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长江中下游地区成矿作用研究新进展和存在问题的思考*

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摘 要 长江中下游地区是中国成矿理论的重要发源地之一，迄今已经完成大量研究，取得了一系列重要进展，前人已进行了多次总结。文章在此工作基础上，概括总结了最新的研究进展，并提出尚待解决的一些科学问题：该带成矿过程的深化研究和新测试、新技术的应用，有望破解层状铜金矿成因难题；越来越多单独或者伴生钨矿被发现，成矿显示多样性和多期次的特点。建立了该带矽卡岩型铜金矿+金稀散金属矿床组合新模型，有望推动在斑岩-矽卡岩型铜金矿外围发现贵金属和稀散金属矿床；研究发现该带含膏盐层在矽卡岩铁矿和玢岩铁矿的成矿过程中贡献明显；利用红外和矿物原位测试技术示踪该带深部矿化中心；通过三维找矿预测和成矿过程数值模拟，为隐伏矿找矿突破增添了新路径。最后，文章提出有待进一步研究的5个方面的科学问题，以期推动深化研究和找矿新突破。

关键词 地质学；层状铜金矿；关键金属；膏盐层；找矿新技术；长江中下游成矿带

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Metallogeny in Middle-Lower Yangtze River Ore Belt: Advances and problems remained

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Abstract

The Middle-Lower Yangtze River Ore Belt (MLYRB) has been a cradle of modern metallogeny in China. In this study, we summarized the new research advances from this century and raise some important scientific problems remained in the ore belt. Based on field investigation, geochronology and ore-forming process, employed with new techniques the stratiform massive Cu-Au ores, which mainly occur in a discordant boundary or along some dolomite layers, were delineated to be component of the Yanshanian porphyry-skarn Cu-Au ore system. In past ten years, more and more W deposits and W-bearing skarn Cu or Cu-Mo-Au deposits have been discovered, exhibiting that W is a new member of the porphyry-skarn Cu-Au-Mo-Fe ore belt. Since more Au, Tl, Te and the other dispersed metals were discovered and explored in the peripheral zones of some porphyry-skarn Cu-Au deposits, a new genetic mineral deposit model entitled in "Cu-Au skarn and distal Au and dispersed metal deposits" was set up, which will promote the discovery of precious and dispersed metals around the porphyry-skarn Cu-Au mines. Widespread evaporites in the Late Paleozoic carbonate rocks may play a key role in the formation of skarn

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iron and porphyry iron deposits. Three-D prospecting prediction and numerical simulation of ore-forming process provide new pathways for searching concealed ore bodies. Infrared and in-situ analysis techniques have been applied to prospecting in the belt, indicating a good start to use new technologies for prospecting. Although the ore belt has been well studied, the other five scientific problems listed are remained for further research.

Key words: geology, stratiform Cu-Au deposit, critical metals, evaporites, new techniques for prospecting, Middle-Lower Yangtze River Ore Belt

长江中下游地区是中国重要的铜多金属成矿带,也是中国成矿理论和成矿新认识的重要发源地之一。矿床成矿系列(程裕淇等,1979)、矿床成矿系统(翟裕生,1999)、玢岩铁矿成矿模式(宁芜研究项目编写小组,1978)、大陆断裂坳陷带中同生海底喷流铜矿(顾连兴等,1986)、层控矽卡岩(常印佛等,1991)及中生代大规模成矿和成矿大爆发(华仁民等,1999;毛景文等,1999)等具有中国特色的成矿理论均以长江中下游成矿带为基地或者与之密切相关。中国地质工作自早期以来,长江中下游地区始终是研究和找矿勘查的主要目标之一,并不断取得新成果与新进展。常印佛等(1991)、翟裕生等(1992)以及其他研究者分别对20世纪90年代之前的成果进行了系统的总结;而进入21世纪以来,矿床研究和找矿勘查的成果又呈爆发式产出,在工作程度这样高的地区找矿又有新突破,相关的新认识和新技术应用不断涌现。常印佛等(2017)、Mao 等(2011)、Xie 等(2015)和周涛发等(2017)对成矿时代、成矿规律和矿床模型等方面进行了深入的研究总结。文章在前人工作基础上,进一步梳理和总结了近年来研究工作的主要进展,提出若干尚待进一步解决的问题,以期与同行交流讨论。

