —    | —    | 0.07 |
|                                                                                                                                |                  | FW-2-8       | 18.9 | 5.03 | 6.63 | 4.58 | 315  | 24.8 | —    | 68.9 | 110  | 188  | 7.05 | —    | 0.35 | —    |
|                                                                                                                                |                  | FW-2-9       | 18.8 | 5.09 | 3.02 | 3.70 | 306  | 26.1 | 297  | 58.9 | 121  | 143  | 7.19 | —    | 0.28 | —    |
|                                                                                                                                | V <sub>2</sub> 脉 | FW-1-1       | 11.5 | 5.01 | 11.7 | 4.84 | 108  | —    | —    | 10.7 | 145  | 91.1 | 6.60 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-2       | 16.0 | 6.10 | 10.7 | 3.55 | 162  | —    | 97.9 | 10.3 | 91.1 | 109  | 6.91 | 1.40 | —    | 0.04 |
|                                                                                                                                |                  | FW-1-3       | 11.5 | 5.98 | 7.98 | 4.63 | 106  | —    | 98.5 | —    | 113  | 95.5 | 6.48 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-4       | 12.9 | 5.83 | 4.89 | 2.49 | 118  | —    | 85.9 | —    | 98.2 | 107  | 5.81 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-5       | 15.7 | 4.14 | 4.88 | 6.50 | 138  | —    | 116  | 6.98 | 96.0 | 116  | 5.91 | 2.06 | —    | —    |
|                                                                                                                                |                  | FW-1-6       | 13.6 | 5.29 | 6.64 | 4.50 | 155  | —    | 97.0 | 11.1 | 124  | 114  | 6.50 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-7       | 10.5 | 5.86 | 11.1 | 2.74 | 110  | 23.9 | —    | 5.24 | 85.0 | 91.7 | 5.85 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-8       | 8.81 | 4.95 | 3.40 | —    | 73.6 | 22.0 | 148  | —    | 125  | 88.0 | 6.02 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-9       | 15.0 | 4.57 | 5.67 | 4.58 | 135  | —    | —    | —    | 85.0 | 106  | 6.05 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-10      | 10.4 | 5.03 | 21.8 | 3.60 | 108  | —    | 148  | 9.69 | 117  | 128  | 7.68 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-11      | 9.51 | 5.29 | 11.7 | 2.58 | 91.0 | —    | —    | —    | 108  | 96.3 | 7.88 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-12      | 4.53 | 5.00 | 40.5 | 4.17 | 76.2 | —    | —    | 12.1 | 134  | 93.1 | 10.8 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-13      | 7.43 | 4.19 | 35.3 | 3.25 | 135  | —    | 1204 | 17.4 | 114  | 111  | 10.5 | —    | —    | —    |
|                                                                                                                                |                  | FW-1-14      | 11.2 | 3.65 | 6.69 | 4.90 | 106  | —    | —    | —    | 119  | 96.0 | 8.34 | —    | —    | —    |
|                                                                                                                                | V <sub>3</sub> 脉 | FW-13-1      | 16.0 | 4.12 | 3.63 | 3.53 | 184  | 19.6 | —    | 27.7 | 132  | 85.1 | 7.88 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-2      | 16.5 | 3.66 | 2.61 | 1.90 | 161  | —    | 224  | 16.2 | 101  | 59.0 | 7.41 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-3      | 3.19 | 5.03 | 86.3 | 3.01 | 183  | —    | 264  | 40.8 | 119  | 51.2 | 11.5 | —    | —    | 0.04 |
|                                                                                                                                |                  | FW-13-4      | 4.70 | 4.48 | 7.23 | 1.98 | 102  | —    | 178  | —    | 137  | 36.4 | 5.93 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-5      | 2.63 | 4.25 | 33.5 | 5.11 | 99.2 | —    | 212  | —    | 115  | 41.6 | 8.53 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-6      | 8.29 | 3.49 | 35.7 | 1.23 | 124  | —    | —    | 11.6 | —    | 31.7 | 11.2 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-7      | 2.21 | 3.95 | 70.4 | 2.10 | 95.2 | —    | —    | 15.1 | 115  | 38.7 | 12.2 | —    | 0.19 | 0.06 |
