

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

中图分类号: P618.4

文献标志码: A

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, Ti, 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

* 本文得到国家自然科学基金项目(编号:41820104010、41925011)资助

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收稿日期 2020-05-11; 改回日期 2020-07-11。赵海杰编辑。

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)、大陆断裂拗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)获得新桥铜金矿区矾头花岗闪长岩的锆石U-Pb年龄为 $(139.6 \pm 1.5)\text{Ma}$,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 $(138.0 \pm 2.3\text{Ma})$ 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 $(136.7 \pm 4.6)\text{Ma}$,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 $(143 \pm 1)\text{Ma}$ (锆石和榍石U-Pb年龄),成矿年龄为 $(143 \pm 2)\text{Ma}$ (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 $(143.31 \pm 2.70) Ma$ (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% (与王先广沟通交流)。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 $(97.22 \pm 0.70) Ma$; 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 $Mo \rightarrow Mo-W \rightarrow W-Pb-Zn \rightarrow Pb-Zn$; 而金属元素由上而下的垂直分带大致为: $Pb-Zn-Ag \rightarrow Pb-Zn-Cu \rightarrow W-Mo$ (周涛发等, 2019)。长江中下游中段南部边缘探明的高家塆 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 127.5 Ma,与成矿有关的花岗斑岩的锆石 U-Pb 年龄为 $(127.6 \pm 1.5) Ma$ (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碲矿体有类似的雄黄+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($\delta^{34}\text{S}$)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 $w(\text{Ti})$ 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-Ti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 $\delta^{34}\text{S}$ 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,形成岩浆型铁矿(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 $\text{H}_2\text{S}/\text{S}^{2-}$,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“Geo-Cube”(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。

References

Anthony J W, Bideaux R A, Bladh K W and Nichols M C. 1990. Hand-

- book of mineralogy[M]. Chantilly: Mineralogical Society of America. 4129.
- Cao Y, Li S R, Shen J F, Yao M J, Li Q K and Mao F L. 2008. Application of portable infrared mineral analyzer (PIMA) in the Qianhe gold mine, Henan Province[J]. *Geology and Prospecting*, 44(2): 82-86(in Chinese with English abstract).
- Chang Y F, Liu X P and Wu C Y. 1991. The copper-iron belt of the Lower and Middle Reaches of the Changjiang River[M]. Beijing: Geological Publishing House. 379(in Chinese with English abstract).
- Chang Y F, Zhou T F and Fan Y. 2017. Review of exploration and geological research progress in the Middle Lower Yangtze River Valley metallogenic belt[J]. *Acta Petrologica Sinica*, 33(11): 3333-3352(in Chinese with English abstract).
- Chen H Y, Zhang S T, Chu G B, Zhang Y, Cheng J M, Tian J and Han J. 2019. The short wave infrared (SWIR) spectral characteristics of alteration minerals and applications for ore exploration in the typical skarn-porphyry deposits, Edong ore district, eastern China[J]. *Acta Petrologica Sinica*, 35(12): 3629-3643(in Chinese with English abstract).
- Chen J P, Lü P, Wu W, Zhao J and Hu Q. 2007. A 3D method for predicting blind orebodies, based on a 3D visualization model and its application[J]. *Earth Science Frontiers*, 14(5): 54-62(in Chinese with English abstract).
- Chen X F, Zhou T F, Zhang D Y, Xiong Z Y, Lv Q L, Yuan F, Ren Z and Fan Y. 2017. Geochronology, geochemistry and geological characteristics of the granite porphyry beneath Guilinzheng Mo deposit, Chizhou, southern Anhui[J]. *Acta Petrologica Sinica*, 33(10): 3200-3216(in Chinese with English abstract).
- Cheng Y Q, Chen Y C and Zhao Y M. 1979. Preliminary discussion on the problems of minerogenetic series of mineral deposits[J]. *Acta Geoscientia Sinica*, 1(1): 32-58(in Chinese with English abstract).
- Cheng Z Z, Xie X J, Pan H J and Yang R. 2012. Tellurium geochemistry of South China[J]. *Geology in China*, 39(2): 295-301(in Chinese with English abstract).
