

长江中下游成矿带成岩成矿作用研究进展*

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Abstract The mineralization belt of the Middle and Lower Reaches of the Yangtze River area is one of the most important mineral belt in China. It is composed of a series of ore deposits-concentrated areas such as the southeast Hubei, Jiurui, Anqing-Guichi, Tongling, Luzong and Ningwu etc. which located in the fault uplift, fault basin and the intermediated units. The formation of this mineralization belt had undergone a Late Mesozoic transitional composite tectonic setting and complex geocontinental dynamic processes of intensive crust-mantle interactions. The characteristics of explosive multistage magmatism, the large scale of Cu, Fe, Au polymetallic mineralization and the multistyle complicated fluid ore-forming systems and the prospective deep mineral resources make this mineral belt an excellent natural laboratory for study the relationships between the inner-continental geodynamic processes and the petrogenesis and metallogeny. In this paper, the authors have a fully extensive discussion and summarization of the newly research progresses on the tectonic settings, the geodynamic processes, the temporal-spatial framework and the evolution of fluid ore-forming systems in this decade by researchers, the existing unsolved scientific questions and the next stage of hot topics for research are also put forward.

Key words Geocontinental dynamics; Petrogenesis and metallogeny; Fluid ore-forming system; Cu, Fe, Au polymetallic ore deposit; The Middle and Lower Reaches of the Yangtze River area

摘要 长江中下游成矿带是中国最主要的铜铁金多金属成矿带之一,由鄂东南、九瑞、安庆—贵池、铜陵、庐枞和宁芜等位于断隆区、断凹区和隆凹过渡区的多个矿集区组成,成矿带形成经历了中生代转换复合的构造体制、强烈的壳幔相互作用等复杂的大陆动力学过程,具有爆发式多阶段岩浆活动、大规模的铜铁金多金属成矿作用和多类型的复杂成矿系统演化,以及深部找矿潜力巨大等特点,是开展陆内动力学过程与成岩成矿作用研究的不可多得的天然实验室。本文从成岩成矿构造背景、地球动力学过程、时空格架以及成矿流体系统演化等方面,对近十年来国内外学者对该成矿带成岩成矿作用研究的主要成果和进展作一初步归纳,并简要分析了下一步研究的主要科学问题。

关键词 大陆动力学; 成岩成矿作用; 成矿流体系统; 铜铁金多金属矿床; 长江中下游成矿带

中图法分类号 P542; P611

长江中下游成矿带位于扬子板块北缘的长江断裂带内,该区自晋宁期以来,经历了古生代盖层沉积阶段和中生代板内变形阶段,受特提斯构造域、古太平洋构造域和深部壳幔

作用过程复合形成的中生代转换构造背景控制(常印佛等,1991; 翟裕生等,1992; 陶奎元等,1998; 戚建中等,2000; 周涛发等,2005),长期的构造作用、岩浆活动和成矿作用形成

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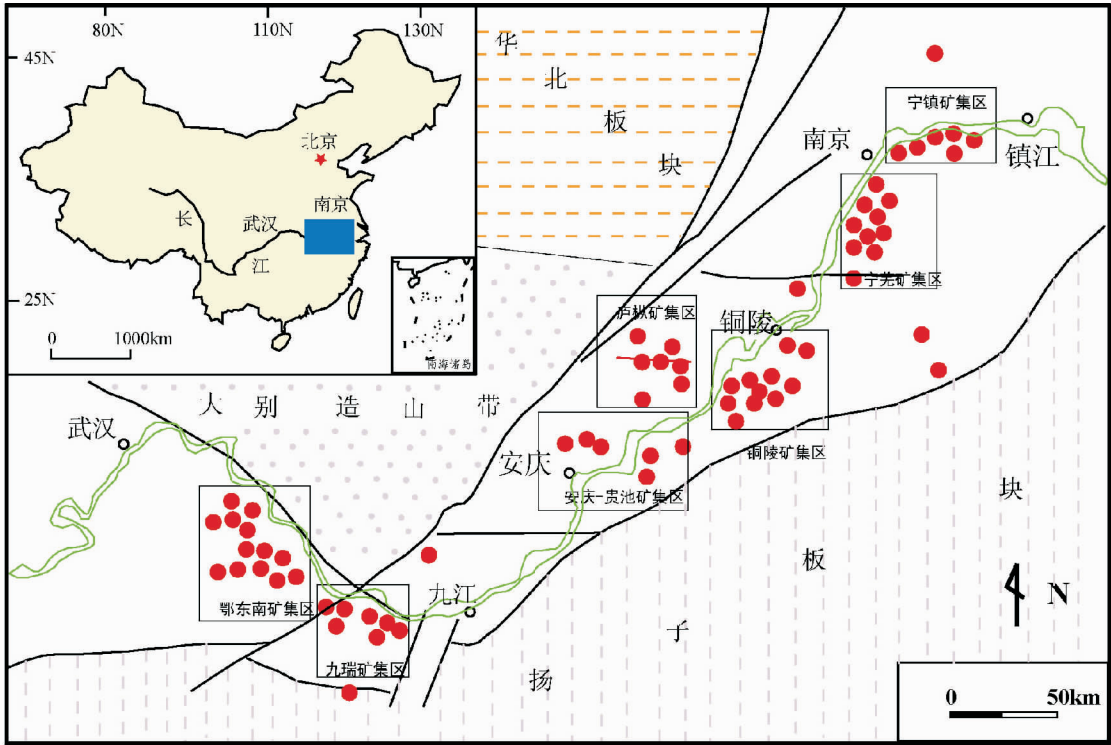


图1 长江中下游成矿带主要矿集区和矿床分布略图(据翟裕生等,1992; Pan and Dong,1999 改绘)

Fig.1 Sketch showing distribution of main metallogenic provinces and deposits in the Middle and Lower Reaches of Yangtze River (after Zhai *et al.*, 1992; Pan and Dong,1999)

