北秦岭铜峪铜矿床铅同位素的 fsLA-MC-ICP-MS 微区原位分析测定及其地质意义

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摘要 利用飞秒激光剥蚀多接收等离子体质谱(fsLA-MC-ICP-MS)微区原位分析技术对铜峪铜矿床的矿石硫化物以及赋矿火山岩、矿区煤沟岩体和火山碎屑岩中的长石进行了Pb同位素组成的系统测定分析. 分析结果表明, 矿石和赋矿火山岩的Pb同位素比值相似, 反映了成矿物质与赋矿火山岩同源, 在Pb同位素构造演化图解中, 二者大多数样点集中于地幔演化线和造山带演化线附近, 表明矿石和赋矿火山岩中的铅主要来源于地幔和下地壳的混合铅; 矿区煤沟岩体Pb同位素组成高于矿石和赋矿火山岩, 分布趋势与矿石和赋矿火山岩相似, 主体落在造山带演化线附近; 火山碎屑岩Pb同位素组成投点落入上地壳演化线附近, 远离于矿石、赋矿火山岩和煤沟岩体分布范围. 在 $\Delta\gamma$ - $\Delta\beta$ 成因分类图解中, 大多数矿石、赋矿火山岩和煤沟岩体样品点落入与岩浆作用有关的俯冲带铅范围内, 且与形成于岛弧环境的东秦岭VHMS型铜矿床、新疆阿尔泰山南缘多金属成矿带矿石的Pb分布范围重叠或接近, 指示成岩成矿与俯冲作用有关的壳-幔相互作用关系密切. 铜峪铜矿床和煤沟岩体形成于与早古生代商丹洋壳北向俯冲作用有关的岛弧环境, 成矿物质与赋矿火山岩同源.

关键词 铜峪铜矿床, 飞秒激光剥蚀, 铅同位素, 成矿物质, 岛弧环境

铅(Pb)同位素由于其质量大, 同位素间的相对质量差较小, 外界条件的变化对其组成的影响很小, 故铅同位素组成具有明显的“指纹特征”^[1-3]. 由于现有不同的地质体的物质来源、成因机制、形成环境及形成时间不一, 因而就各自具有不同的铅同位素标记特征, 故铅同位素可作为判断物质来源的可靠示踪剂^[2,4-9]. 铅同位素组成的变化不仅遵循放射性衰变规律, 而且还与其形成的大地构造环境密切相关, 如地幔、地壳及造山带有其特定的铅同位素组成^[2,4-6,10,11], 铅同位素组成被认为是判断矿床成矿物

质来源及其形成大地构造环境的理想指标^[2,3,9,12-16], 铅同位素组成的准确分析测定备受重视^[17-24]. 长期以来, 铅同位素的分析方法主要为采用整体化学溶样法后利用TIMS或MC-ICP-MS对样品整体分析测定^[17,20,25]. 整体分析法虽精度较高, 但样品处理复杂、易污染、实验周期长, 且所得到的铅同位素组成针对性不强, 难以反映地质样品形成过程中体系同位素组成的变化细节, 如岩浆受到围岩的混染作用、不同性质流体的混合作用等导致铅同位素组成的变化信息难以在整体分析获得的铅同位素组成被识别.

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微区原位Pb同位素分析可针对不同的矿物颗粒或同一矿物颗粒的不同组成部分进行分析,因此选择合适的矿物开展微区原位Pb同位素分析,根据矿物颗粒代表不同结晶时间的部分(如结晶环带、增生核与增生边等)的组成特征,将为认识地质事件的演化过程提供整体分析法难以获得的重要信息。