- Duan C, Li Y H, Mao J W, Hou K J and Yuan S D. 2012. Zircon trace element characteristics of intrusions in the Washan iron deposit of Ningwu volcanic basin and their geological significance[J]. *Geology in China*, 39(6): 1882-1892(in Chinese with English abstract).
- Duan C, Li Y H, Mao J W, Hou K J, Wang C L, Yang B Y, Wang Q and Li W. 2019. Ore formation at the Washan iron oxide-apatite deposit in the Ningwu ore district, eastern China: Insights from in situ LA-ICP-MS magnetite trace element geochemistry[J]. *Ore Geology Reviews*, 112, 103064.
- Duan L A, Yang X Y, Liu X M and Sun W D. 2013. Discovery of gold deposit in the Silurian system in Shujiadian, Tongling ore cluster region and its significance[J]. *Geotectonica et Metallogenia*, 37(2): 333-339(in Chinese with English abstract).
- Gu L X and Xu K Q. 1986. On the South China type massive sulfide ore deposits formed in marine fault depression troughs on the continental crust[J]. *Mineral Deposits*, 5(2): 1-13(in Chinese with English abstract).
- Guo N, Liu D, Tang J X, Zheng L, Huang Y R, Shi W X, Fu Y, Tang N and Wang C. 2018a. Characteristics of alteration minerals and prospecting model revealed by shortwave infrared technique: Take Sinongduo Ag-Pb-Zn deposit as an example[J]. *Mineral Deposits*, 37(3): 556-570(in Chinese with English abstract).
- Guo N, Shi W X, Huang Y R, Zheng L, Tang N, Wang C and Fu Y. 2018b. Alteration mapping and prospecting model construction in the Tiegelongnan ore deposit of the Duolong ore concentration area, northern Tibet, based on shortwave infrared technique[J]. *Geological Bulletin of China*, 37(2/3): 446-457(in Chinese with English abstract).
- Hauff P L and Cocks T. 1992. Short wave infra-red spectroscopy techniques applied to exploration: Emphasis for alteration mineralogy[J]. *Contribution to Economic Geology Research Unit*, 44: 72-74.
- He G H, Zhou T F, Fan Y, Wang S W and Xiao Q L. 2018. Geochemical characteristics and exploration implications of chlorite in Shaxi porphyry copper gold deposit, Lujiang[J]. *Mineral Deposits*, 37(6): 1247-1259(in Chinese with English abstract).
- Hou T, Charlier B, Holtz F, Veksler I, Zhang Z C, Thomas R and Namur O. 2018. Immiscible hydrous Fe-Ca-P melt and the origin of iron oxide-apatite ore deposits[J]. *Nature Communications*, 9: 1415.
- Hu X Y, Yuan F, Li X H, Jowitt S M, Jia C, Zhang M M and Zhou T F. 2018. 3D characteristic analysis-based targeting of concealed Kiruna-type Fe oxide-apatite mineralization within the Yangzhuang deposit of the Zhonggu ore field, southern Ningwu volcanic basin, middle-lower Yangtze River metallogenic belt, China[J]. *Ore Geology Reviews*, 92: 240-256.
- Hu X Y, Li X H, Yuan F, Jowitt S M, Ord A, Li Y, Dai W Q, Ye R and Zhou T F. 2019. Numerical simulation based targeting of the Magushan skarn Cu-Mo deposit, Middle-lower Yangtze Metallogenic belt, China[J]. *Minerals*, 9: 588.
- Hu X Y, Li X H, Yuan F, Ord A, Jowitt S M, Li Y, Dai W Q and Zhou T F. 2020. Numerical modeling of ore-forming processes within the Chating Cu-Au porphyry-type deposit, China: Implications for the longevity of hydrothermal systems and potential uses in mineral exploration[J]. *Ore Geology Reviews*, 116, 103230.
- Hua R M and Mao J W. 1999. A preliminary discussion on the Mesozoic metallogenic explosion in East China[J]. *Mineral Deposits*, 18(4): 300-308(in Chinese with English abstract).
- Ji Y H, Xie G Q, Zhu Q Q, Sun X F and Li X H. 2019. Influence of carbonaceous strata on skarn tungsten deposits: A case study of the Fujiashan deposit in eastern Hubei Province[J]. *Mineral Deposits*, 38: 917-934(in Chinese with English abstract).
- Jia C, Yuan F, Li X H, Hu X Y, Liao B S, Sun W A, Zhang M M and Shen L. 2018. Metallogenic dynamics simulation based on multi-source data constraint: A case study of the typical deposit in Zhonggu ore field in Ningwu basin[J]. *Chinese Journal of Geology*, 53(4): 1327-1346(in Chinese with English abstract).