了断隆区和断凹区的次级构造格局及丰富多样的铁、铜、金多金属等矿床组合,金属矿床(点)计有 200 余处,由多个各具特点的矿集区组成(图 1),自西向东为鄂东南、九瑞、安庆—贵池、庐枞、铜陵、宁芜和宁镇等,其中,庐枞、宁芜矿集区主要位于断陷火山盆地(断凹区),铜陵、安庆—贵池、九瑞、宁镇等矿集区位于隆起区(断隆区),鄂东南矿集区则具有断隆区和断凹区的过渡性质。长江中下游地区矿床类型多样(常印佛等,1991),其中,由(层控)矽卡岩型、斑岩型(玢岩型)和热液脉型矿床为主组成的内生铜、铁、金成矿系列是长江中下游成矿带的主要的成矿系列,与燕山期岩浆作用和演化有关,成矿带的成岩成矿特色显著。

该区是我国重要的铜铁矿产资源的生产基地,矿产资源开发利用历史悠久,也是我国“玢岩铁矿”(宁芜研究项目编写小组,1978)、“层控矽卡岩型矿床”理论(常印佛和刘学圭,1983)和复合叠加成矿理论(翟裕生等,1992)的发祥地,在国际成矿理论研究领域占有重要的一席之地。过去的半个世纪,前人对长江中下游成矿带中的铜金铁矿床的地质地球化学特征、成矿作用和成矿过程以及控矿构造和成岩成矿关系进行了大量研究,取得了丰硕的研究成果,其代表性成果有宁芜研究项目编写小组,1978、常印佛等(1991)、翟裕生等(1992)和唐永成等(1998)以及众多的研究论文等。近年来,在已积累了重要的矿产资源勘察方法和丰富的成矿理论成矿规律研究成果(常印佛等,1991;翟裕生等,1992;唐永

成等,1998)的基础上,长江中下游成矿带的成岩成矿作用研究又取得了多方面重要的研究进展,在铜陵、庐枞、九瑞和鄂东南等地深部找矿工作也取得明显突破,同时,揭示出越来越多有待解决的科学问题。本文对近十年来国内外学者对该成矿带成岩成矿作用研究主要成果和进展作一初步归纳,并分析了下一步研究的主要科学问题,以期推动对该成矿带的成岩成矿作用研究。

1 成岩成矿构造背景

已有研究表明,长江中下游成矿带作为中国东部的组成部分之一,在中生代经历了区域构造体制转换与重大调整的过程,主构造格局由近 EW 向转换为 NE-NNE 向。Hilde (1976)曾提出 135Ma 前东亚大陆边缘的俯冲—转换的构造动力模式,该模式后来得到其他研究者的支持(陶奎元等,1998;戚建中等,2000)。

关于中国东(南)部成岩成矿的构造背景,基于南岭、东南沿海、下扬子等地区岩石构造组合研究,陶奎元等(1998)提出晚侏罗纪后中国的东南部进入大陆拉张环境,扬子陆块和华夏陆块处于统一的动力体系,大约在 145 ± 5 Ma 构造机制从挤压向拉张转换,发生较早期的华北板块与华南板块碰撞拼贴及稍后的古太平洋板块(法拉龙—伊泽奈崎—库拉)相对于亚洲大陆的非均—西向俯冲。中国东南部的构造

背景既不同于安第斯型活动大陆边缘,也不是完全的大陆裂谷带。戚建中等(2000)将中国东部的构造演化与北美西部相比,认为中国东部 180 ~ 90Ma 的燕山期为由活动大陆边缘向陆内过渡的构造属性,郟庐断裂以西属陆内,以东主体属大陆边缘,大陆边缘演化可分为地壳缩短增厚和伸展减薄两个阶段,二者的过渡时间约为 140Ma。在低角度 B 型俯冲和左行走滑的双重作用下产生了不同的岩浆岩组合,并衍生出丰富的内生金属矿产。任纪舜等(1999)和陈培荣等(2002)研究认为中国东部的构造体制转换的时间位于侏罗纪与早白垩世之间。李锦轶等(1999)基于年代学研究认为这一转换时限应为 166 ~ 135Ma 之间。而李文达等(1998)提出中国东南大陆岩石圈的构造环境经历了 176 ~ 150Ma 的挤压、145Ma 由挤压向伸展扩张的转换、125 ~ 105Ma 的扩张增强、以及 92Ma 左右进入裂解阶段,中生代大规模的火山—侵入作用和成矿作用主要发生在大陆伸展—地壳减薄期,董树文等(2007)则认为构造体制的重大转换发生于中晚侏罗世初期(165 ± 5Ma)。

多年来,众多研究者一直致力于长江中下游成矿带构造背景的探讨。长江中下游地区的岩浆作用和成矿作用主要发生于 145 ~ 120Ma 之间(周涛发和岳书仓,2000; 陈江峰等,2005; Zhou *et al.*, 2008), 岩浆岩主要由三个系列组成: 高碱钙碱性系列(常印佛等,1991)、橄榄安粗岩系列(王德滋等,1996)和碱性(A 型)花岗岩系列(邢凤鸣和徐祥,1999)。对其形成的大地构造背景认识,有观点认为是属于与古太平洋板块俯冲作用有关的大陆边缘岩浆弧(吴利仁等,1982; 邓晋福等,1992),常印佛等(1991)、唐永成等(1998)强调地幔上隆和长江断裂带的控制作用,常印佛等(1991)、翟裕生等(1992)认为长江中下游地区中生代的成岩成矿作用位于板内断块岩浆活动带,陈衍景等(2004)主张矽卡岩型金矿及相关矿床形成于陆陆碰撞过程挤压伸展转换期,周涛发(1993)认为属大陆边缘环境向陆内断块环境的过渡与转换期,131Ma 以后进入典型的伸展拉张背景(周涛发等,2007),也有人提出与板内裂谷带(邢凤鸣和徐祥,1999)及类盆岭式的岩石圈伸展(Li, 2000)或拆沉作用等深部动力学过程(张旗等,2001; 王强等,2001; 吕庆田等,2004)有关。