1 层状铜金矿的成因认识在争议中前进

长江中下游地区以冬瓜山和新桥为代表的层状铜金矿的成因是大家关注的科学问题,自从20世纪50年代以来,存在同生沉积成矿(同生海底喷流成矿)与燕山期花岗岩有关的岩浆热液系统成矿的争议。Pan 等(1999)通过综合研究认为长江中下游地区铜多金属矿床属于斑岩-矽卡岩系统,毛景文等(2009)通过与世界上典型的产于以火山岩为容岩的海底喷流型块状硫化物铜矿对比,认为铜陵矿集区冬瓜山和新桥主要层状矿体产于不整合界面,并非是深海喷流沉积环境,广泛发育的碳酸盐岩也指示出滨海环境;层状块状硫化物矿体中的层纹状和曲卷状构造为镁质矽卡岩退化蚀变过程自组织的结果,而胶状含铜金黄铁矿为来自岩浆流体在后碰撞滑覆构造和扩容空间快速沉淀,是凝华的产物;层状矿体为流体沿层交代而形成,即西方国家通常称谓的Manto型矿体。

最近,Zhang 等(2017)获得新桥铜金矿区矶头花岗闪长岩的锆石U-Pb 年龄为(139.6 ± 1.5)Ma,与层状矿体底盘网脉状矿(曾经被认为是同生成矿的补给通道)中石英流体包裹体 Rb-Sr 等时线年龄(138.0 ± 2.3 Ma)基本一致,表明两者具有密切的成因联系。对新桥铜金矿床的铁同位素研究表明,其是岩浆与地层的交代形成的矽卡岩矿床(Wang et al., 2011)。Liu 等(2019)对冬瓜山铜矿进行解剖研究,通过流体包裹体、硫和铅同位素示踪研究发现从矽卡岩、退化蚀变岩和热液硫化物是一个连续过程,表明成矿与岩浆流体具有一致性。Li 等(2017; 2018)通过对层状矿体中胶状黄铁矿 Re-Os 同位素和微量元素的精确测试,不仅厘定新桥铜金矿形成于(136.7±4.6)Ma,而且证明成矿物质主要来自于岩浆热液。此外,还发现岩浆-热液作用造成富含金属元素的沉积岩(即黑色页岩)和早期矿化中的金属元素再循环是成矿的重要机制(Li et al., 2018)。因此,应用新测试技术对成矿过程进行深化研究,有望破解关于层状铜金矿床成因的难题。

2 发现了越来越多的独立或伴生钨矿,成为新的研究热点

早在20世纪80年代,就有部分学者提到长江中下游成矿带发育有钨矿(孙加富, 1984;杨松生等, 1985;常印佛等,1991)。阮家湾钨矿床位于鄂东南矿集区阳新岩体南端,为一大型矽卡岩型钨铜矿床,该矿床于1955年发现,已探明WO_3资源量60 300吨,品位为0.26%~0.41%,Cu资源量6300吨,品位为0.52%~1.37%(舒全安等,1992),其成岩年龄为(143±1)Ma(锆石和榍石U-Pb年龄),成矿年龄为(143±2)Ma(辉