- Jia C, Yuan F, Zhang M M, Li X H, Zhou T F, Shao W, Zheng T K and Gao D M. 2014. Numerical simulation of the process of deposit formation in Baixiangshan iron deposit, Ningwu basin[J]. *Acta Petrologica Sinica*, 30(4): 1031-1040(in Chinese with English abstract).
- Jiangxi Volume Editorial Committee of the History of Mineral Deposit Discovery in China. 1996. History of mineral deposit discovery in China (Jiangxi volume)[M]. Beijing: Geological Publishing House. 1-245(in Chinese).
- Lei X F, Duan D F, Jiang S Y and Xiong S F. 2018. Ore-forming fluids and isotopic (H-O-C-S-Pb) characteristics of the Fujiashan-Longjiaoshan skarn W-Cu-(Mo) deposit in the Edong district of Hubei Province, China[J]. *Ore Geology Reviews*, 102: 386-405
- Li C H, Jiang Y H, Xing G F, Guo K Y, Li C, Yu M G, Zhao P and Wang Z. 2015. Two periods of skarn mineralization in the Baizhangyan W-Mo deposit, Southern Anhui Province, Southeast China: Evidence from zircon U-Pb and molybdenite Re-Os and sulfur isotope data[J]. *Resource Geology*, 65: 193-209.
- Li R, Wang G W and Carranza E J M. 2016. GeoCube: A 3D mineral resources quantitative prediction and assessment system[J]. *Computers & Geosciences*, 89: 161-173.
- Li W T, Audétat A and Zhang J. 2015. The role of evaporites in the formation of magnetite-apatite deposits along the Middle and Lower Yangtze River, China: Evidence from LA-ICP-MS analysis of fluid inclusions[J]. *Ore Geology Reviews*, 67: 264-278.
- Li W, Xie G Q and Zhu Q Q. 2016. He-Ar-S-Pb isotopic compositions of pyrite: Constraints on the source of ore-forming materials of the Chengchao skarn iron deposit, SE Hubei Province, eastern China[J]. *Acta Geologica Sinica (English Edition)*, 90(5): 1780-1794.
- Li W, Xie G Q, Mao J W, Zhu Q Q and Zheng J H. 2019. Mineralogy, fluid inclusion and stable isotope studies of the Chengchao deposit, Hubei Province, eastern China: Implications for the formation of high-grade Fe skarn deposits[J]. *Econ. Geol.*, 114: 325-352.
- Li X H, Yuan F, Jowitt S M, Zhou K F, Wang J L, Zhou T F, Hu X Y, Zhou J and Li Y. 2017. Singularity mapping of fracture fills and its relationship to deep concealed orebodies—A case study of the Shaxi porphyry Cu-Au deposit, China[J]. *Geochemistry Exploration Environment Analysis*, 17(3): 252-260.
- Li X H, Yuan F, Ma L, Tang M H, Zhang M M, Zhou T F, Jia C and Hu X Y. 2017. Development of 3D mineral prospectivity modelling system and case study[J]. *Chinese Journal of Geology*, 52(3): 755-770(in Chinese with English abstract).
- Li X H, Yuan F, Zhang M M, Jia C, Jowitt S M, Ord A, Zheng T K, Hu X Y and Li Y. 2015. Three-dimensional mineral prospectively modeling for targeting of concealed mineralization within the Zhonggu iron orefield, Ningwu basin, China[J]. *Ore Geology Reviews*, 71: 633-654.
- Li X H, Yuan F, Zhang M M, Jowitt S M, Ord A, Zhou T F and Dai W Q. 2019. 3D computational simulation-based mineral prospectivity modeling for exploration for concealed Fe-Cu skarn-type mineralization within the Yueshan orefield, Anqing district, Anhui Province, China[J]. *Ore Geology Reviews*, 105: 1-17.
- Li Y H, Xie G Q, Duan C, Han D and Wang C Y. 2013. Effect of sulfate evaporate salt layer over the formation of skarn-type iron ores[J]. *Acta Geologica Sinica*, 87(9): 1324-1334(in Chinese with English abstract).
- Li Y H, Duan C, Han D, Chen X W, Wang C L, Yang B Y, Zhang C and Liu F. 2014. Effect of sulfate evaporate salt layer for formation of porphyrite iron ores in the Middle-Lower Yangtze River area[J]. *Acta Petrologica Sinica*, 30(5): 1355-1368(in Chinese with English abstract).
- Li Y, Li J W, Li X H, Selby D, Huang G H, Chen L J and Zheng K. 2017. An Early Cretaceous carbonate replacement origin for the Xinqiao stratabound massive sulfide deposit, Middle-Lower Yangtze metallogenic belt, China[J]. *Ore Geology Reviews*, 8: 985-1003.
- Li Y, Selby D, Li X H and Ottley C J. 2018. Multisourced metals enriched by magmatic-hydrothermal fluids in stratabound deposits of the Middle-Lower Yangtze River metallogenic belt, China[J]. *Geology*, 46: 391-394.
- Lian C Y, Zhang G, Yuan C H and Yang K. 2005. Application of SWIR reflectance spectroscopy in mapping of hydrothermal alteration minerals: A case study of the Tuwu porphyry copper prospect, Xinjiang[J]. *Geology in China*, 32(3): 482-495(in Chinese with English abstract).
- Liu E M, Zhao Y L and Zhao C B. 2010. Coupled geodynamics in the formation of Cu skarn deposits in the Tongling-Anqing district, China: Computational modeling and implications for exploration[J]. *Journal of Geochemical Exploration*, 106(1-3): 146-155.
- Liu W H, Jiang M R, Zhang X J, Xia Y, Algeo T J and Li H. 2018. An evolving magmatic-hydrothermal system in the formation of the Mesozoic Meishan magnetite-apatite deposit in the Ningwu volcanic basin, eastern China[J]. *Journal of Asian Earth Sciences*, 158: 1-17.
- Liu Y N, Fan Y and Zhang L J. 2017. Precipitation mechanism, REE characteristics of anhydrite in Nihe deposit and its relation to mineralization[J]. *Acta Petrologica Sinica*, 33(11): 3531-3544(in Chinese with English abstract).
- Liu Z F, Shao Y J, Wang C and Liu Q Q. 2019. Genesis of the Dongguashan skarn Cu-(Au) deposit in Tongling, eastern China: Evidence from fluid inclusions and H-O-S-Pb isotopes[J]. *Ore Geology Reviews*, 10: 462-476.
- Lü Q T, Qi G and Yan J. 2013. 3D geologic model of Shizishan ore field constrained by gravity and magnetic interactive modeling: A case history[J]. *Geophysics*, 78(1): 25-35.
- Ma F, Jiang S Y, Jiang Y H, Ni P and Ling H F. 2006. Fluid inclusions and H-O isotopic compositions in the Washan and Dongshan iron deposits, Ningwu basin, China[J]. *Acta Petrologica Sinica*, 22(10): 2581-2589(in Chinese with English abstract).
- Mao J W, Chen M H, Yuan S D and Guo C L. 2011. Geological characteristics of the Qinhang (or Shihang) metallogenic belt in South