长江中下游成矿带与同处中国东部的其他构造单元如华北东部、大别以及东南沿海等相比,在成岩成矿时空特点、地质地球化学特征以及成矿背景方面既存在一定的共性,又表现出相当大的差异性,发生于 145 ~ 120Ma 之间的岩浆成矿热事件在中国东部普遍,但在东南沿海地区不明显; 华南、扬子南缘、华北等地出现老于 153 ~ 220Ma 的岩浆成矿热事件在长江中下游地区缺失; 小于 120 Ma 的岩浆成矿热事件在东南沿海地区大量发育,但在长江中下游地区也不发育(陈江峰等,2005; 毛景文等,2005; Zhou *et al.*, 2007)。董树文和邱瑞龙(1993)、侯增谦(2004)、李曙光等(1998)、Mao *et al.* (2006)等皆强调了大别山演化或大别山前陆环境对长江中下游成矿带成岩成矿构造背景的重要制约作用。董树文

和邱瑞龙(1993)认为大别山前陆挤压环境控制成岩成矿,侯增谦等(2004)认为区域成矿流体的大规模侧向运移与大别造山带的演化有关,李曙光(2001)提出华北与扬子陆块的深部缝合线可能位于长江中下游一带的假说,认为它是长江中下游成矿带在早白垩世发生大规模引张及地幔上隆的深部构造背景。Mao *et al.* (2006)基于成矿年代学研究结果认为,大别造山带演化塑造了长江中下游地区深部近东西向的地幔隆起背景,对燕山期成岩成矿起控制作用,作为中国东部大规模成矿作用的组成部分,长江中下游地区铜金矿床的形成与岩石圈构造体制大转换之地球动力学事件相耦合,为中生代第二期大规模成矿作用的产物。吕庆田等(2004)认为长江中下游地区自二叠纪末经历了碰撞挤压、拆沉伸展、底侵熔融等重要地球动力学过程,并最终形成了长江中下游巨型成矿带。

很多学者强调古太平洋板块运动的影响(Sun *et al.*, 2007; Li *et al.*, 2000)。朱光等(2003)认为,早白垩世时期古太平洋板块的不断斜向俯冲导致郟庐断裂带的左行平移,引发同期的岩浆活动,本区处于转换挤压的岩浆弧环境,盆地经历了不同的大地构造和地球动力学背景,与早期前陆变形和晚期库拉—太平洋板块的俯冲导致的岩石圈上拱拉张有关。汪洋等(2004)认为长江中下游地区早白垩世早期处于大陆边缘岩浆弧内陆一侧,与铜金矿床有关的岩浆活动与白垩世初(约 140 Ma)古太平洋板块高速斜向俯冲(Maruyama *et al.*, 1997)有关,而早白垩世晚期(约 130 Ma 之后)俯冲板块变陡,诱发造山崩塌和弧后伸展,形成具有弧后环境特征的高度富钾的火山岩和 A 型花岗岩。尚彦军等(1999)通过盆地构造分析认为,长江中下游地区陆相火山盆地为侏罗—白垩纪的走滑引张盆地,但杜旭东等(2000)认为包括宁芜和庐枞盆地在内的中国东部中生代火山盆地是中生代滨太平洋板块俯冲挤压中国大陆板块的结果,是在总体挤压背景下形成的。

2 成岩成矿地球动力学过程

在岩浆成岩动力学方面,众多研究者认为,中国东部燕山期大面积出露的花岗质岩石是壳幔相互作用的直接产物(Richards and Noble, 1998; 周新民等,2006; 吴福元等,2003; 徐夕生等,2004,徐夕生和谢昕,2005; 杨德彬等,2008),基性岩浆底侵并与地壳间的相互作用是形成这些花岗质岩石的主要机制,幔源岩浆在大陆地壳生长与演化过程中起到重要作用。

长江中下游地区大陆壳的形成具有多阶段演化特点,该区的基底主要是晚太古—早、中元古代变质岩系,具有由晚太古—早元古代和中元古代变质岩系组成的“双层结构”和以震旦系—三叠系为盖层的多个基底块体构成“一盖多底”的地壳结构特点(常印佛等,1991,1996),唐永成等(1998)划分了该区 4 种变质基底,这些基底的化学分区明显(马振东

和单光祥,1997; Zhou and Yue,2000)。幔源岩浆与不同类型地壳岩石的相互作用对该区岩浆岩的成分变化有重要影响(常印佛等,1991;周涛发,1993;邢凤鸣和徐祥,1999;陈江峰和江博明,1999)。邢凤鸣和徐祥(1999)基于岩浆岩的深部构造信息认为岩石圈地幔上隆参与成岩成矿作用。基于 Sr-Nd 同位素组成,陈江峰和江博明(1999)认为扬子板块东南部的基底是不均一的,长江中下游的安徽段晚中生代花岗岩类的同位素组成可分为三组:江北的花岗岩类显示略亏损、富集地幔与大别基底的混合的特征,江北沿大别造山带东缘的基底很可能与大别造山带是一样的;沿江地区闪长岩、石英闪长岩和花岗闪长岩小岩株属略亏损、富集地幔或富集的古老地壳(与崆岭群相似)端元,沿江地区的基底可能存在老到太古宙的古老地壳;江南地区花岗岩和花岗闪长岩岩基属略亏损/富集地幔与相当于上溪群的地壳物质的混合。