|                                                                                                                                |                  | FW-13-8      | 2.73 | 3.58 | 9.88 | 1.08 | 96.7 | —    | —    | —    | 108  | 38.3 | 7.92 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-9      | —    | 2.74 | 47.9 | 1.73 | 81.1 | —    | 283  | —    | 124  | 29.6 | 12.1 | —    | —    | —    |
|                                                                                                                                |                  | FW-13-10     | 13.8 | 4.00 | 2.05 | 1.90 | 105  | —    | 324  | —    | 95.8 | 43.5 | 6.69 | —    | —    | —    |
|                                                                                                                                | V <sub>4</sub> 脉 | FW-24-1      | 14.0 | 3.30 | 1.01 | 1.67 | 118  | —    | 111  | 4.70 | 102  | 6.80 | 6.72 | —    | —    | 0.02 |
|                                                                                                                                |                  | FW-24-2      | 12.8 | 2.70 | 1.90 | 2.70 | 114  | —    | 101  | 8.50 | 102  | 6.20 | 6.30 | —    | —    | —    |
|                                                                                                                                |                  | FW-24-3      | 11.5 | 3.10 | 0.93 | 1.54 | 95.3 | —    | 136  | —    | 124  | 3.30 | 8.07 | 1.22 | —    | —    |
|                                                                                                                                |                  | FW-24-4      | 13.2 | 3.90 | 12.8 | 1.88 | 113  | —    | —    | 10.2 | 194  | 7.10 | 9.00 | 1.55 | —    | —    |
|                                                                                                                                |                  | FW-24-5      | 11.0 | 4.20 | 0.98 | 1.48 | 86.1 | —    | 120  | —    | 144  | 11.5 | 5.70 | —    | —    | —    |
|                                                                                                                                |                  | FW-24-6      | 12.7 | 4.00 | 1.28 | 1.70 | 96.3 | 20.0 | 156  | —    | 111  | 10.7 | 5.90 | 1.73 | —    | —    |
|                                                                                                                                |                  | FW-24-7      | 10.9 | 3.60 | 0.53 | 2.30 | 90.0 | —    | 108  | —    | 131  | 26.6 | 4.90 | —    | —    | —    |
|                                                                                                                                |                  | FW-24-8      | 9.51 | 3.40 | 1.13 | —    | 76.0 | —    | 131  | —    | 121  | 18.7 | 6.10 | —    | —    | —    |
|                                                                                                                                |                  | FW-24-9      | 11.2 | 4.00 | 0.64 | —    | 93.8 | —    | 123  | —    | 155  | 12.0 | 7.20 | —    | —    | —    |
|                                                                                                                                |                  | FW-24-10     | 11.5 | 3.80 | 1.46 | —    | 95.6 | —    | 148  | —    | 97.0 | 16.2 | 7.70 | —    | —    | —    |
|                                                                                                                                |                  | FW-24-11     | 11.8 | 3.10 | 6.00 | 8.80 | 103  | 20.0 | 222  | 16.5 | 109  | 15.1 | 9.70 | 1.54 | —    | —    |