- China and spatial-temporal distribution regularity of mineral deposits[J]. *Acta Geologica Sinica*, 85(5): 636-658(in Chinese with English abstract).
- Mao J W, Duan C, Liu J L and Zhang C. 2012. Metallogeny and corresponding mineral deposit model of the Cretaceous terrestrial volcanic-intrusive rocks-related polymetallic iron deposits in Middle-Lower Yangtze River Valley[J]. *Acta Petrologica Sinica*, 28(1): 1-14(in Chinese with English abstract).
- Mao J W, Hua R M and Li X B. 1999. A preliminary study of large-scale metallogenesis and large clusters of mineral deposits[J]. *Mineral Deposits*, 18(4): 291-299(in Chinese with English abstract).
- Mao J W, Shao Y J, Xi G Q, Zhang J D and Chen Y C. 2009. Mineral deposit model for porphyry-skarn polymetallic copper deposits in Tongling ore dense district of Middle-Lower Yangtze Valley metallogenic belt[J]. *Mineral Deposits*, 28(2): 109-119(in Chinese with English abstract).
- Mao J W, Wu S H, Song S W, Dai P, Xie G Q, Su Q W, Liu P, Wang X G and Yu Z Z. 2020. The world-class Jiangnan tungsten belt: Geological characteristics, metallogenic regularity, and ore deposit model[J]. *Chinese Science Bulletin*(in press).
- Mao J W, Xie G Q, Duan C, Pirajno F, Ishiyama D and Chen Y C. 2011. A tectonogenetic model for porphyry-skarn-stratabound Cu-Au-Mo-Fe and magnetite-apatite deposits along the Middle-Lower Yangtze River Valley, eastern China[J]. *Ore Geology Reviews*, 43: 294-314.
- Mao X C, Zou Y H, Chen J, Lai J Q, Peng X L, Shao Y J, Shu Z M, Lü J W and Lü C Y. 2010. Three-dimensional visual prediction of concealed ore bodies in the deep and marginal parts of crisis mines: A case study of the Fengnangshan ore field in Tongling, Anhui, China[J]. *Geological Bulletin of China*, 29(2-3): 401-413 (in Chinese with English abstract).
- Mao X C, Zou Y H, Chen J, Lai J Q and Peng X L. Three-Dimensional visual prediction of concealed orebodies[M]. Changsha: Central South University Press. 170p(in Chinese).
- Ningwu Research Group. 1978. Magnetite porphyry deposits in Ningwu area[M]. Beijing: Geological Publishing House. 196p(in Chinese).
- Ord A, Hobbs B E and Lester D R. 2012. The mechanics of hydrothermal systems: I. Ore systems as chemical reactors[J]. *Ore Geology Reviews*, 49: 1-44.
- Pan Y M and Dong P. 1999. The Lower Changjiang (Yangzi/Yangtze River) metallogenic belt, East China: Intrusion and wall rock-hosted Cu-Fe-Au, Mo, Zn, Pb, Ag deposits[J]. *Ore Geology Reviews*, 15: 177-242.
- Qin Y, Wang D H, Li Y H, Wang K Y, Wu L B and Mei Y P. 2010. Rock-forming and ore-forming ages of the Baizhangyan tungsten-molybdenum ore deposit in Qingyang, Anhui Province and their geological significance[J]. *Earth Science Frontiers*, 17(2): 170-177 (in Chinese with English abstract).
- Shu Q A, Chen P L and Cheng J R. 1992. Geology of iron-copper deposits in eastern Hubei Province, China[M]. Beijing: Metallurgical Industry Press. 510p(in Chinese).
- Song G X, Qin K Z, Li G M, Liu T B, Li J X, Li X H and Chang Z S. 2012. Geochronologic and isotope geochemical constraints on magmatism and associated W-Mo mineralization of the Jitoushan W-Mo deposit, middle-lower Yangtze Valley[J]. *International Geology Review*, 54: 1532-1547.
- Su Z K, Zhao X F, Zeng L P, Zhao K D and Hofstra A. 2019. Tourmaline boron and strontium isotope systematics reveal magmatic fluid pulses and external fluid influx in a giant iron oxide-apatite (IOA) deposit[J]. *Geochimica et Cosmochimica Acta*, 259: 233-252.
- Sun J F. 1984. Metallogenic characteristics of skarn type scheelite deposits in Daye-Yangxin area[J]. *Geology and Exploration*, 20(8): 9-11, 29(in Chinese).
- Thompson A J B, Hauff P L and Rabitaille J A. 1999. Alteration mapping in exploration: Application of short wave infra-red (SWIR) spectroscopy[J]. *SEG Newsletter*, 39: 16-27.
- Wang X G, Hu Z H, Huang Q Y, Yi W, Cheng G H, Hu L M and You W. 2019. Zircon U-Pb age of ore-forming magmatic rocks in the Tongjiangling copper-tungsten deposit in the Jiurui ore concentration area and its significance[J]. *Geology of China*, 46(4): 832-840 (in Chinese with English abstract).
- Wang Y, Zhu X K, Mao J W, Li Z H and Cheng Y B. 2011. Iron isotope fractionation during skarn-type metallogeny: a case study of Xinqiao Cu-S-Fe-Au deposit in the middle-lower Yangtze valley[J]. *Ore Geology Reviews*, 43(1): 194-202.
- Weis P, Driesner T and Heinrich C A. 2012. Porphyry-copper ore shells form at stable pressure-temperature fronts within dynamic fluid plumes[J]. *Science*, 338(6114): 1613-1616.
- Xiao K Y, Chen X G, Li N, Zou W and Sun L. 2010. 3D visualization technology of geological mineral exploration and evaluation and software development of Minexplorer[J]. *Mineral Deposits*, 29 (Supp): 758-760(in Chinese with English abstract).
- Xiao K Y, Li N, Sun L, Zou W and Li Y. 2012. Large scale 3D mineral prediction methods and channels based on 3D information technology[J]. *Journal of Geology*, 36(3): 229-236(in Chinese with English abstract).
- Xie G Q, Han Y X and Li X H. 2019. A preliminary study of characteristics of dispersed metal-bearing deposits in Middle-Lower Yangtze River metallogenic belt[J]. *Mineral Deposits*, 38(4): 729-738 (in Chinese with English abstract).
- Xie G Q, Mao J W, Richards J P, Han Y X and Fu B. 2019. Distal Au deposits associated with Cu-Au skarn mineralization in the Fengshan area, eastern China[J]. *Econ. Geol.*, 114: 127-142.
- Xie G Q, Han Y X and Mao J W. 2017. A new type of gold deposit discovered in Fengshan ore field of the Middle Lower Yangtze River metallogenic belt: Distal disseminated gold deposit[J]. *Mineral Deposits*, 36(1): 265-268(in Chinese with English abstract).
- Xie G Q, Mao J W, Zhu Q Q, Yao L, Li Y H, Li W and Zhao H J. 2015. Geochemical constraints on Cu-Fe and Fe skarn deposits in the