近年来,众多研究皆发现,长江中下游地区晚中生代与成矿作用关系密切的中酸性岩的形成是一种壳幔物质混合过程的产物,长江中下游地区陆下地幔具有富集特征,为扬子型岩石圈地幔与软流圈地幔混合的产物(常印佛等,1991;邢凤鸣和徐祥,1999;唐永成等,1998;陈江峰等,2001;周涛发,1993;周涛发等,2005),AFC 过程为主要成岩机制(邢凤鸣和徐祥,1999;周涛发,1993;周涛发等,2005)。陶奎元等(1998)基于 Nd-Sr 同位素模拟提出长江中下游地区在 140 Ma 前后次富集型石榴子石二辉橄榄岩上地幔 5%~10% 的部分熔融并与下地壳岩石混染形成的富碱玄武岩岩浆经过结晶分异和同化混染作用(AFC 过程)形成高钾钙碱性的闪长岩类,而富集型石榴子石二辉橄榄岩上地幔在 125 Ma 前后发生大约 8% 的部分熔融形成的碱性玄武岩岩浆经过下地壳 15%~20% 的 AFC 过程形成橄榄安粗岩系岩石,A 型花岗岩是交代地幔部分熔融形成的闪长质岩浆进一步发生角闪石、斜长石和钛磁铁矿的高压分离结晶作用形成的。周涛发等(2005)和邢凤鸣和徐祥(1999)等模拟认为,安庆和铜陵矿集区的高钾钙碱性闪长岩类为 70% 的幔源岩浆和 30% 的地壳物质经过 AFC 过程形成的。

张旗等(2001)将该区与铜金矿床有关的高 Sr 低重稀土元素的燕山期中酸性岩岩体归入埃达克岩,赵振华和涂光炽(2003)、王强等(2001,2003)和许继峰等(2001)认为这些岩石为下地壳部分熔融形成的埃达克岩。由于埃达克岩的形成与俯冲洋壳的熔融、玄武岩岩浆的底侵、下地壳拆沉等深部过程有关(Defant *et al.*,2002; Petford and Atherton,1996; 吴福元等,2003),且常与大型斑岩及热液型铜金矿床关系密切(Oyarzun *et al.*,2001; Cooke *et al.*,2005),因此,长江中下游地区存在埃达克岩的认识,对于深入理解该区岩石大地构造背景和区域成矿作用机理有着重要的促进意义。不同于张旗、王强等人(张旗等,2001;王强等,2001;朱光等,2003; Robert *et al.*,2002)强调的下地壳作用,唐永成等(1998)、邢凤鸣和徐祥(1999)、陈江峰等(2005)认为长江中下游地区

包括埃达克岩在内的高钾钙碱性系列和橄榄安粗岩系列岩石等为伸展背景下富集岩石圈地幔部分熔融形成的玄武岩岩浆经 AFC 过程进一步演化的产物。

包括长江中下游地区在内的中国东部中生代基性岩也普遍反映富集岩石圈地幔的特征(李曙光,2001;毛景文等,2005;陈江峰等,2001;闫峻等,2003;袁峰等,2008)。基性岩的地幔源区可看作为亏损端元(DMM)和富集端元(EMII)的混合,DMM 端元很可能是软流圈地幔,而 EMII 端元则可能代表扬子地块的岩石圈地幔,但是软流圈地幔和岩石圈地幔之间的混合机理尚须深入研究。长江中下游基性岩源区表现出来的富集特征与北大别基性岩—超基性岩很相似(李全忠等,2008;石永红等,2008),整个中国东部的中生代基性岩都表现出类似的富集特征,不能排除中国东部中生代基性岩地幔源区的富集是一种共同特征。

邓晋福等(1999),邓晋福和吴宗絮(2001)研究认为包括长江中下游地区在内的中国东部燕山期岩石圈—软流圈系统大灾变事件形成了深部的成矿环境。杜杨松等(2004,2007)、秦新龙等(2003)通过对铜陵地区闪长岩中岩石包体及其矿物学和包裹体研究发现,角闪石中硫化物包裹体是上地幔的硫化物随着玄武岩岩浆底侵到下地壳后进一步演化的结果,该认识为该区大陆动力学演化过程中复杂的壳幔作用导致成岩成矿提供了有说服力的证据。

3 成岩成矿作用时空格架

长江中下游地区的成岩成矿作用是中国东部中生代大规模成岩成矿作用(常印佛等,1991;翟裕生等,1992;Pan and Dong,1999)的典型代表,特色显著,具有爆发性、阶段性、分区性和专属性等特点。翟裕生等(1992)通过一大批早期发表的 K-Ar,Rb-Sr 同位素数据,曾提出长江中下游地区燕山期成岩成矿时代为 170~90Ma,其中,矽卡岩型—斑岩型 Cu-Mo-Au 矿床的形成时间为 170~130Ma,矽卡岩型铁矿及 Fe-Cu 矿床为 160~120Ma,玢岩铁矿为 130~90Ma。近年来随着同位素定年技术的提高和对长江中下游地区成岩成矿时代研究的不断深入,获得了成矿带中主要岩浆岩的一系列高质量同位素年代数据(杜杨松等,2007;陈江峰等,2005;周涛发等,2007;Kempe *et al.*,2001;华仁民和毛景文,1999;吴才来等,2003;王彦斌等,2004;Xie *et al.*,2007;Ding *et al.*,2006;刘洪等,2002;谢智等,2007;谢成龙等,2007,2008,牛漫兰等,2008),本区岩浆活动的时空格架已基本建立。同时,关于该区燕山期成矿作用的时间,随着成矿年代学的发展,近年来该成矿带已积累了部分矿床的精确同位素年龄数据。周涛发等(2003)测得安庆—贵池矿集区中月山热液脉状铜矿的 Ar-Ar 同位素年龄为 134.8 ± 0.7 Ma, Sun *et al.* (2003)测得安庆月山热液脉状铜矿中辉钼矿的 Re-Os 年龄为 136.1 ± 2.0 Ma,铜陵狮子山矿田辉钼矿的 Re-Os 年龄为 138.0 ± 2.5 Ma,毛景文等(2004)测得铜陵等矿集区 5 个