钼矿 Re-Os年龄)(Xie et al., 2007; 颜代蓉, 2012)。

谢桂青团队通过对比研究阮家湾、龙角山-付家山矽卡岩钨铜矿与铜山口矽卡岩铜钨矿床的特征,提出矽卡岩铜矿存在上铜下钨的分带特征,钨矿化与铜矿化是同一热液成矿系统的产物,为氧化性矽卡岩钨矿,地层含碳量对氧化性矽卡岩钨矿的形成有明显的影响(谢桂青等,2013;朱乔乔等, 2019; 纪云昊等,2019),氧化性矽卡岩钨矿的认识也得到龙角山-付家山矽卡岩钨铜矿的地球化学证据的佐证(Lei et al., 2018)。九瑞矿区的通江岭铜钨矿是新发现的矽卡岩型矿床,目前正在勘查中,其中M9矿体为区内规模最大的铜钨矿体,走向延伸超1200 m,倾向延深超500 m,真厚度10.43~27.66 m;Cu品位多介于0.45%~0.68%,最高可达9.73%;WO_3品位多介于0.05%~0.17%,矿石矿物以黄铜矿、白钨矿为主,矿石构造以浸染状、细脉—网脉状为主。矿体具有“上铜下钨铜”的矿化分带特征,与成矿有关的花岗闪长斑岩的锆石U-Pb年龄为(143.31±2.70)Ma(王先广等,2019)。

类似于钦杭成矿带中的永平、龙头岗、东乡、铜山口和大宝山等Cu-W矿床(毛景文等,2011),长江中下游越来越多斑岩-矽卡岩型铜多金属矿床中发现钨是重要的伴生组分,钨矿物均为白钨矿。常印佛等(1991)提出铜陵矿集区铜官山和狮子山矿田白钨矿主要见于矿体上部的矽卡岩中,多产于岩体附近甚至内矽卡岩中,新发现的姚家岭锌金矿床矽卡岩中可见少量的白钨矿(钟国雄等, 2014)。近年来,大冶和九瑞矿集区深部钻孔资料表明矽卡岩铜矿床深部可见到钨矿体和钨铜共生矿体,如铜山口深部发现厚大的钨矿体和钨铜共生矿体,西部500 m深部可见厚30 m钨矿体,WO_3平均品位为0.12%(朱乔乔等, 2019)。武山和东雷湾矽卡岩铜矿床中可见白钨矿主要产于含铜矽卡岩和含铜块状黄铁矿矿石中,如武山矿区西部可见3.18 m厚钨矿体,WO_3平均品位0.72%(与王先广通讯交流)。甚至在庐枞矿集区龙桥铁矿床磁铁矿矿体中可见白钨矿矿脉(周涛发等, 2019)。

除了与铜矿共生的钨矿外,近年来还在该成矿带发现几个钨钼矿床。在庐枞盆地北侧探明的东顾山大型矽卡岩型钨钼矿床,WO_3资源量72 500吨,平均品位0.19%(周涛发等,2019),主要金属矿物为白钨矿、辉钼矿、方铅矿、闪锌矿以及少量磁铁矿、黄铁矿和黄铜矿。该矿床围岩蚀变主要为矽卡岩化,矽卡岩矿物主要有石榴子石、透辉石、透闪石、硅镁石等。辉钼矿 Re-Os同位素年龄为(97.22±0.70)Ma;成矿金属元素在空间上具有一定的分带性,其总的分带趋势是:由岩体一侧的内矽卡岩→外矽卡岩→碳酸盐围岩,矿化分带为Mo→Mo-W→W-Pb-Zn→Pb-Zn;而金属元素由上而下的垂直分带大致为:Pb-Zn-Ag→Pb-Zn-Cu→W-Mo(周涛发等,2019)。长江中下游中段南部边缘探明的高家塝W-Mo矿床,与阳新-常州断裂南侧的几个规模较小的钨矿如百丈岩、鸡头山和马头均处于九华复合花岗质岩体的外接触带,其成岩成矿时代为146~136 Ma(秦燕等,2010;Song et al., 2012; Li et al., 2015)。最近,在该区探明的桂林郑钨钼矿床,控制WO_3资源量44 000吨,平均品位0.09%,Mo资源量15 000吨,平均品位0.13%;Zn+Pb储量210 000吨、平均品位4.62%。但桂林郑钨钼矿床辉钼矿 Re-Os年龄为127.5Ma,与成矿有关的花岗斑岩的锆石U-Pb年龄为(127.6±1.5)Ma(陈雪峰,2017)。