近年来,基于激光剥蚀(LA)进样系统的多接收电感耦合等离子体质谱(MC-ICP-MS)联用技术得到了迅速发展^[26],但LA-MC-ICP-MS分析Pb同位素存在仪器的质量歧视效应、激光剥蚀和传输过程中的分馏效应和外标参考物质的基体匹配等问题^[24,27]。飞秒激光剥蚀(femtosecond-Laser Ablation)即fsLA是激光剥蚀技术的最新研究进展,其激光脉宽(时间)100 fs (10^{-15} s)左右,故飞秒激光剥蚀过程中激光在样品表面作用时间极短,大大降低了基体的热效应,并可在低脉冲能量下获得极高峰值功率,剥蚀颗粒物小于1 μm ,大大提高了传输效率和信号灵敏度,降低了激光剥蚀过程中的元素分馏效应,从而提高同位素分析的精密度和准确度^[28,29]。由于飞秒激光的优越性能,国内外已将fsLA-MC-ICP-MS分析测试技术应用于包裹体、矿物、玻璃和合金等样品的Pb同位素组成分析^[22,23,30]。西北大学大陆动力学国家重点实验室首先在国内建立了fsLA-MC-ICP-MS Pb同位素的高精度微区原位分析方法^[22,24],然而迄今为止,国内外开展过fsLA-MC-ICP-MS Pb同位素微区原位分析研究过的典型矿床鲜见报道^[23]。

火山喷流型块状硫化物矿床(VHMS)是重要的工业矿床,其成矿物质来源和成矿大地构造环境一直是该类矿床研究的关键问题^[31~38]。铜峪铜矿床是陕西省重要的铜矿床,也是北秦岭西部少数认定为与加里东期俯冲增生生成矿有关的典型VHMS型铜矿床^[39,40],大地构造位置上处于北秦岭造山带西部(图1)。前人对铜峪铜矿床的研究工作主要集中在矿床地质特征^[40~43]及成岩成矿时代^[40,44]方面的研究,有关该矿床成矿物质来源及大地构造环境研究仍缺少系统的同位素地球化学研究。本文在铜峪铜矿床矿化地质特征研究基础上,首次利用fsLA-MC-ICP-MS铅同位素微区原位分析技术对该矿床进行了Pb同位素组成的系统测定分析,通过详细的矿床铅同位素地球化学研究,进一步限定了成矿物质来源及成矿大地构造环境,为fsLA-MC-ICP-MS微区原位铅同位素分析技术在矿床学中的推广和应用积累了基础数

据和研究经验。

1 区域地质背景及矿床地质特征

铜峪铜矿床在大地构造位置上处于北秦岭造山带,秦岭与祁连造山带的交汇部位^[45],矿床产于斜峪关群中(图1(a))。北秦岭地区发育的震旦纪至早古生代地层主要为变沉积-火山地层系统。斜峪关群分布于北秦岭中段,西起眉县铜峪,东至商州,东西向延伸达500 km。南、北两侧分别与秦岭群、宽坪群断层接触(图1(a))。斜峪关群时代上归为早古生代,矿区的斜峪关群以中-基性火山岩为主,夹变砂岩及少量火山碎屑岩,地层总体走向为北西西,东西两端分别被太白花岗岩和宝鸡花岗岩所截(图1(b))^[46~48]。整个地层构成了以赋矿火山岩层为核部的北西西向背斜构造,且构造断裂发育,北西-北西西向断裂构造是矿区的主要构造(图1(b)),归属秦岭东西向构造体系^[42],该断裂构造为控矿构造,主要分布于矿区的中心部位,规模不大,大致顺层产出,平行排列,长一般在200~400 m,走向110°~130°,倾向北东,倾角30°~50°,其断裂特征主要以挤压破碎和挤压片理化带表现出来,断裂面普遍光滑平直,两侧片理发育,有时可见擦痕。北东向构造发育程度仅次于北西西向构造,是矿区晚期的一组断裂,此组断裂切穿北西西向断裂和部分花岗岩脉,未见与成矿有明显关系。矿体主要赋存于斜峪关群的一套变玄武岩、变安山岩和变英安岩中(图1(b)),该赋矿火山岩出露于背斜核部,呈层状、透镜状产出,岩石为灰白-灰绿色,普遍遭受蚀变,主要有阳起石化、透辉石化、绿帘石化、绿泥石化、绢云母化和石榴子石化等。矿区南带出露的粗玄岩,同属斜峪关群赋矿火山岩层位,呈近东西向分布,构成了背斜的南翼,于四十亩地处发现铜矿化。火山碎屑岩是矿区分布较广的沉积岩类型之一,主要见于矿区北带(图1(b)),以变安山质角砾岩和变安山质凝灰岩为主,变安山质集块岩、变英安质角砾岩和变英安质凝灰岩零星分布。矿区中部分布有早奥陶世石墨-绢云石英片岩段,组成该段的主要岩石为炭质石英岩、含碳硅质板岩、绢云母石英片岩,局部夹大理岩。其中有稳定的工业石墨矿层。