| 续附表 2 |                  |          |      |      |       |      |      |      |     |      |      |      |      |      |      |      |
|-------|------------------|----------|------|------|-------|------|------|------|-----|------|------|------|------|------|------|------|
| 矿床    | 类型               | 样品号      | Li   | B    | Na    | Mg   | Al   | P    | Cl  | K    | Ca   | Ti   | Mn   | Ge   | Rb   | Cs   |
| 铜厂    | 斑晶               | TC-26-1  | 9.85 | 3.70 | 7.40  | —    | 105  | —    | 260 | —    | 126  | 94.4 | 6.19 | —    | —    | —    |
|       |                  | TC-26-2  | 10.6 | —    | 0.52  | 1.74 | 108  | —    | 510 | —    | 74.0 | 76.0 | 8.10 | —    | —    | —    |
|       |                  | TC-26-3  | 8.09 | 2.50 | 3.15  | —    | 91.8 | —    | 450 | —    | 77.0 | 31.6 | 6.80 | —    | —    | —    |
|       |                  | TC-26-4  | 8.82 | —    | 0.93  | —    | 93.4 | —    | —   | —    | 83.0 | 90.2 | 7.90 | —    | —    | —    |
|       |                  | TC-26-5  | 9.47 | 3.40 | 1.56  | —    | 103  | —    | 440 | —    | 74.0 | 110  | 8.10 | —    | —    | —    |
|       |                  | TC-26-6  | 10.6 | —    | 0.390 | 2.00 | 104  | —    | —   | —    | 73.0 | 58.5 | 8.30 | —    | —    | —    |
|       |                  | TC-26-7  | 11.7 | —    | 1.06  | —    | 125  | —    | —   | —    | 89.0 | 34.0 | 7.80 | —    | —    | —    |
|       | V <sub>1</sub> 脉 | TC-3-1   | 11.6 | 3.21 | 14.3  | 1.48 | 149  | —    | —   | —    | 129  | 69.3 | 6.51 | 1.71 | —    | —    |
|       |                  | TC-3-2   | 12.0 | —    | 25.6  | 2.26 | 153  | —    | —   | 8.98 | 141  | 79.3 | 11.0 | —    | —    | —    |
|       |                  | TC-3-3   | 13.6 | 2.53 | 47.7  | 1.30 | 149  | 18.3 | 218 | 15.0 | 73.1 | 59.3 | 13.6 | —    | 0.29 | —    |
|       |                  | TC-3-4   | 206  | 4.83 | 13.2  | 2.62 | 1682 | —    | 378 | 33.1 | 103  | —    | 6.60 | 13.3 | —    | —    |
|       |                  | TC-14-1  | 7.88 | 4.70 | 10.5  | 0.83 | 83.4 | —    | 412 | —    | 100  | 40.8 | 8.00 | —    | 0.15 | 0.02 |
|       |                  | TC-14-2  | 7.55 | 5.20 | 24.4  | 1.39 | 93.4 | —    | 238 | 7.50 | 117  | 38.4 | 9.40 | —    | 0.16 | —    |
|       |                  | TC-14-3  | 9.37 | 5.60 | 22.9  | 2.04 | 107  | —    | 246 | —    | 108  | 72.8 | 9.20 | —    | —    | 0.06 |
|       |                  | TC-14-4  | 6.08 | 4.10 | 30.8  | 1.17 | 105  | —    | 230 | 22.8 | 97.0 | 36.4 | 10.4 | 1.35 | 0.31 | 0.07 |
|       |                  | TC-14-5  | 10.9 | 5.10 | 23.3  | 1.43 | 126  | —    | 295 | 18.9 | 104  | 51.8 | 7.60 | —    | 0.15 | 0.04 |
|       |                  | TC-14-6  | 11.3 | 4.00 | 39.0  | 1.89 | 120  | —    | 183 | 8.20 | 108  | 43.7 | 8.20 | —    | —    | —    |
|       |                  | TC-14-7  | 11.0 | 5.10 | 0.96  | 3.60 | 110  | —    | 183 | 8.10 | 87.0 | 44.2 | 6.30 | —    | —    | —    |
|       |                  | TC-14-8  | 10.3 | 3.60 | 3.66  | —    | 127  | —    | 180 | 5.70 | 108  | 43.8 | 6.20 | —    | —    | —    |
|       |                  | TC-14-9  | 10.4 | 4.00 | 1.93  | 1.56 | 107  | 24.7 | 277 | 7.70 | 116  | 39.1 | 6.00 | —    | —    | —    |
|       |                  | TC-14-10 | 10.4 | 3.70 | 5.50  | —    | 130  | 19.9 | 396 | —    | 87.0 | 68.6 | 7.60 | —    | —    | —    |
|       | V <sub>2</sub> 脉 | TC-21-1  | 12.9 | 3.70 | 1.70  | —    | 127  | —    | 341 | —    | 89.0 | 50.3 | 6.40 | 1.13 | —    | —    |
|       |                  | TC-21-2  | 10.6 | —    | 1.11  | —    | 106  | —    | —   | —    | 106  | 25.7 | 5.33 | 2.56 | —    | —    |
|       |                  | TC-21-3  | 9.93 | 4.10 | 1.33  | —    | 104  | 21.0 | 214 | —    | 74.0 | 20.2 | 5.80 | —    | —    | —    |
|       |                  | TC-21-4  | 13.2 | —    | 1.55  | 1.31 | 127  | —    | 255 | —    | 83.0 | 37.4 | 6.60 | —    | —    | —    |