现有研究成果及资料表明,长江中下游成矿带中钨的成矿作用可以分为2期,分别为146~136 Ma和127~97 Ma,这与长江中下游南侧与之平行的江南钨矿带基本相同(毛景文等,2020),两期成矿可能分别与古太平洋板片俯冲和后俯冲有关。越来越多的独立或伴生钨矿床,以及钨矿化与其他金属矿化的时空关系,已经成为长江中下游铜多金属成矿带新的研究热点,而矿床中金属的空间分带现象,也为深部找矿提供了新的思路。

3　建立斑岩-矽卡岩型铜金矿+远接触带金-稀散金属矿床模型

长江中下游成矿带多数矽卡岩铜矿共伴生金,据统计金资源储量超过600吨,铜与金含量呈明显正相关性,为氧化性含金矽卡岩矿床(Zhao et al., 1999)。根据已有的勘探报告资料,长江中下游多处矽卡岩铜金矿床共、伴生碲、硒、铊等稀散金属,而其中的63%集中于九瑞和鄂东南矿集区,例如,铜绿山矿床的碲含量达到工业品位(136×10^{-6})(程志中等, 2012),城门山矿床的碲资源储量为5571吨(中国矿床发现史江西卷编委会, 1996)。在矽卡岩铜金矿外围的碳酸盐岩中发现了多个受断裂控制的热液低温金矿床,如鄂东丰山矿田(谢桂青等, 2017)。在铜陵矿集区发现产于志留纪碎屑岩受断裂控制的金矿床,如杨冲里和亮石山金矿(段留安等, 2013),以细网脉和微细粒浸染状矿石为特征,与金伴生有Tl、Hg和Te等稀散元素,具有类卡林型金矿的基本特点。

以丰山矿田中矽卡岩铜金矿和外围的金矿为例，谢桂青等（2017）通过系统研究，提出产于碳酸盐岩的低温金矿床属于远接触带岩浆热液产物，是长江中下游成矿带新矿床类型，并认为这类低温金矿床与矽卡岩铜金矿床属于同一成矿系统（Xie et al., 2019），主要依据如下：① 矽卡岩铜金矿床中存在大量Bi-Te矿物，低温金矿床中亦有大量碲化物和自然金，低温金矿与矽卡岩铜金矿中的金砷矿体有类似的雄黄+雌黄和碲汞矿（HgTe）矿物组合；② 低温金矿与矽卡岩铜金矿的成矿时代基本一致，分别为~146 Ma和144~149 Ma；③ 低温金矿与矽卡岩铜金矿硫化物的硫同位素（$\delta^{34}S$）类似，分别为−4.8‰~+2.6‰和−2.5‰~+6.4‰。

红铊矿是稀散元素铊矿床中最重要的矿石矿物，曾在美国卡林型金矿床和贵州滥木厂铊汞矿床中发现（Anthony et al., 1990），在矽卡岩成矿系统中未见红铊矿和铊矿化的报道。通过拉曼和XRD等研究，在丰山矿田矽卡岩成矿系统的远接触带金矿床中发现了红铊矿，矿石w(Tl)高达2016×10^{-6}，是铊矿床工业品位（1000×10^{-6}）的2倍以上，与传统远接触带浸染状银金矿相比，长江中下游远接触带低温金矿床具有独特的Au-Tl组合。结合元素分带，建立了矽卡岩铜金矿床+远接触带低温金-稀散金属矿床组合新模型（Xie et al., 2019）。该矿床模型指示在长江中下游成矿带及其具有类似成矿背景的成矿带中，关注在斑岩-矽卡岩型铜金矿外围寻找低温金矿床和稀散元素矿床。