- Edong district, Middle-Lower Yangtze River metallogenic belt, China[J]. *Ore Geology Reviews*, 64: 425-444.
- Xie G Q, Zhu Q Q, Yao L, Wang J and Li W. 2013. Discussion on regional metal mineral deposit model of Late Mesozoic Cu-Fe-Au polymetallic deposits in the Southeast Hubei Province[J]. *Bulletin of Mineralogy, Petrology and Geochemistry*, 32(4): 418-426(in Chinese with English abstract).
- Xie G Q, Mao J W, Li R L, Qu W J, Pirajno F and Du A D. 2007. Re-Os molybdenite and Ar-Ar phlogopite dating of Cu-Fe-Au-Mo (W) deposits in southeastern Hubei, China[J]. *Mineralogy and Petrology*, 90(3-4):249-270.
- Yan D R, Deng X D, Hu H and Li J W. 2012. U-Pb age and petrogenesis of the Ruanjiawan granodiorite pluton and Xiniushan granodiorite porphyry, Southeast Hubei Province: Implications for Cu-Mo mineralization[J]. *Acta Petrologica Sinica*, 28(10): 3373-3388(in Chinese with English abstract).
- Yang K, Huntington J F and Scott K M. 1999. Spectroscopy of the hydrothermal alteration of Hishikari, Japan[C]. *Proceedings of International Symposium on Water-Rock interaction*, 9: 587-590.
- Yang K, Browne P R L, Huntington J F and Walshe J L. 2001. Characterising the hydrothermal alteration of the Broadlands—Ohaaki geothermal system, New Zealand, using short-wave infra-red spectroscopy[J]. *Journal of Volcanology and Geothermal Research*, 106: 53-65.
- Yang S S, Duan J C, Ju Z F and He J G. 1985. Geological characteristics and genetic mechanism of Jianbi tungsten-molybdenum deposit[J]. *Geology and Exploration*, 21(8): 20-27(in Chinese).
- Yang Z M, Hou Z Q, Yang Z S, Qu H C, Li Z Q and Liu Y F. 2012. Application of short wavelength infrared (SWIR) technique in exploration of poorly eroded porphyry Cu district: A case study of Niancun ore district, Tibet[J]. *Mineral Deposits*, 31(4): 699-717(in Chinese with English abstract).
- Yuan F, Li X H, Zhang M M, Jowitt S M, Jia C, Zheng T K and Zhou T F. 2014. Three-dimensional weights of evidence-based prospectively modeling: A case study of the Baixiangshan mining area, Ningwu basin, Middle and Lower Yangtze Metallogenic belt, China [J]. *Journal of Geochemical Exploration*, 145: 82-97.
- Yuan F, Li X H, Zhang M M, Zhou T F, Gao D M, Hong D L, Liu X M, Wang Q N and Zhu J B. 2014. Three dimension prospectively modelling based on integrated geoinformation for prediction of buried orebodies[J]. *Acta Geologica Sinica*, 88(4): 630-643(in Chinese with English abstract).
- Yuan F, Li X H, Hu X Y, Li Y, Jia C, Ord A, Zhang M M, Dai W Q and Li H. 2019b. A new approach for researching hydrothermal deposit: Numerical simulation[J]. *Chinese Journal of Geology*, 54(3): 678-690(in Chinese with English abstract).
- Yuan F, Zhang M M, Li X H, Ge Can, Lu S M, Li J S, Zhou Y Z and Lan X Y. 2019. Prospectively modeling: From two-dimension to three-dimension[J]. *Acta Petrologica Sinica*, 35(12): 3863-3874(in Chinese with English abstract).
- Zeng L P, Zhao X F, Li X C, Hu H and McFarlane C. 2016. In situ elemental and isotopic analysis of fluorapatite from the Taocun magnetite-apatite deposit, eastern China: Constraints on fluid metasomatism[J]. *American Mineralogist*, 101: 2468-2483.
- Zhai Y S, Lin X D and Yao S Z. 1992. Fe-Cu-Au metallogeny of the Middle-Lower Changjiang region[M]. Beijing: Geological Publishing House. 235p(in Chinese).
- Zhai Y S. 1999. On the metallogenic system[J]. *Earth Science Frontiers*, 6(1): 13-27.
- Zhang G, Liang C Y and Wang R S. 2005. Application of the portable infrared mineral analyser (PIMA) in mineral mapping in the Qulong copper prospect, Mozhugongka County, Tibet[J]. *Geological Bulletin of China*, 24(5): 480-484(in Chinese with English abstract).
- Zhang M M, Zhou G Y, Shen L, Zhao W G, Liao B S, Yuan F, Li X H, Hu X Y and Wang C. 2019. Comparison of 3D prospectively modeling methods for Fe-Cu skarn deposits: a case study of the Zhuchong Fe-Cu deposit in the Yueshan orefield (Anhui), Eastern China[J]. *Ore Geology Reviews*, 114: 103126.
- Zhang S T, Chen H Y, Zhang X B, Zhang W F, Xu C, Han J S and Chen M. 2017. Application of short wavelength infrared (SWIR) technique to exploration of skarn deposit: A case study of Tonglvshan Cu-Fe-Au deposit, Edongnan (southeast Hubei) ore concentration area[J]. *Mineral Deposits*, 36(6): 1263-1288(in Chinese with English abstract).
- Zhang Y, Shao Y J, Li H B, and Liu Z F. 2017. Genesis of the Xinqiao Cu-S-Fe-Au deposit in the Middle-Lower Yangtze River Valley metallogenic belt, eastern China: Constraints from U-Pb-Hf, Rb-Sr, S, and Pb isotopes[J]. *Ore Geology Reviews*, 86: 100-116.
- Zhao L Q, Deng J, Yuan H T and Li X Y. 2008. Short wavelength infrared spectral analysis of alteration zone in the Taishang gold deposit[J]. *Geology and Prospecting*, 44(5): 58-63(in Chinese with English abstract).
- Zhao Y M, Zhang Y N and Bi C S. 1999. Geology of gold-bearing skarn deposits in the Middle and Lower Yangtze River Valley and adjacent regions[J]. *Ore Geology Reviews*, 14: 227-249.
- Zhong G X, Zhou T F, Yuan F, Jiang Q S, Fan Y, Zhang D Y and Huang J M. 2014. Discovery of scheelite in Yaojialing Large zinc-gold deposit in Tongling ore district, Anhui Province, China[J]. *Acta Geologica Sinica*, 88(4): 620-629(in Chinese with English abstract).
- Zhou T F, Fan Y and Yuan F. 2008. Advances on petrogenesis and metallogenic study of the mineralization belt of the Middle and Lower Reaches of the Yangtze River area[J]. *Acta Petrologica Sinica*, 24(8): 1665-1678(in Chinese with English abstract).
- Zhou T F, Fan Y, Wang S W and White N. 2017. Metallogenic regularity and metallogenic model of the Middle-Lower Yangtze River Valley Metallogenic belt[J]. *Acta Petrologica Sinica*, 33(11): 3353-3372(in Chinese with English abstract).
- Zhou T F, Fan Y, Yuan F and Zhong G X. 2012. Progress of geological study in the Middle-Lower Yangtze River Valley metallogenic belt[J]. *Acta Petrologica Sinica*, 28(10): 3051-3066(in Chinese