|       |                  | TC-21-5  | 13.4 | 3.10 | 1.76  | 1.04 | 125  | —    | 242 | —    | 77.0 | 52.1 | 7.27 | —    | 0.09 | —    |
|       |                  | TC-21-6  | 11.5 | —    | 0.85  | —    | 102  | —    | —   | —    | 95.0 | 21.1 | 6.60 | —    | —    | —    |
|       |                  | TC-21-7  | 15.1 | —    | 1.87  | 3.70 | 312  | —    | 360 | 62.3 | 116  | 33.9 | 7.80 | —    | 0.36 | 0.07 |
|       |                  | TC-21-8  | 13.2 | 3.50 | 1.09  | 1.71 | 126  | —    | —   | —    | 107  | 36.5 | 7.40 | —    | —    | —    |
|       |                  | TC-21-9  | 11.6 | 3.70 | 0.79  | —    | 112  | —    | 340 | —    | 93.0 | 24.5 | 7.19 | —    | —    | —    |
|       |                  | TC-21-10 | 11.5 | 3.90 | 1.16  | —    | 105  | —    | —   | —    | 113  | 37.9 | 6.90 | —    | —    | —    |
|       |                  | TC-21-11 | 12.5 | 4.20 | 0.37  | —    | 121  | —    | 310 | —    | 126  | 37.1 | 5.00 | —    | —    | —    |
|       |                  | TC-21-12 | 10.8 | 3.60 | 0.83  | —    | 90.7 | —    | 440 | —    | 93.0 | 35.8 | 7.30 | —    | —    | —    |
|       |                  | TC-21-13 | 12.5 | 3.20 | 0.55  | 1.32 | 126  | —    | 260 | —    | 110  | 53.9 | 7.00 | —    | —    | —    |
|       |                  | TC-21-14 | 14.2 | 5.70 | 0.58  | —    | 132  | —    | 420 | —    | 95.0 | 35.5 | 7.20 | —    | —    | —    |
|       |                  | TC-10-1  | 9.06 | 4.73 | 6.39  | 1.97 | 136  | 19.8 | —   | —    | 87.4 | 59.7 | 7.12 | —    | —    | —    |
|       |                  | TC-10-2  | 6.58 | —    | 1.22  | —    | 72.1 | 17.6 | —   | —    | 90.2 | 57.1 | 8.31 | —    | —    | —    |
|       |                  | TC-10-3  | 34.7 | 5.65 | 72.4  | —    | 1067 | —    | —   | 251  | 131  | 19.1 | 7.30 | 3.98 | 0.35 | 0.35 |
|       |                  | TC-10-4  | 1.26 | —    | 10.1  | —    | 69.7 | —    | —   | —    | 98.7 | 26.9 | 7.03 | —    | —    | —    |
|       |                  | TC-10-5  | 3.81 | —    | 13.4  | —    | 67.1 | —    | 271 | 6.18 | 95.2 | 18.9 | 8.66 | —    | —    | —    |
|       |                  | TC-10-6  | 5.16 | —    | 1.06  | —    | 68.1 | —    | —   | —    | 112  | 23.8 | 6.83 | —    | —    | —    |
|       |                  | TC-10-7  | 1.29 | —    | 4.15  | —    | 63.2 | —    | 358 | —    | 74.9 | 25.7 | 7.50 | —    | —    | —    |
|       | V <sub>3</sub> 脉 | TC-3-K1  | 14.3 | 4.42 | 6.79  | 6.26 | 301  | 25.8 | 269 | 61.3 | 91.1 | 7.72 | 6.59 | —    | 0.27 | 0.06 |
|       |                  | TC-3-K2  | 320  | 13.2 | 37.2  | —    | 3349 | —    | —   | 56.7 | 94.0 | —    | 6.48 | 21.8 | —    | 0.07 |
|       |                  | TC-3-K3  | 79.8 | 8.88 | 41.1  | 1.02 | 1127 | 23.1 | 161 | 81.4 | 120  | 8.55 | 7.86 | 7.00 | —    | 0.21 |
|       |                  | TC-3-K4  | 141  | 4.65 | 3.16  | 1.27 | 1157 | —    | —   | —    | 116  | —    | 7.50 | 10.5 | —    | —    |
|       |                  | TC-3-K5  | 49.9 | 5.38 | 24.5  | —    | 680  | 46.6 | —   | 34.3 | 141  | —    | 7.35 | 11.4 | —    | 0.12 |
|       |                  | TC-3-K6  | 373  | 12.0 | 37.4  | —    | 3498 | 24.3 | 268 | 38.3 | 98.1 | —    | 6.74 | 17.0 | —    | 0.09 |
|       |                  | TC-3-K7  | 16.0 | 5.32 | 5.75  | —    | 222  | —    | 322 | —    | 92.4 | 6.59 | 7.36 | 2.07 | —    | —    |
|       |                  | TC-3-K8  | 10.0 | 4.56 | 13.2  | —    | 140  | 20.9 | —   | —    | 105  | 11.1 | 8.35 | 2.29 | —    | —    |
|       |                  | TC-3-K9  | 4.10 | 5.01 | 40.9  | —    | 107  | —    | 345 | 10.9 | 224  | 14.8 | 13.5 | —    | —    | 0.09 |
|       |                  | TC-3-K10 | 98.4 | 4.87 | 12.1  | —    | 1001 | —    | —   | 14.7 | 97.0 | —    | 6.56 | 7.15 | —    | 0.07 |
|       |                  | TC-3-K11 | 178  | 9.03 | 50.2  | —    | 2024 | —    | 318 | 99.1 | 89.2 | —    | 8.14 | 11.2 | 0.53 | 0.50 |

注：“—”代表无数据。