4 膏盐层普遍存在，并在成矿过程中贡献明显

在长江中下游多金属成矿带中发育大量130 Ma左右的玢岩铁矿（或者Iron oxide-apatite deposit，简称IOA）和矽卡岩型铁矿，集中分布于宁芜、庐枞和鄂东南3个矿集区。铁矿床的发育与三叠纪膏盐层存在密切的空间关系，铁矿中石膏广泛发育，并在一些矿床中形成独立的石膏矿体，铁矿床-石膏矿-硫铁矿空间上紧密共生。铁矿床中硫酸盐和硫化物均具有较高的$\delta^{34}S$同位素值（毛景文等，2012；朱乔乔等，2013；2018李延河等，2013；2014；周涛发等，2014；Xie et al., 2015；Zhu et al., 2015；Li et al., 2016; Liu et al., 2018;）及较高比例的地层硫的参与（李延河等，2014；朱乔乔等，2018），指示膏盐层参与了成矿过程。

对铁矿床C、Sr-Nd、He-Ar、Pb、B等同位素和矿物学的研究亦证实了膏岩层参与成矿（周涛发等，2014；Li W et al., 2016；2019；Zhu et al., 2015；朱乔乔等，2016；刘一男等，2017；Zeng et al., 2016；Su et al., 2019；Duan et al., 2019）。李延河等（2014）提出膏盐层在岩浆阶段就加入到成矿体系中，将岩浆熔体中的Fe^{2+}氧化成Fe^{3+}，使Fe^{3+}无法进入辉石和角闪石等造岩矿物，而形成铁氧化物和不含铁的透辉石和透闪石等，石膏与透辉石、透闪石组合在玢岩铁矿中普遍存在，被称为"膏辉岩"；同时模拟实验得出较高的氧逸度可以促进岩浆体系中富铁熔体和富硅熔体的两相分离，形成矿浆型铁矿（Hou et al., 2018）。Li等（2019）对程潮矽卡岩型铁矿床的研究发现，成矿流体具有高温、高盐度特征，膏岩层在石榴子石和辉石矽卡岩形成阶段已经加入流体。朱乔乔等（2013）和Zhu等（2015）研究发现金山店矽卡岩型铁矿床广泛发育有富氯方柱石和富氯角闪石，推测含膏盐层在早期高温岩浆热液阶段已经加入到金山店铁矿成矿体系之中。高温、高盐度的流体特征存在于梅山、凹山、罗河和泥河等玢岩型铁矿床中（Li et al.，2015）。对梅山、罗河和泥河等玢岩铁矿床石榴子石、辉石中流体包裹体的研究显示，成矿流体富含Na^+、K^+、Ca^{2+}、Fe^{2+}、Cl^-和不同含量的SO_4^{2-}，同时它们的Cl^-/Br^-、Na^+/K^+和Na^+/B^+比值介于岩浆流体和蒸发盐之间，表明膏盐层在铁矿床成矿的高温阶段已经加入到成矿体系（Li et al.，2015）并发挥了重要的作用。对凹山铁矿床不同成矿阶段磁铁矿微区成分特征的研究发现，铁矿床成矿过程4个阶段中成矿流体的氧逸度变化不大，富含膏盐的地层在成矿过程的不同阶段不断加入到成矿系统（Duan et al.，2019）。此外，段超等（2012）利用锆石微量元素计算获得凹山铁矿床成矿岩体辉石闪长玢岩的氧逸度很低，而岩浆-热液成矿系统的氧逸度却很高，表明膏岩层加入成矿系统的最早时间可能在岩浆锆石结晶之后。膏岩层富含的K、Na、Ca、Cl等元素进入成矿系统，提高了Fe在流体中的溶解度，促进了铁质富集。同时，膏盐层的加入使成矿系统中Na^+的浓度大幅提高，导致了在长江中下游多金属成矿带玢岩型铁矿和矽卡岩型铁矿中大规模的钠长石化/钠柱石化/方柱石化的出现。膏盐层将Fe^{2+}氧化成Fe^{3+}并富集形成铁矿床的同时，石膏等硫酸盐自身被还原，形成H_2S/S^{2-}，向成矿系统提供硫源，S^{2-}与Fe^{2+}结合，形成黄铁矿等硫化物，使得铁矿床中磁铁矿、硫铁矿与石膏矿三者空间上密切相关（李延河等，2014），