矿区共有矿体73个,其中主矿体9个,呈大小不等的透镜状、似层状顺层产出,彼此呈雁行状排列。矿体主体走向为120°~140°,倾角30°~50°,连续性较好,厚度变化大,与背斜轴线及北西西向断裂走向一

图1 北秦岭区域地质及铜峪铜矿床地质简图。(a) 据文献[48]修改;(b) 据文献[41]修改

Figure 1 Geological sketch maps of the North Qinling Orogen and the Tongyu copper deposit. (a) Modified after Ref. [48]; (b) modified after Ref. [41]

致,分枝膨缩现象常见.矿体的规模一般长80~300 m,最长可达704 m,延伸一般60~200 m,最大延伸466 m,厚度一般2~15 m,最厚矿体37 m^[43].阳起石化、透辉石化、石榴子石化和绿泥石化与矿化关系密切^[44].矿石中的金属矿物主要有黄铜矿、黄铁矿、磁黄铁矿,次为闪锌矿、磁铁矿,偶尔见有少量的方铅矿和毒砂等.脉石矿物主要有阳起石、透辉石、方解石、绿帘石、石榴子石,次有石英、绿泥石等.矿石结构主要为他形晶粒状结构、半自形-自形晶粒状结构和交代溶蚀结构,次有填间结构、压碎结构等,矿石多为细脉浸染状、脉状及不规则团块状.

矿区内出露煤沟岩体侵入于矿区背斜南翼,北部与铜峪变中-基性赋矿火山岩接触,南部与石墨-绢

云石英片岩段均呈侵入接触(图1(b)),煤沟岩体平面上呈东西延长的椭圆状,其产状与矿区褶皱、断层构造产状基本一致^[40],岩体内仅有零星矿化,未构成工业矿体.

2 样品特征、分析测试方法及分析结果

2.1 样品特征

本文选取了铜峪铜矿床885平硐内2件矿石样品、2件赋矿火山岩、2件煤沟岩体及1件火山碎屑岩样品进行了分析测试.首先将样品磨制成探针片或光片,然后进行了岩(矿)相学显微镜下观察,选择其中的硫化物单矿物(黄铁矿、磁黄铁矿和黄铜矿)和较新鲜的

长石进行了飞秒激光剥蚀多接收等离子体质谱(fsLA-MC-ICP-MS)微区原位Pb同位素分析,实验分析在西北大学大陆动力学国家重点实验室完成。

矿石样品(编号KOS2)的金属硫化物以黄铜矿和闪锌矿为主,黄铁矿次之,黄铜矿为铜黄色,多呈不规则他形散晶粒,粒径一般<0.2 mm,或呈团块浸染状(图2(c));闪锌矿为浅黄棕色或红棕色,呈半自形-他形晶粒或聚晶,粒径在0.2~0.6 mm(图2(a)),含量大于50%,与黄铜矿共生;黄铁矿为黄白色,呈他形-半自形,粒径在0.1~0.7 mm不等,多被闪锌矿、黄铜矿和脉石矿物交代呈残晶或溶蚀呈港湾结构(图2(c), (d)). 矿石TY35样品的金属硫化物主要为磁黄铁矿和黄铁矿,含量大于70%,伴生少量的黄铜矿,磁黄铁矿为暗青铜黄色,呈半自形-他形粒状或聚晶,粒径一般在0.4~0.8 mm(图2(b), (f));黄铁矿多呈半自形-自形晶体与磁黄铁矿共生,粒径在0.2~0.8 mm之间(图2(e)).