辉钼矿样品的 Re-Os 年代,认为长江中下游地区 Cu-Mo-Au (Fe) 矿床形成于 $134.7 \pm 2.2\text{Ma} \sim 143.7 \pm 1.6\text{Ma}$ 之间。Xie *et al.* (2007, 2008a) 测得鄂东南矿集区 Cu-Mo-Au 矿床的 Re-Os 年龄为 $137.7 \pm 1.7\text{Ma} \sim 144.0 \pm 2.1\text{Ma}$ 之间,程潮和金山店矽卡岩型铁矿床中金云母的 $^{40}\text{Ar}-^{39}\text{Ar}$ 同位素坪年龄分别为 $132.6 \pm 1.4\text{Ma}$ 和 $131.6 \pm 1.2\text{Ma}$, 对应等时线年龄为 $136 \pm 4\text{Ma}$ 和 $132.0 \pm 2.8\text{Ma}$ 。关于玢岩铁矿形成时代,余金杰和毛景文(2002)通过对宁芜玢岩铁矿中的钠长石的 Ar-Ar 法测定,获得 $122.9 \pm 0.2\text{Ma}$ 和 $124.9 \pm 0.3\text{Ma}$ 的 2 个年龄数据,马芳等(2006)测得宁芜地区铁矿床中磷灰石的 $^{208}\text{Pb}-^{232}\text{Th}$ 等时线年龄为 124Ma , 晚于张旗等(2003)利用 SHRIMP 锆石 U-Pb 方法测得大王山组火山岩年龄 ($127 \pm 3\text{Ma}$) 和龙王山组火山岩年龄 ($131 \pm 4\text{Ma}$), 初步说明了玢岩铁矿的形成略晚于火山岩,表明产于宁芜—庐枞火山盆地中的玢岩铁矿床与盆地中的岩浆活动有关,断凹区铁矿床的成矿时代略晚于断隆区的铜铁金矿床。但玢岩铁矿的同位素年龄数据仍然十分缺乏,还不足以形成规律性认识,与碱性岩有关的成矿流体系统还缺乏同位素年龄制约。

以上表明,相比中国东部大规模花岗岩活动发生于 $80 \sim 180\text{Ma}$ 之间(华仁民和毛景文,1999; 毛景文等,2005),长江中下游成矿带的成岩成矿作用发生的时间和空间相对更集中。岩浆岩的形成时间主要介于 $145 \sim 120\text{Ma}$ 之间(图 2),同一矿

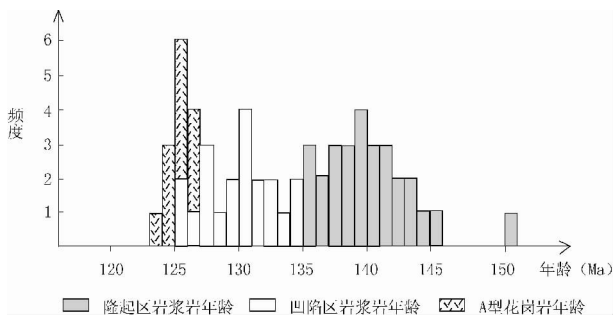


图 2 长江中下游岩浆岩年龄频谱图

资料据: 周泰僖等,1993; 吴才来,2003; 张旗等,2003; 王彦斌等,2004; 徐夕生等,2004; 丁昕等,2005; 张达等,2006; 楼亚儿和杜杨松,2006; Xue *et al.*, 2006; 杜杨松等,2007; 谢成龙等,2007; 谢桂青等,2006b; Li *et al.*, 2008; Wang *et al.*, 2007; 周涛发等,2007; Zhou *et al.*, 2008; 范裕等,2008; 徐晓春等,2008a; 王建中等,2008; 杨小男等,2008; 张乐骏等,2008; Xie and Mao, 2008

Fig. 2 Age frequency spectrum for magmatic rocks around the Middle and Lower Reaches of the Yangtze River

Data after Zhou *et al.*, 1993; Wu, 2003; Zhang *et al.*, 2003; Wang *et al.*, 2004; Xu *et al.*, 2004; Ding *et al.*, 2005; Zhang *et al.*, 2006; Lou and Du, 2006; Xue *et al.*, 2006; Du *et al.*, 2007; Xie CL *et al.*, 2007, 2008; Xie GQ *et al.*, 2006b; Li *et al.*, 2008; Wang *et al.*, 2007; Zhou *et al.*, 2007, 2008; Fan *et al.*, 2008; Xu *et al.*, 2008a; Wang *et al.*, 2008; Yang *et al.*, 2008; Zhang *et al.*, 2008; Xie and Mao, 2008

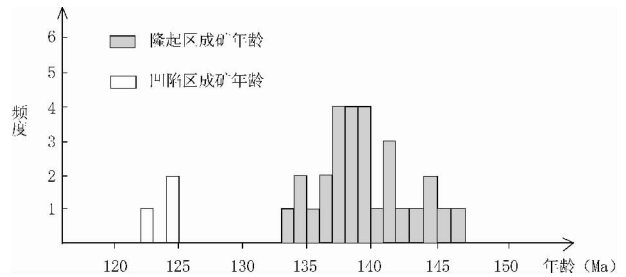


图 3 长江中下游成矿年龄频谱图

资料据: 吴良士和邹晓秋,1997; 余金杰和毛景文,2002; Sun *et al.*, 2003; 周涛发等,2003; 毛景文等,2004; 曾普胜等,2004; 蒙义峰等,2004; 梅燕雄等,2005; 李进文等,2007; 马芳等,2006; 谢桂青等,2006a, 2008a

Fig. 3 Age frequency spectrum for mineralization around the Middle and Lower Reaches of the Yangtze River

Data after Wu and Zhou, 1997; Yu and Mao, 2002; Sun *et al.*, 2003; Zhou *et al.*, 2003; Mao *et al.*, 2004; Zeng *et al.*, 2004; Meng *et al.*, 2004; Mei *et al.*, 2005; Li *et al.*, 2007; Ma *et al.*, 2006; Xie *et al.*, 2006a, 2008a