with English abstract).

- Zhou T F, Fan Y, Yuan F, Wu M A, Zhao W G, Qian B, Ma L, Wang W C, Liu Y N and White N. 2014. The metallogenic model of Nihe iron deposit in Lu-Zong basin and genetic relationship between gypsum-salt layer and deposit[J]. *Acta Geologica Sinica*, 88(4): 562-573(in Chinese with English abstract).
- Zhou T F, Nie L Q, Wang S W, Wang F Y and Zhang Q M. 2019. Tungsten deposits in the Middle-Lower Yangtze Metallogenic belt, China[J]. *Acta Petrologica Sinica*, 35(12): 3592-3608(in Chinese with English abstract).
- Zhu Q Q, Xie G Q, Wang J, Li W and Yu B F. 2013. The relationship between the evaporate and skarn-type iron deposit: A case study of the Jinshandian iron skarn deposit in Hubei[J]. *Acta Geologica Sinica*, 87(9): 1419-1429(in Chinese with English abstract).
- Zhu Q Q, Xie G Q, Mao J W, Li W, Li Y H, Wang J and Zang P. 2015. Mineralogical and sulfur isotopic evidence for the incursion of evaporates in the Jinshandian skarn Fe deposit, Edong district, eastern China[J]. *Journal of Asian Earth Sciences*, 113: 1253-1267.
- Zhu Q Q, Li W, Zhang Z Y, Han Y X and Wang J. 2016. Tracing incursion of the evaporates into Jinshandian skarn Fe deposit, Hubei Province, by combination of multiple stable isotopes[J]. *Acta Geologica Sinica*, 90(2): 361-375(in Chinese with English abstract).
- Zhu Q Q and Xie G Q. 2018. Sulfur isotopic character and geological implications for the Jinshandian Fe skarn ore field, Hubei Province[J]. *Acta Petrologica Sinica*, 34(9): 2518-2534(in Chinese with English abstract).
- Zhu Q Q, Xie G Q and Han Y X. 2019. Characteristics of tungsten mineralization from the Tongshankou skarn-porphyry Cu (Mo) deposit in Daye, Hubei Province, and its geological implications[J]. *Earth Science*, 44(2): 441-455(in Chinese with English abstract).

附中文参考文献

- 曹烨,李胜荣,申俊峰,要梅娟,李庆康,毛付龙. 2008. 便携式短波红外光谱矿物测量仪(PIMA)在河南前河金矿热液蚀变研究中的应用[J]. *地质与勘探*, 44(2): 82-86.
- 常印佛,刘湘培,吴昌言. 1991. 长江中下游地区铜铁成矿带[M]. 北京:地质出版社. 379页.
- 常印佛,周涛发,范裕. 2017. 长江中下游成矿带矿产勘查-科研工作回顾和展望[J]. *岩石学报*, 33(11): 3333-3352.
- 陈华勇,张世涛,初高彬,张宇,程佳敏,田京,韩金. 2019. 鄂东南矿集区典型砂卡岩-斑岩矿床蚀变矿物短波红外(SWIR)光谱研究与勘查应用[J]. *岩石学报*, 35(12): 3629-3643.
- 陈建平,吕鹏,吴文,赵洁,胡青. 2007. 基于三维可视化技术的隐伏矿床预测[J]. *地学前缘*, 14(5): 54-62.
- 陈雪锋,周涛发,张达玉,熊珍银,吕启良,袁峰,任志,范裕. 2017. 皖南池州桂林铅矿床成矿岩体的年代学和地球化学特征及其地质意义[J]. *岩石学报*, 33(10): 3200-3216.
- 程裕淇,陈毓川,赵一鸣. 1979. 初论矿床的成矿系列问题[J]. *地球*

学报, 1(1): 32-58.