变玄武岩(样品TY43)为绿-暗绿色,块状构造,斑状、变余斑状结构,斑晶主要是半自形-自形斜长石,粒度0.5~1.5 mm(图3(a)),有的可见变斑晶辉石呈短柱状或短柱状假象. 基质主要为显微粒状结构、

霏细结构,副矿物有磷灰石和榍石等,岩石局部受到阳起石化、绿泥石化、绿帘石化、绢云母化等蚀变作用,蚀变矿物往往具定向排列。

粗玄岩(样品SG6)呈灰黑色,块状构造,全晶质细粒-等粒结构. 主要矿物由基性斜长石(50%)和普通辉石(35%)组成,次要矿物为角闪石(10%)、橄榄石(5%)和少量的黑云母(图3(b), (c)). 斜长石为半自形粒状、板条状结构,粒度0.4~1 mm,可见聚片双晶、卡钠复合双晶. 普通辉石为浅黄绿色,半自形短柱状,具两组完全解理. 橄榄石为半自形粒状结构,0.3~1 mm,可见橄榄石被辉石包裹,构成包橄结构. 角闪石呈半自形长柱状,粒度较小,常小于0.5 mm,具有轻微绿泥石化. 金属硫化物常充填于辉石和角闪石解理中或构成暗化边。

煤沟岩体岩性为花岗闪长岩(样品MG7和MGG2),呈浅灰色,均一块状构造,半自形粒状结构,粒径在0.5~2 mm之间,主要矿物由斜长石(45%)、碱性长石(20%)和石英(15%)组成,次要矿物有角闪石(10%)和黑云母(5%),斜长石多呈半自形粒状结构,具聚片双晶和卡钠复合双晶,少量具有环带结构;碱性长石主

图2 测定样品的矿相学特征(图中黑色粗线表示飞秒激光剥蚀轨迹). (a) 黄铜矿、闪锌矿及黄铁矿呈稠密浸染状分布于蚀变玄武岩中; (b) 蚀变玄武岩中可见磁黄铁矿和黄铜矿颗粒; (c), (d) 半自形黄铁矿被黄铜矿与闪锌矿交代溶蚀呈港湾状结构; (e) 磁黄铁矿与自形黄铁矿共生; (f) 团块状磁黄铁矿与浸染状黄铜矿共生

Figure 2 Mineralogy characteristics of the measuring samples (thick lines in black represent the femtosecond laser-ablation tracks). (a) Densely disseminated pyrite, sphalerite, and chalcopyrite in altered basalt; (b) chalcopyrite and pyrrhotite association; (c), (d) chalcopyrite and sphalerite replace and corrode subhedral pyrite in harbour texture; (e) association of pyrrhotite and euhedral pyrite; (f) association of massive pyrrhotite and sparsely disseminated chalcopyrite

图3 测定样品的岩相学特征(图中折线表示飞秒激光剥蚀轨迹)。(a) 变玄武岩的斑状结构, 斑晶斜长石, 显微粒状结构基质; (b), (c) 全晶质细粒-等粒状结构粗玄岩; (d), (e) 煤沟花岗闪长岩, 主要矿物为斜长石、碱性长石和石英; (f) 变安山质凝灰岩钾长石斑晶和基质假流纹构造

Figure 3 Petrographic characteristics of the measuring samples (broken lines represent the femtosecond laser-ablation tracks). (a) Porphyritic texture of the meta-basalt, plagioclase phenocrysts and matrix with micrograined texture; (b), (c) dolerite with holocrystalline fine grained-equigranular texture; (d), (e) Meigou granodiorite comprise of plagioclase, alkali-feldspar and quartz; (f) K-feldspar phenocrysts in meta-andesitic tuff and matrix with pseudo-flow structure

要为半自形的条纹长石和微斜长石, 发育较弱的高岭土化。副矿物以锆石(1%)和少量的磷灰石为主(图3(d), (e))。

变安山质凝灰岩(样品XSS1), 呈灰白色, 块状构造, 凝灰或变余凝灰结构, 碎屑物成分主要由晶屑和玻屑组成, 晶屑含量高达60%, 一般具有棱角状、次棱角状, 以碱性长石和斜长石为主, 石英晶屑少量<5%。岩石受次生蚀变不强, 主要为绿泥石化、绿帘石化和绢云母化。局部可见由塑变晶屑和玻屑定向排列所构成的假流纹构造(图3(f))。