例如:庐枞矿集区中罗河和泥河铁矿以及宁芜矿集区中与玢岩型铁矿床密切相关的硫铁矿床。膏盐在岩浆-热液作用过程中发生迁移和再沉淀,形成石膏脉(矿体),例如,罗河铁矿床、程潮铁矿床、金山店铁矿床,李延河等(2013; 2014)提出了"双层成矿结构",认为在中生代火山盆地深部岩体与膏盐层的接触部位能够产出"大冶式"充填-接触交代型富铁矿床,规模可能超过了赋存于浅部火山-次火山中的狭义"玢岩铁矿"。通过对鄂东矿集区矽卡岩铜、铁矿床的含矿地层、伴生热液硬石膏规模、方柱石成分和He-Ar-S同位素的系统研究,Xie 等(2015; 2019)提出膏盐层参与矽卡岩铁矿床成矿作用的比例大于矽卡岩铜铁矿床。

5 红外(SWIR)等测试技术示踪矿体及矿化中心研究取得新进展

运用红外技术(Short wavelength infra-red, 简称SWIR)开展热液矿床的蚀变填图和钻孔编录在西方发达国家广泛应用,以至于成为矿权上市不可或缺的地质内容。西方国家早在20世纪末和21世纪初就开展了这项工作(Hauff et al., 1992; Yang et al., 1999; 2001; Thompson et al., 1999),而中国仅有零星研究,主要是针对围岩蚀变发育的斑岩-浅成低温热液型矿床(章革等,2005;连长云等,2005;杨志明等,2012;郭娜等,2018a;2018b)和脉状金矿(赵利青等,2008;曹烨等,2008),并开始尝试进行蚀变填图,取得了初步进展,但在中国尚未广泛推广应用。

周涛发团队以长江中下游成矿带中沙溪斑岩型铜金矿床为对象,利用 LA-ICP-MS 技术对沙溪斑岩型铜金矿床中绿泥石进行了主微量元素成分的空间变化研究,探讨绿泥石的地球化学特征及其对矿化中心的指示意义,试图建立陆内环境斑岩型矿床绿泥石地球化学特征找矿模型。结果显示沙溪铜金矿床绿泥石中 Ti、Ba、Co、K、Pb、Sr、Fe、V/Ni 靠近矿化中心的位置含量高,Mn、Mg 元素远离矿化中心的位置含量高(何光辉等,2018)。矿床中绿泥石元素含量分布主要受温度、被交代矿物、流体 pH 值和氧化还原环境、围岩性质影响。受交代矿物的影响,绿泥石中的有些元素(Si、Na、Mg、K、Al)的含量的高低不能直接对矿化中心进行指示,但有些元素(Ti、Ba、Co、Pb、Sr、Fe)和元素比值(V/Ni)具有指示斑岩矿化中心的作用。通过对鄂东南矿集区的铜绿山矽卡岩Cu-Fe-Au矿床、鸡冠嘴矽卡岩Cu-Au矿床以及铜山口矽卡岩-斑岩Cu-Mo-W矿床开展SWIR的研究,揭示出主要蚀变矿物SWIR特征值的指示规律(张世涛等,2017;陈华勇等,2019),并进一步提取各个矿床的蚀变矿物SWIR勘查标志,如铜绿山矿床富Fe绿泥石(Pos2250>2253 nm)、高结晶度高岭石族(Pos2170>2170 nm, Dep2170>0.18)、白云母族-蒙脱石异常 Pos2200 值(>2212 nm 或<2202 nm)、高岭石、迪开石及皂石的大量出现,可以作为铜绿山矿床有效的蚀变矿物勘查标志;鸡冠嘴矿床白云母族-蒙脱石 Pos2200 特征值的高值(>2209 nm)区域对矿体位置具有较好的指示性;铜山口矿床绿泥石的高Fe-OH吸收峰位值(Pos2250>2249 nm)和高 Mg-OH 吸收峰位值(Pos2335>2333 nm)的高频出现,可以作为铜山口矿床的有效勘查标志。这些研究成果表明蚀变矿物可以为鄂东南矿集区提供有效的勘查标志体系,同时,这些勘查标志也在铜绿山铜铁金矿床得到了初步的应用。