- 程志中, 谢学锦, 潘含江, 杨榕. 2012. 中国南方地区稀地球化学特征[J]. *中国地质*, 39(2): 295-301.
- 段超, 李延河, 毛景文, 侯可军, 袁顺达. 2012. 宁芜火山岩盆地凹山铁矿床侵入岩锆石微量元素特征及其地质意义[J]. *中国地质*, 39(6): 1882-1892.
- 段留安, 杨晓勇, 刘晓明, 孙卫东. 2013. 铜陵舒家店地区志留纪地层中金矿的发现及其意义[J]. *大地构造与成矿学*, 37(2): 333-339.
- 顾连兴, 徐克勤. 1986. 论大陆断裂陷带中华南型块状硫化物同矿床[J]. *矿床地质*, 5(2): 1-13.
- 郭娜, 刘栋, 唐菊兴, 郑龙, 黄一入, 史维鑫, 伏媛, 唐楠, 王成. 2018a. 基于短波红外技术的蚀变矿物特征及勘查模型——以斯弄多银铅锌矿床为例[J]. *矿床地质*, 37(3): 556-570.
- 郭娜, 史维鑫, 黄一入, 郑龙, 唐楠, 王成, 伏媛. 2018b. 基于短波红外技术的西藏多龙矿集区铁格隆南矿床荣那矿段及其外围蚀变填图-勘查模型构建[J]. *地质通报*, 37(2/3): 446-457.
- 何光辉, 周涛发, 范裕, 王世伟, 肖庆玲. 2018. 庐江沙溪斑岩型铜金矿床绿泥石的地球化学特征及找矿指示[J]. *矿床地质*, 37(6): 1247-1259.
- 华仁民, 毛景文. 1999. 试论中国东部中生代成矿大爆发[J]. *矿床地质*, 18(4): 300-308.
- 纪云昊, 谢桂青, 朱乔乔, 孙孝峰, 李新昊. 2019. 含碳质层对矽卡岩矿床的影响——以鄂东付家山钨矿床为例[J]. *矿床地质*, 38: 917-934.
- 贾蔡, 袁峰, 张明明, 李晓晖, 周涛发, 邵尉, 郑通科, 高道明. 2014. 宁芜盆地白象山铁矿床成矿作用过程数值模拟[J]. *岩石学报*, 30(4): 1031-1040.
- 贾蔡, 袁峰, 李晓晖, 胡训宇, 廖宝胜, 孙维安, 张明明, 沈乐. 2018. 基于多源数据约束的成矿动力学模拟——以宁芜盆地钟姑矿田典型矿床为例[J]. *地质科学*, 53(4): 1327-1346.
- 李晓晖, 袁峰, 马良, 唐敏慧, 张明明, 周涛发, 贾蔡, 胡训宇. 2017. 三维成矿定量预测系统设计与应用实例研究[J]. *地质科学*, 52(3): 755-770.
- 李延河, 谢桂青, 段超, 韩丹, 王成玉. 2013. 膏岩层在砂卡岩型铁矿成矿中的作用[J]. *地质学报*, 87(9): 1324-1334.
- 李延河, 段超, 韩丹, 陈新旺, 王丛林, 杨秉阳, 张成, 刘锋. 2014. 膏盐层氧化障在长江中下游玢岩铁矿成矿中的作用[J]. *岩石学报*, 30(5): 1355-1368.
- 连长云, 章革, 元春华, 杨凯. 2005. 短波红外光谱矿物测量技术在热液蚀变矿物填图中的应用——以土屋斑岩铜矿床为例[J]. *中国地质*, 32(3): 482-495.
- 刘一男, 范裕, 张乐骏. 2017. 庐枞盆地泥河铁矿床中硬石膏微量元素特征、沉淀机制及其对铁成矿作用的制约[J]. *岩石学报*, 33(11): 3531-3544.
- 毛景文, 华仁民, 李晓波. 1999. 浅议大规模成矿作用与大型矿集区[J]. *矿床地质*, 18(4): 291-299.
- 毛景文, 邵拥军, 谢桂青, 张建东, 陈毓川. 2009. 长江中下游成矿带铜陵矿集区铜多金属矿床模型[J]. *矿床地质*, 28(2): 109-119.
- 毛景文, 陈懋弘, 袁顺达, 郭春丽. 2011. 华南地区钦杭成矿带地质特征和矿床时空分布规律[J]. *地质学报*, 85(5): 636-658.
- 毛景文, 段超, 刘佳林, 张成. 2012. 陆相火山-侵入岩有关的铁多金属