2.2 样品分析测试方法及分析结果

首先利用酒精、2% HNO₃、高纯水擦拭样品表面以去除可能存在的污染, 实验测定利用fsLA-MC-ICP-MS和膜去溶装置联机完成。激光剥蚀系统为ESI公司的NWR UP Femto, 该系统由钛宝石放大器的飞秒激光Integra-He和飞秒激光传输光路及样品池和观察系统组成。数据采集采用TRA(Time Resolved Analysis)模式, 积分时间0.2 s, 激光剥蚀能量为6 J/cm², 束斑直径为40 μm, 采用4~20 μm/s的线扫描, 剥蚀时间约50 s。Pb同位素分析采用Nu Instruments公司的多接收等离子体质谱(Nu Plasma II MC-ICPMS)。膜去

溶进样系统由CETAC公司(CETAC Technologies, USA)生产的Aridus II膜去溶系统和Cetac ASX110-24自动进样器组成, 干气溶胶模式灵敏度的提升大于10倍, 氧化物产率维持在极低的水平($CeO^+/Ce^+ < 0.03\%$)。通过Aridus加入Tl标准溶液(NIST SRM 997)校正仪器的质量歧视效应, 校正方法依据幂定律以Tl的分馏因子(Tl校正参数: $^{205}Tl/^{203}Tl=2.38890$, 据文献[49])来校正Pb的分馏因子。国际标准物质NIST SRM 610作为外部标准以监控分析结果的可靠性, 其给出的 $^{208}Pb/^{204}Pb=36.968\pm0.007$, $^{207}Pb/^{204}Pb=15.512\pm0.003$, $^{206}Pb/^{204}Pb=17.051\pm0.003$ 。详细的分析方法和过程可见文献[22~24]。考虑到该方法目前适用于Pb含量高于10 ppm的硫化物^[23], 而铜峪铜矿床矿石中闪锌矿的Pb含量较低(6.52 ppm, 作者未发表的数据), 故本研究选用了铅含量高于10 ppm的硫化物如黄铜矿、黄铁矿和磁黄铁矿的铅同位素测定结果。这些矿物的铅同位素初始比值根据成矿年龄(440 Ma^[44])和其中U, Th和Pb含量计算获得(表S1)。

铜峪铜矿床的矿石、赋矿火山岩、矿区煤沟岩体和火山碎屑岩的Pb同位素数据见表S1。矿石硫化物黄铜矿、黄铁矿和磁黄铁矿的Pb同位素组成较一致(图4), 其中黄铜矿 $^{207}Pb/^{206}Pb=0.857\sim0.858$ (加权平均

值=0.857), $^{208}\text{Pb}/^{206}\text{Pb}$ =2.098~2.105(加权平均值=2.102); 黄铁矿 $^{207}\text{Pb}/^{206}\text{Pb}$ =0.851~0.855(加权平均值=0.854), $^{208}\text{Pb}/^{206}\text{Pb}$ =2.094~2.106(加权平均值=2.100); 磁黄铁矿 $^{207}\text{Pb}/^{206}\text{Pb}$ =0.854~0.856(加权平均值=0.855), $^{208}\text{Pb}/^{206}\text{Pb}$ =2.103~2.114(平均值=2.110).

赋矿火山岩中长石的 $^{207}\text{Pb}/^{206}\text{Pb}$ =0.848~0.855(加权平均值=0.851), $^{208}\text{Pb}/^{206}\text{Pb}$ =2.092~2.112(平均值=2.098); 煤沟岩体的长石 $^{207}\text{Pb}/^{206}\text{Pb}$ 比值介于0.839~0.857之间(加权平均值=0.849), $^{208}\text{Pb}/^{206}\text{Pb}$ 比值明显分为高低两组, 分别介于2.104~2.150之间(加权平均值=2.114)和2.073~2.099之间(加权平均值=2.090). 火山碎屑岩中长石的Pb同位素比值与矿石、赋矿火山岩和煤沟岩体相比明显偏低, $^{207}\text{Pb}/^{206}\text{Pb}$ 和 $^{208}\text{Pb}/^{206}\text{Pb}$ 分别介于0.810~0.849之间(加权平均值=0.835)和2.004~2.100之间(加权平均值=2.069)(图4).