6 三维找矿预测及成矿过程数值模拟,助推隐伏矿找矿突破

近年来,随着深部找矿工作的需要,三维成矿预测及成矿过程数值模拟发展迅速,为隐伏矿找矿突破提供了新方法,三维成矿预测方法体系在实践中已逐步形成(陈建平等,2007;毛先成等,2011;肖克炎等,2012;袁峰等,2014),特别是已开发出较为成熟的三维成矿预测软件系统,其中以中国地质科学院"探矿者"(肖克炎等,2010)、中国地质大学"GeoCube"(Li et al., 2016)及合肥工业大学"GeoPMS3D"(李晓晖等,2017)为代表,基本实现了成矿预测从二维向三维的发展(袁峰等,2019a; b)。同时,成矿过程数值模拟这一新方法在成矿作用和成矿预测领域的研究和实践也逐渐深入,有望成为研究成矿过程和进行隐伏矿床预测的新的有力工具(Weis et al. , 2012; Ord et al., 2012)。

目前,长江中下游成矿带已经成为国内开展三维成矿预测及成矿过程数值模拟研究与实践程度最高的地区之一,并以多尺度(矿田-矿床)三维成矿预测为特征。矿田尺度上,Lü 等(2013)针对铜陵矿集区狮子山矿田开展了三维地质建模,通过分析岩体和赋矿地层的三维空间关系,指出深部找矿方向并圈定深部找矿靶区。毛先成等(2010)基于三维成矿预测方法,在铜陵矿集区凤凰山矿田深处圈定找矿靶区,

并提供预测品位和金属量等信息。Li 等(2015; 2019)基于自主研发的“GeoPMS3D”系统,融合三维隐式建模、三维空间分析、三维物性反演和三维成矿预测,对宁芜矿集区钟姑矿田和安庆贵池矿集区月山矿田,分别开展了玢岩铁矿床和矽卡岩型铜铁多金属矿床的深部隐伏矿床预测,取得了较好的预测效果。

矿床尺度上,Yuan 等(2014)对宁芜盆地白象山玢岩型铁矿床开展了综合三维成矿预测,在已知矿体深部、边部圈定多处找矿靶区。Hu 等(2018)基于特征分析法,在宁芜盆地杨庄玢岩型铁矿床取得了定位、定深度、定储量的三维成矿预测效果。在庐枞矿集区沙溪斑岩型铜金矿床,Li 等(2017)在三维空间对二维裂隙化探数据与三维矿化信息进行耦合分析,进而圈定深部靶区并给出有利找矿深度。Zhang等(2019)对月山矿田朱冲矽卡岩型铁铜矿床开展了大比例尺三维成矿预测,同时还对三维预测方法进行了系统对比研究。