集区内的岩体与矿床的形成年龄几乎相同或相近(图 3)。该区大规模成矿作用与中酸性岩浆活动有关(翟裕生等,1992; 常印佛等,1991),成岩成矿作用的发生集中在 25Ma 左右的时间内,呈现显著的爆发式的成岩成矿作用特点。

同时,长江中下游地区的岩浆活动在时空上表现出明显的分区性和演化趋势(Zhou *et al.*, 2008)。145 ~ 135Ma 的岩浆活动主要发生在断隆区(如铜陵地区等),是铜金矿化的主要时期;而 135 ~ 127 Ma 的岩浆活动主要发生在断凹区(如庐枞盆地、宁芜盆地等),是铁矿化的主要时期;之后的 A 型花岗岩集中形成于 127 ~ 123Ma,既可以产于断隆区,又可以产于断凹区(图 2, 图 3),与铀、金矿化有关(范裕等,2008)。

成岩成矿还具有较明显的阶段性和分带(区)性(Zhou *et al.*, 2008),自西向东,成岩成矿的时代有变小的趋势(常印佛等,1991; 周涛发等,2008)。陈江峰等(2005)、周涛发和岳书仓(2000)、Zhou *et al.* (2008)的研究表明,长江中下游地区不同矿集区的成岩成矿时代阶段性大致为 145 ~ 137Ma、135 ~ 127Ma、126 ~ 123Ma 等三个阶段。

长江中下游地区断隆区和断凹区的成岩成矿差别十分明显,矿化类型、岩浆岩的岩石组合及岩性也表现较明显的分区性和分带性,如下扬子地区中间带(主带)为高碱钙碱性岩系和橄榄安粗岩系,两侧为钙碱性岩系。主带的岩石组合多样,如铜陵矿集区等地的高钾钙碱性岩石组合(由辉石二长闪长岩、闪长岩、石英闪长岩和花岗闪长岩等组成)、宁芜和庐枞矿集区高钠钙碱性侵入岩(以辉石闪长岩和二长岩为主)、橄榄安粗岩系火山岩组合(粗安岩、粗面岩、安山岩和玄武岩等)、宁芜地区的碱性火山岩组合(假白榴石响岩、蓝方石响岩)等(常印佛等,1991; 邢凤鸣和徐祥,1999)。以鄂东南为代表的隆凹过渡区,出现钙碱性—碱钙性岩浆岩为主,

包括闪长岩、石英闪长岩、花岗闪长(斑)岩、花岗岩等,以及双峰式火山岩(粗面岩和流纹岩等)。在成岩成矿关系方面,断隆区的高钾钙碱性岩石与矽卡岩型—斑岩型铜铁金矿床关系密切,断凹区的橄榄安粗岩系火山一次火山岩与玢岩型(或 IOCG 型)铁矿化有关(常印佛等,1991;翟裕生等,1999;唐永成等,1998),但同为断凹区的上叠式火山盆地和继承性火山盆地的铁矿化强度和规模存在很大差异,有研究者将其归咎于三叠系中膏盐层的影响和控制作用(胡文瑄和胡受奚,1991;常印佛等,1991),而隆凹过渡区的花岗闪长(斑)岩与铜金铂矿床关系密切,石英闪长岩与铁(铜)矿床关系密切,前者早于后者(谢桂青等,2006a,2008a)。秦克章等(1999)强调断裂控矿作用,认为长江中下游地区燕山早期 NWW—EW 向深断裂控制铜、铂、铁、金矿带的分布,而燕山晚期 NNE—NE 向深断裂控制铁及铁、铜、硫等矿带的分布,二者重叠和交接处则形成复合的矿带。

长江中下游地区爆发式的成岩成矿作用是中国东部大陆岩石圈减薄环境中大规模成矿作用的一个重要组成部分,虽然在成岩成矿时代上与中国东部其他地区有着一定的相似性,但在岩浆岩成分、矿化类型与矿床组合等方面存在较大的差异,显示了长江中下游地区在中国东部中生代大规模成岩成矿作用中的独特性,表明成矿作用既与壳幔作用、岩浆作用等深部过程密切相关,又在很大程度上受制于浅部过程的制约。浅部过程主要反映在浅部构造、地层、岩浆岩和其他围岩等对成矿流体系统的化学和物理化学演化和矿质沉淀的重要影响,是成矿流体系统演化最终能否成矿的关键。常印佛等(1991)曾总结出长江中下游成矿带“一断裂、二序列、三环境、四层位”的区域控矿基本规律,周涛发(1993)、周涛发等(2002,2005)量模拟和确定了矽卡岩型铜金矿床水岩作用过程中岩浆(岩)和地层对成矿物质的贡献,郭吉保等(2000)应用氧同位素交换动力学原理讨论了矽卡岩的形成过程,揭示了成矿浅部过程研究的意义,但浅部过程仍有待深入研究。

4 成矿流体系统演化

长江中下游成矿带矿床类型多样,成矿流体系统演化复杂(邓军等,2004,2006;周涛发等,2002;肖新建等,2002),对部分矿床特别是层状、似层状矿床如新桥、冬瓜山、武山、城门山等矿床的成因存在争论(Pan and Dong,1999;Mao et al.,2006;Guo et al.,2001;杨竹森等,2004;陆建军等,2008;蒋少涌等,2008)。长江中下游成矿带中生代铜铁金多金属矿床成矿流体(子)系统的基本类型有:(1)与高钾钙碱性岩系有关的“广义矽卡岩型”成矿流体系统(常印佛等,1991;周涛发和岳书仓,2000;周涛发等,2005)或称矽卡岩—斑岩—层状铜铁金矿床(Pan and Dong,1999;Mao et al.,2006)的成矿流体系统,可进一步划分为与高碱富钾(花岗)闪长岩类有关的铜金矿床成矿系统和与高碱富钠闪长岩