3 铅同位素组成对成矿物质来源及成矿大地构造环境的指示

本次研究所选长石和矿石矿物大多较新鲜且表

面平整, 受蚀变影响微弱. 长石中具有较高的普通Pb和较低的U和Th含量, 形成后由U和Th衰变产生的放射成因铅可忽略不计^[4,10,50], 因此本文长石的铅同位素组成基本可代表成岩时铅同位素初始比值. 矿石硫化物和赋矿火山岩中长石的 $^{207}\text{Pb}/^{206}\text{Pb}$ 和 $^{208}\text{Pb}/^{206}\text{Pb}$ 比值变化范围较为一致(图4), 指示二者具有相同的Pb来源并且形成于统一的构造岩浆事件中; 而煤沟岩体的 $^{207}\text{Pb}/^{206}\text{Pb}$ 和 $^{208}\text{Pb}/^{206}\text{Pb}$ 比值变化范围较大(图4), 可能与其同位素存在一定程度的不均一性有关或者岩石源区成分相对复杂.

在 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 和 $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 图解中, 矿石、赋矿火山岩和煤沟岩体Pb同位素组成均具有高斜率Pb混合线的特征, 表明成矿物质和岩浆至少同时从两个源区起源活化出来并发生混合所形成^[51]. 铜峪铜矿床矿石硫化物的铅同位素组成不均一($^{208}\text{Pb}/^{204}\text{Pb}$ =37.711~38.475, 平均值=38.246; $^{207}\text{Pb}/^{204}\text{Pb}$ =15.388~15.645, 平均值=15.555; $^{206}\text{Pb}/^{204}\text{Pb}$ =17.903~18.321, 平均值=18.164), 其中2/3投点与赋矿火山岩中长石($^{208}\text{Pb}/^{204}\text{Pb}$ =38.229~38.735, 平均值=

图4 铜峪铜矿床 $^{207}\text{Pb}/^{206}\text{Pb}$ 和 $^{208}\text{Pb}/^{206}\text{Pb}$ 同位素比值分布图

Figure 4 Distribution diagram of $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ results for the Tongyu copper deposit

38.547; $^{207}\text{Pb}/^{204}\text{Pb}=15.496\sim15.678$, 平均值=15.615; $^{206}\text{Pb}/^{204}\text{Pb}=18.196\sim18.490$, 平均值=18.347)的Pb同位素投点重合, 少量的矿石Pb同位素(以黄铜矿为主)投点分散在地幔演化线或下延方向. 矿石和赋矿火山岩的大多数样点集中于地幔演化线和造山带演化线附近(图5), 反映了矿石与赋矿火山岩具有亲缘性, 指示矿石和赋矿火山岩中的铅主要属于来自于地幔和下地壳的混合铅. 煤沟岩体MG7样品($^{208}\text{Pb}/^{204}\text{Pb}=38.222\sim38.562$, 平均值=38.410; $^{207}\text{Pb}/^{204}\text{Pb}=15.554\sim15.664$, 平均值=15.618; $^{206}\text{Pb}/^{204}\text{Pb}=18.235\sim18.541$, 平均值=18.397)的Pb同位素组成略高于矿石和赋矿火山岩的Pb同位素组成, 但总体分布趋势与二者相似, 主体落在造山带演化线附近, 指示煤沟岩体与矿石和赋矿火山岩形成的大地构造环境相似, 但煤沟岩体MGG2样品($^{208}\text{Pb}/^{204}\text{Pb}=38.687\sim39.819$, 平均值=39.225; $^{207}\text{Pb}/^{204}\text{Pb}=15.552\sim15.759$, 平均值=15.637; $^{206}\text{Pb}/^{204}\text{Pb}=18.296\sim18.644$, 平均值=18.449)在 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 图解中, 部分样点落入上地壳演化线附近, 推测这部分铅可能是上地壳Pb部分混入的结果. 火山碎屑岩的Pb同位素组成($^{208}\text{Pb}/^{204}\text{Pb}=38.591\sim39.211$, 平均值=38.852; $^{207}\text{Pb}/^{204}\text{Pb}=15.603\sim15.760$, 平均值=15.673; $^{206}\text{Pb}/^{204}\text{Pb}=18.455\sim19.389$, 平均值=18.819)投点落入上地壳演化线附近, 远离于矿石、赋矿火山岩和煤沟岩体分布范围, 表明火山碎屑岩不可能是矿石中铅的主要源区. 矿石硫化物与赋矿火山岩总体上具有相似的Pb同位素组成特征, 显示了成矿物质与赋矿火山岩同源. 已有研究