成矿过程数值模拟作为一种新的方法手段,在矿床学和成矿预测的定量化发展方面显示了很好的潜力。贾蔡等(2014; 2018)对宁芜矿集区开展了矿田和矿床尺度的成矿过程数值模拟研究,在多物理场耦合条件下分析了矿体形态与流体运移的关系,并预测圈定了找矿靶区。Liu 等(2010)分别对铜陵矿集区铜山铜矿床和安庆贵池矿集区安庆铜铁矿床开展了基于成矿过程数值模拟的矿床深部靶区预测研究。Hu 等(2019)对南陵-宣城矿集区麻姑山矽卡岩型钼铜矿床开展了耦合物理和化学场的成矿过程数值模拟,定量评价了矿床北部隐伏岩枝的含矿性。Li 等(2019)基于三维数值模型,对月山矿田开展了矽卡岩型矿床热液运移和汇聚过程数值模拟,为三维成矿预测提供了新的预测约束信息,极大地提高了三维成矿预测能力。在南陵-宣城矿集区最新发现的茶亭斑岩型铜矿床,Hu等(2020)开展了多场耦合成矿过程数值模拟,提出茶亭矿床在钻孔控制外的−1800 m以下仍然具有较好成矿潜力,同时基于模拟给出的定量化信息,认为矿床的成矿持续时间应在十万年尺度以内。

7 科学问题及进一步找矿勘查的思考

尽管长江中下游成矿学研究和找矿工作不断深入,取得了一系列重要进展,但仍然存在不少科技难题有待攻克,找矿勘查的难度日益增大,作者就如何实现找矿重要突破,提出以下几个问题供参考。

(1) 查明为什么在长江中下游成矿带斑岩-矽卡岩铜多金属矿床中有大量伴生钨?铜钨共生产出机制是什么?钨和锡具有类似的地球化学性质,在地质循环中通常共生成矿,为什么在这种与氧化性高的钾钙碱性花岗质岩体有关的钨矿中,锡明显缺失,其控制因素是什么?

(2) 以冬瓜山和新桥矿床为代表的层状铜金矿被证明是与岩浆热液成矿系统的组成部分,甚至早期存在的沉积硫化物在成矿过程中可能已经被完全改造,那么在远离燕山期高钾钙碱性花岗质岩体的赋矿地层中是否存在原始沉积硫化物层?如果存在,这些硫化物对于燕山期成矿的贡献如何?亟待查清楚。

(3) 按照斑岩-矽卡岩铜金矿床+远接触带低温金-稀散金属矿床组合模型,有必要对长江中下游地区某些斑岩-矽卡岩型铜金矿外围开展系统调查研究,有望发现更多金矿和稀散元素矿床,也必将进一步检验和发展提出的初步矿床模型。

(4) 面对矽卡岩成矿系统和成矿过程的复杂性,三维成矿预测过程需要进一步挖掘约束信息以提高预测的有效性和精度,其理论和方法体系有待不断发展完善;成矿过程数值模拟则面临与矿床学理论有效融合的问题以及“力-热-流-化学”多场耦合的技术瓶颈。

(5) 就整个长江中下游成矿带比较而言,九瑞矿集区及邻区剥蚀程度较浅,目前出露地表的都是小岩株或者隐伏岩体,推测深部进一步找矿潜力很大,运用现代“三位一体”理念和新的隐伏矿床找矿方法开展找矿勘查,有望取得进一步的找矿新突破。

致 谢 本文是在前人工作基础上的总结研究成果,为了尽量不与前人近十年的成果总结的重复,此次仅选择部分成果进行了总结。资料浩瀚,在总结研究过程中难免挂一漏万,不足之处,敬请各位同行批评指正。今年适逢矿床学界两位大师翟裕生院士和常印佛院士90华诞,两位先生对长江中下游成矿带的科学研究和找矿勘查做出了杰出贡献。作者以此文表达对两位先生的衷心祝福,祝愿他们健康长寿,继续指引中国矿床学研究取得更辉煌的成就。衷心感谢华仁民教授和蒋少涌教授在百忙之中审稿,提出诸多建设性建议和意见,明显提升了本论文的质量。

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