类有关的铁矿床成矿系统;(2)与橄榄安粗岩系有关的“玢岩铁矿型”成矿流体系统(宁芜研究项目编写小组,1978;陈毓川等,2006);(3)与碱性岩有关的铜铅锌铂金矿床成矿流体系统(Zhao et al.,2004;Zhou et al.,2008)等;(4)与碱性岩有关的 U, Au, Fe, Cu, Pb, Zn 矿床成矿流体系统(Zhao et al.,2004;Zhou et al.,2008)(5)与岩浆活动关系不明显的 Tl, Au, Sb, Pb, Zn 低温成矿流体系统(周涛发等,2007;范裕等,2007;Zhou et al.,2005)。此外在系统(2)中新近识别出与橄榄安粗岩系有关的高硫型浅成低温成矿流体系统(Zhou et al.,2008)。上述不同类型成矿流体系统的来源、形成的动力学背景和过程、流体系统演化的 p - T - t - x 结构及其不同类型成矿流体系统的相互关系等是该成矿带今后成矿流体系统研究的中心内容。

长江中下游成矿带矽卡岩型矿床成矿流体系统的研究程度相对较高,前人对铜陵矿集区(赵斌等,2002;徐兆文等,2005;赵劲松等,2003;肖新建等,2002;徐晓春等,2008b;刘亮明等,2008)鄂东南矿集区(赵斌等,2002;徐兆文等,2005;Xie et al.,2007;赵新福等,2006;谢桂青等,2008a,b)和安庆—贵池矿集区(周涛发等,2002,2005)的成矿流体系统开展了较多和深入的研究工作,主要表现在对成矿流体性质、来源与演化方面的研究。邓晋福等(2002)识别出长江中下游成矿带 8 个岩浆—流体—成矿系统和多个亚系统,邓军等(2004,2006)总结了铜陵矿集区构造流体成矿系统演化格架,并模拟和构筑了矿集区浅层含矿岩浆输运网络与运移机制。矽卡岩中熔融包裹体的发现(凌其聪等,1998;邓晋福等,2002;徐兆文等,2005)深化了这类矿床成矿流体来源研究程度。谢桂青等(2006a)认为形成鄂东南地区的矽卡岩型铁、铜矿床的成矿流体为深源流体。Pan and Dong(1999)通过综合对比研究,认为下扬子地区的矽卡岩—斑岩—层状块状硫化物矿床的形成与燕山期侵入岩浆作用有关,成矿流体主要为演化的岩浆热液。肖新建等(2002)、徐兆文等(2005)发现铜陵狮子山铜金矿床来源于岩浆的成矿流体发生了多次沸腾作用导致了成矿富集,黄顺生等(2003)通过冬瓜山铜矿床的流体包裹体地球化学研究发现,形成矿床的成矿热液为岩浆热液和少量大气降水混合形成的,但陆建军等(2008)认为该矿床成矿流体系统的演化经历了石炭纪的海底喷流作用和燕山期的岩浆热液叠加,Xu et al.(2000)通过流体包裹体研究认为繁昌长龙山层状铁矿床为岩浆热液交代成因而非前人认为的同生沉积成因。在蚀变—流体填图的基础上,曾普胜等(2004)、杨竹森等(2004)提出铜陵矿集区存在海西期喷流沉积和燕山期岩浆热液两种流体成矿系统。顾连兴等(2003)则认为,长江中下游成矿带的铜金矿床主要是古生代海底喷流成矿流体系统形成的,燕山期受岩浆流体系统影响,原块状硫化物矿床中的成矿物质被活化、迁移和改造形成矽卡岩等类型的铜矿床。侯增谦等(2004)提出了与大别造山带演化有关的长江中下游成矿带区域成矿流体的大规模侧向运移成矿模式。

近年来,长江中下游成矿带流体演化过程中的水-岩反应及动力学过程模拟(於崇文等,1998;岑况和於崇文,2001;周涛发等,2000a,2005)的研究也取得较大进展。基于流体动力学、流变学、传热学和热力学以及微量元素和同位素地球化学的研究,於崇文等(1998)、岑况和於崇文(2001)对铜陵矿集区开展了成矿动力学的深入研究,周涛发等(2000a,2005)对安庆—贵池矿集区内岩浆的分凝、上升、对流、定位和结晶等岩浆作用过程的速度与机理、熔体—流体分离作用程度及其对含矿岩浆热液系统的形成具重要的制约作用进行了计算和分析,提出巨量金属堆积需要一个巨大的岩浆—流体成矿系统来供给和支持。余金杰等(2003,2007)等还探讨了玢岩铁矿中磷灰石地球化学对成矿流体来源的示踪,范裕等(2007)、Zhou *et al.* (2007)对成矿带北外侧以铈为代表的低温成矿流体系统进行了较系统研究,并初步讨论了长江中下游成矿带高中温成矿流体系统与中低温成矿流体系统之间的关系。

5 有待解决的主要科学问题

对长江中下游成矿带以往大量的研究取得了上述重要的研究进展和成果,但揭示出许多重要科学问题有待进一步研究。

(1) 长江中下游成矿带的构造背景既受整个中国东部的构造背景控制,又存在自身演化的特殊性,处于明显的转换复合的构造背景。这种构造背景可能与扬子板块、华北板块、古太平洋板块相互作用及其与壳幔作用的耦合过程密切相关。长江中下游成矿带燕山期成岩成矿作用的陆内转换的构造背景及其与多块体之间的关系仍存在较多争论,本区构造格局及其演化的具体方式、过程、时限和阶段性及其与成岩成矿作用的关系需要更多的资料积累与支持,亟待开展相关研究与探索。