- 矿成矿作用及矿床模型-以长江中下游为例[J]. 岩石学报, 28(1):1-14.
- 毛景文, 吴胜华, 宋世伟, 戴盼, 谢桂青, 苏蔷薇, 刘鹏, 王先广, 余忠珍, 陈祥云, 唐维新. 2020. 江南世界级钨矿带:地质特征、成矿规律和矿床模型[J]. 科学通报(出版中).
- 毛先成, 邹艳红, 陈进, 赖健清, 彭省临, 邵拥军, 疏志明, 吕俊武, 吕才玉. 2010. 危机矿山深部、边部隐伏矿体的三维可视化预测——以安徽铜陵凤凰山矿田为例[J]. 地质通报, 29(2-3):401-413.
- 毛先成, 邹艳红, 陈进, 赖健清, 彭省临. 2011. 隐伏矿体三维可视化预测[M]. 长沙:中南大学出版社. 170页.
- 宁芜研究项目编写小组. 1978. 宁芜玢岩铁矿[M]. 北京:地质出版社. 196页.
- 秦燕, 王登红, 李延河, 王克友, 吴礼彬, 梅玉萍. 2010. 安徽青阳百丈岩钨铅矿床成岩成矿年龄测定及地质意义[J]. 地学前缘, 17(2):170-177.
- 舒全安, 陈培良, 程建荣. 1992. 鄂东铁铜矿产地质[M]. 北京:冶金工业出版社. 510页.
- 孙家富. 1984. 大冶—阳新地区夕卡岩型白钨矿床的成矿特点[J]. 地质与勘探, 20(8):9-11, 29.
- 王先广, 胡正华, 黄秋芸, 易伟, 陈国华, 胡朗明, 游玮. 2019. 九瑞矿集区通江岭铜钨矿成矿岩浆岩锆石 U-Pb 年龄及意义[J]. 中国地质, 46(4):832-840.
- 肖克炎, 陈学工, 李楠, 邹伟, 孙莉. 2010. 地质矿产勘探评价三维可视化技术及探矿者软件开发[J]. 矿床地质, 29(增):758-760.
- 肖克炎, 李楠, 孙莉, 邹伟, 李莹. 2012. 基于三维信息技术大比例尺三维立体矿产预测方法及途径[J]. 地质学刊, 36(3):229-236.
- 谢桂青, 朱乔乔, 姚磊, 王建, 李伟. 2013. 鄂东南地区晚中生代铜铁多金属矿的区域成矿模型探讨[J]. 矿物岩石地球化学通报, 32(4):418-426.
- 谢桂青, 韩颖霄, 毛景文. 2017. 长江中下游成矿带丰山矿田发现新类型金矿:远端浸染型金矿床[J]. 矿床地质, 36(1):265-268.
- 谢桂青, 韩颖霄, 李新昊. 2019. 长江中下游成矿带含稀散金属矿床特征初探[J]. 矿床地质, 38(4):729-738.
- 颜代蓉, 邓晓东, 胡浩, 李建威. 2012. 鄂东南地区阮家湾和犀牛山花岗岩闪长岩的时代、成因及成矿和找矿意义[J]. 岩石学报, 28(10):3373-3388.
- 杨松生, 段家才, 鞠在富, 何建国. 1985. 谏壁钨铅矿床地质特征和成因机制讨论[J]. 地质与勘探, 21(8):20-27.
- 杨志明, 侯增谦, 杨竹森, 曲焕春, 李振清, 刘云飞. 2012. 短波红外光谱技术在浅剥蚀斑岩铜矿区勘查中的应用——以西藏念村矿区为例[J]. 矿床地质, 31(4):699-717.
- 袁峰, 李晓晖, 张明明, 周涛发, 高道明, 洪东良, 刘晓明, 汪启年, 朱将波. 2014. 隐伏矿体三维综合信息成矿预测方法[J]. 地质学报, 88(4):630-643.
- 袁峰, 张明明, 李晓晖, 葛黎, 陆三明, 李建设, 周宇章, 兰学毅. 2019a. 成矿预测:从二维到三维[J]. 岩石学报, 35(12):3863-3874.
- 袁峰, 李晓晖, 胡训宇, 李跃, 贾蔡, Ord Alison, 张明明, 戴文强, 李贺. 2019b. 热液矿床成矿作用研究新途径:数值模拟[J]. 地质科学, 54(3):678-690.
- 翟裕生, 林新多, 姚书振. 1992. 长江中下游地区铁铜(金)成矿规律[M]. 北京:地质出版社. 235页.
- 翟裕生. 1999. 论成矿系统[J]. 地学前缘, 6(1):13-27.
- 章草, 连长云, 王润生. 2005. 便携式短波红外矿物分析仪(PIMA)在西藏墨竹工卡县驱龙铜矿区矿物填图中的应用[J]. 地质通报, 24(5):480-484.
- 张世涛, 陈华勇, 张小波, 张维峰, 许超, 韩金生, 陈觅. 2017. 短波红外光谱技术在矽卡岩型矿床中的应用——以鄂东南铜绿山铜铁金矿床为例[J]. 矿床地质, 36(6):1263-1288.
- 赵利青, 邓军, 原海涛, 李晓英. 2008. 台上金矿床蚀变带短波红外光谱研究[J]. 地质与勘探, 44(5):58-63.
- 中国矿床发现史江西卷编委会. 1996. 中国矿床发现史(江西卷)[M]. 北京:地质出版社. 1-245.
- 钟国雄, 周涛发, 袁峰, 蒋其胜, 范裕, 张达玉, 黄建满. 2014. 安徽铜陵姚家岭大型锌金矿床中新发现白钨矿[J]. 地质学报, 88(4):620-629.
- 周涛发, 范裕, 袁峰. 2008. 长江中下游成矿带成岩成矿作用研究进展[J]. 岩石学报, 24(8):1665-1678.
- 周涛发, 范裕, 袁峰, 钟国雄. 2012. 长江中下游成矿带地质与矿产研究进展[J]. 岩石学报, 28(10):3051-3066.
- 周涛发, 范裕, 袁峰, 吴明安, 赵文广, 钱兵, 马良, 王文财, 刘一男, White N. 2014. 安徽庐枞盆地泥河铁矿床与膏盐层的成因联系及矿床成矿模式[J]. 地质学报, 88(4):562-573.
- 周涛发, 范裕, 王世伟, White N. 2017. 长江中下游成矿带成矿规律和成矿模式[J]. 岩石学报, 33(11):3353-3372.
- 周涛发, 聂利青, 王世伟, 汪方跃, 张千明. 2019. 长江中下游成矿带钨矿床[J]. 岩石学报, 35(12):3592-3608.
- 朱乔乔, 谢桂青, 王建, 李伟, 于炳飞. 2013. 含膏盐地层与矽卡岩型铁矿的关系:以湖北金山店铁矿为例[J]. 地质学报, 87(9):1419-1429.
- 朱乔乔, 李伟, 张志远, 韩颖霄, 王建. 2016. 多元稳定同位素组合示踪含膏盐层参与湖北金山店矽卡岩型铁矿成矿作用[J]. 地质学报, 90(2):361-375.
- 朱乔乔, 谢桂青. 2018. 湖北金山店矽卡岩型铁矿田硫同位素特征及其地质意义[J]. 岩石学报, 34(9):2518-2534.
- 朱乔乔, 谢桂青, 韩颖霄. 2019. 湖北大冶铜山口铜(钨)矿床中钨矿化特征及其地质意义[J]. 地球科学, 44(2):441-455.