表明^[40], 煤沟花岗闪长岩为O型埃达克岩, 埃达克型花岗岩与斑岩型金铜成矿作用密切相关, 可以作为寻找斑岩型金铜矿床的标志^[52,53], 然而铜峪铜矿床属于火山喷流块状硫化物矿床^[40,44], 矿体顺层赋存于中-基性火山岩内, 且煤沟岩体内未发现工业矿体, 说明煤沟岩体对铜峪铜矿成矿可能没有直接的控制作用, 这与煤沟岩体的Pb同位素比值普遍高于矿石和赋矿火山岩(图5)的事实相吻合.

在朱炳泉^[2]铅同位素 $\Delta\gamma$ - $\Delta\beta$ 成因分类图解中, 大多数矿石硫化物、赋矿火山岩和煤沟岩体样品点落入受岩浆作用控制的混合的俯冲带铅范围内(图6), 少部分落入地幔及造山带铅范围内, 指示成矿与俯冲作用相关的壳-幔混合作用有关. 在铅同位素构造环境图解中(图7), 矿石和赋矿火山岩的数据点落入岛弧区域, 并与形成于岛弧环境的东秦岭^[54]和新疆阿尔泰南缘^[55]的VHMS型铜多金属矿床的Pb分布范围重叠或接近, 煤沟岩体的数据点落入岛弧或下地壳区域, 这与 $\Delta\gamma$ - $\Delta\beta$ 成因分类图(图6)和铅构造模式图(图5)中铅同位素数据的分布特征一致, 进一步说明铜峪铜矿床成岩成矿为与俯冲作用相关的岛弧环境, Pb来自于壳-幔混合源区.

已有研究表明, 秦岭造山带由2条主缝合带和由其分划的3个地块, 即由商丹缝合带、勉略缝合带、华北地块南缘、秦岭微地块和扬子地块北缘组成, 商丹带是秦岭主造山期板块的俯冲碰撞缝合带, 商丹一线曾有一个消失的古秦岭有限洋盆, 商丹带就是其消亡的俯冲碰撞缝合线^[45,56]. 赋矿火山岩及煤沟

图5 铜峪铜矿床矿石、赋矿火山岩及矿区岩体的 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 和 $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 比值图解(底图据文献[4])

Figure 5 $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams of the ores, volcanic host rocks, and rock mass from the Tongyu mine district (after Ref. [4])

图6 铜峪铜矿床铅同位素 $\Delta\gamma$ - $\Delta\beta$ 成因判别图解(底图据文献[2])

Figure 6 $\Delta\gamma$ vs. $\Delta\beta$ genetic classification diagram of the Tongyu copper deposit (after Ref. [2])

图7 铜峪铜矿床Pb同位素大地构造判别图解(底图据文献[4]; 东秦岭VHMS型矿床数据来自文献[54]; 新疆阿尔泰山南缘VHMS型矿床数据来自文献[55])

Figure 7 Pb isotopic discrimination diagram of tectonic environments (after Ref. [4]; data of the VHMS deposits in the East Qinling are from Ref. [54]; data of the VHMS deposits of the southern margin of Altai in Xinjiang are from Ref. [55])

岩体的锆石U-Pb年龄介于 $437\pm 4\sim 440\pm 5$ Ma之间^[40,44], 与早古生代商丹洋壳北向俯冲造山事件的时间吻合。因此, 煤沟岩体和铜峪铜矿床形成于与440 Ma左右商丹洋壳北向俯冲作用有关的岛弧环境。考虑到赋

矿岛弧火山岩是商丹洋壳俯冲脱水促使地幔楔部分熔融的产物^[44], 俯冲板片脱水产生的高氧逸度热液流体能有效萃取地幔楔中的金属硫化物^[57-60], 铜峪铜矿床矿石与赋矿火山岩的铅同位素组成及分布趋

势相似, 因此认为~440 Ma北向俯冲的商丹洋壳部分熔融产生的高氧逸度热液流体进入地幔楔, 活化萃取了地幔楔中Cu等成矿物质, 并促使地幔楔部分熔融, 产生含矿火山热液作用并形成了铜峪VHMS型铜矿床。