(2) 长江中下游地区燕山期的岩浆岩和铜铁金多金属矿床是复杂的大陆动力学过程的产物,岩石圈伸展—减薄、玄武质岩浆底侵和大规模岩浆活动,可能是包括长江中下游地区在内的中国东部显著的大陆动力学事件。但关于地幔端元性质、富集地幔的成因、壳幔作用的方式与精细过程及其对成岩成矿的制约作用仍有待深入研究。成矿流体系统形成与岩石圈伸展减薄、壳幔相互作用、不同系列岩浆岩的形成等大陆动力学过程之间的关系研究亟待加强,构造演化过程与成矿带、矿集区的形成、岩浆活动、成矿作用发生的动力学机制、内在联系及耦合关系及其对壳幔作用等深部过程的响应等还缺乏更多具体和有说服力的地质地球化学证据支持。在注重成岩成矿深部过程研究的同时,浅部过程对成矿的控制作用研究需重视与加强,如区域主要断裂构造、主要赋矿地层以及火山盆地(上叠式盆地和继承式盆地)沉积学差异、膏盐层沉积学特征及其对成矿流体系统演化的影响等。

(3) 长江中下游成矿带岩浆活动与成矿作用的时空结构特点、成岩成矿作用分区、分带性和阶段性等,需要开展更多高精度的同位素定年特别是不同类型矿床的成矿年代学工作。控制成岩成矿分区性和阶段性的根本原因是什么?为何在三类不同的次级构造环境中出现不同的成岩成矿作用类型?不同类型岩浆岩和矿床的成因、成岩成矿关系研究尚需进一步加强。成矿浅部过程的研究仍有待重视和加强,长江中下游成矿带主要区域构造和矿田构造性质与演化、主要赋矿地层的沉积学和地球化学特征、不同性质火山盆地的构造与沉积学差异特别是膏盐层等成矿等浅部要素和背景对成矿流体系统演化的影响、不同系列的岩浆岩和矿床以及不同矿集区的流体成矿系统演化的机制、过程及精细的时空格架有待更深入的研究。

(4) 长江中下游成矿带成矿流体系统类型及相互关系、成矿流体的来源、组成、形成与演化的物化条件和动力学过程、成矿物质沉淀和聚集机制等研究尚不系统,特别是与玢岩型铁矿及中低温热液型多金属矿床的成矿流体系统形成、演化过程及精细时间结构仍有待进一步的成矿流体地质地球化学和成矿年代学研究工作,成矿流体系统演化的 p - T - t - x 轨迹与模型的构筑,需要大力加强不同类型成矿流体系统特别是与橄榄安粗岩系有关的“玢岩铁矿型”成矿流体系统、与高碱富钠闪长岩类有关的铁矿床成矿系统、与碱性岩有关的铜铅锌铀金矿床成矿流体系统以及浅成低温成矿流体系统等形成与演化及其相互关系的深入研究。

(5) 对同一矿集区中不同产出形式的矿床如铜陵的矽卡岩型矿床和层状硫化物矿床成因认识争议仍很大,复合叠加型矿床的形成机制需要更多地质证据支持,矽卡岩型铜矿与斑岩型铜矿的关系、高中温矿床和中低温矿床的关系、高硫型浅成低温热液矿床与玢岩铁矿的关系等需要加强研究。成矿带及矿集区时空结构及矿化分带的决定因素及其与成矿流体系统演化的关系有待进一步理清,岩浆岩成矿专属性、基底和地层系统对矿床产生的影响和制约、成矿规律和深部成矿潜力等方面有着广阔的研究前景。

上述科学问题的解决必将导致对长江中下游成矿带的形成演化和成矿作用认识的又一次飞跃,推动该重要成矿带成矿理论的发展和找矿勘查的进步,为促进成矿带成矿流体系统研究、深化成矿系统和大陆成矿理论做出重要的贡献。

6 结语

综上所述,长江中下游成矿带由于其形成处于中生代转换复合的构造体制、强烈的壳幔相互作用等复杂的大陆动力学过程、爆发式的多阶段岩浆活动和大规模的铜铁金多金属成矿作用、多类型的流体成矿系统以及巨大的“第二找矿空间”找矿潜力等特点,奠定了该区作为探索陆内动力学过程与多金属成矿关系、开展陆内成矿带成岩成矿作用和成矿系统研究的不可多得的天然实验室和绝佳场所。为了总结和

展示长江中下游成矿带成岩成矿作用研究现状,本辑《岩石学报》汇集了国内不同研究机构的 20 余位中青年研究者近年来对该区及其邻区开展的与成岩成矿作用有关的研究成果,相信这些成果的刊出将会把长江中下游成矿带成岩成矿作用研究推向一个新的阶段。

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长江中下游成矿带成岩成矿作用研究进展

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- 鄂尔多斯盆地三叠-侏罗系的成岩作用显示出受周边活动带干扰的类克拉通型特征。来自北部老山的岩浆岩碎屑、铁镁质矿物及火山喷发的火山灰导致在同生。早期成岩阶段孔隙水中释放大量的铁、硅、铝等离子, 从而析出大量蒙脱石和富铁的绿泥石、沸石类和硅质矿物; 在上三叠统中夹有由火山灰成岩转变而成的多层斑脱岩; 同时导致富铀碎屑的聚集和由于粘土矿物、褐煤等的吸附作用造成的轴离子的预富集。在中成岩阶段, 石油生成并在粘土矿物放出大量孔隙水作为载体的情况下初次运移, 有机溶液进入储层使铝硅酸盐矿物溶解产生次生孔隙; 同时蒙脱石和伊利石对油和气的生成具有催化作用, 显示出典型的有机-无机成岩成藏作用过程。中晚燕山运动是一次构造热事件, 此时期发生的表生成岩阶段是鄂尔多斯盆地成藏成矿的重要时期, 不但促进了三叠系油和古生界天然气的生成, 而且提供了油气运聚成藏的动力学条件; 另一方面, 天然气向盆地北东向的大规模运移散失造成强还原环境, 促使具备储矿形成条件的东胜地区侏罗系中大型铀矿的形成, 是典型的有机-无机成岩成矿作用的结果。
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