4 结论

飞秒激光剥蚀多接收等离子体质谱(fsLA-MC-ICP-MS)微区原位分析技术对铜峪铜矿床的矿石硫

化物、赋矿火山岩、矿区煤沟岩体和火山碎屑岩长石的Pb同位素组成的系统测定分析表明, 矿石和赋矿火山岩的Pb同位素比值相似, 反映了成矿物质与赋矿火山岩具有同源性, 二者具有地幔-地壳混合特征。铜峪铜矿床和煤沟岩体形成于统一的构造岩浆事件中, 属于早古生代商丹洋壳向北俯冲作用有关的岛弧环境, 但Pb同位素特征显示赋矿火山岩和煤沟岩体铅同位素存在一定差异, 成矿物质与赋矿火山岩同源, 而非煤沟岩体及火山碎屑岩。

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参考文献

- Zhu L M, Guo L D, Gao Z Y, et al. Source and distribution of lead in the surface sediments from the South China Sea as derived from Pb isotopes. *Mar Pollut Bull*, 2010, 60: 2144–2153
- Zhu B Q. Theory and Applications of Isotope Systematics in Geosciences: Evolution of Continental Crust and Mantle in China (in Chinese). Beijing: Science Press, 1998. 1–330 [朱炳泉. 地球科学中同位素体系理论与应用——兼论中国大陆壳幔演化. 北京: 科学出版社, 1998. 1–330]
- Zhu B Q. Pb-Sr-Nd isotopic systematics in mantle derived rocks (in Chinese). *Earth Sci Front*, 2007, 14: 24–36 [朱炳泉. 全球幔源岩 Pb-Sr-Nd 同位素体系. 地学前缘, 2007, 14: 24–36]
- Zartman R E, Doe B R. Plumbotectonics-the model. *Tectonophysics*, 1981, 75: 135–142
- Zhang L G. Block-geology of Eastern Asia Lithosphere Isotope Geochemistry and Dynamics of Upper Mantle, Basement and Granite (in Chinese). Beijing: Science Press, 1995. 1–216 [张理刚. 东南亚岩石圈块体性质——上地幔、基底和花岗岩同位素地球化学及其动力学. 北京: 科学出版社, 1995. 1–216]
- Zhang L G. Lead isotopic compositions of feldspar and ore and their geologic significance (in Chinese). *Miner Deposits*, 1988, 7: 55–64 [张理刚. 长石铅和矿石铅同位素组成及其地质意义. 矿床地质, 1988, 7: 55–64]
- Bellucci J J, McDonough W F, Rudnick R L. Thermal history and origin of the Tanzanian Craton from Pb isotope thermochronology of feldspars from lower crustal xenoliths. *Earth Planet Sci Lett*, 2011, 301: 493–501
- Bindler R, Renberg I, Anderson N J, et al. Pb isotope ratios of lake sediments in West Greenland: Inferences on pollution sources. *Atmos Environ*, 2001, 35: 4675–4685
- Rddad L, Bouhrel S. The Bou Dahar Jurassic carbonate-hosted Pb-Zn-Ba deposit (Oriental High Atlas, Morocco): Fluid-inclusion and C-O-S-Pb isotope studies. *Ore Geol Rev*, 2016, 72: 1072–1087
- Cumming G L, Richards J R. Ore lead isotope ratios in a continuously changing earth. *Earth Planet Sci Lett*, 1975, 28: 155–171
- Zhang H F, Gao S, Zhang B R, et al. Pb isotopic study on crustal structure of Dabie Mountains, central China (in Chinese). *Geochimica*, 2001, 30: 395–401 [张宏飞, 高山, 张本人, 等. 大别山地壳结构的 Pb 同位素地球化学示踪. 地球化学, 2001, 30: 395–401]
- Chang X Y, Zhu B Q, Zou R. Lead isotope geochemical profile and depth prediction of concealed ore: A case study of copper of Yunnan Jinpinglong River (in Chinese). *Sci China Ser D-Earth Sci*, 2000, 30: 33–39 [常向阳, 朱炳泉, 邹日. 铅同位素系统剖面化探与隐伏矿深度预测: 以云南金平龙勃河铜矿为例. 中国科学 D 辑: 地球科学, 2000, 30: 33–39]
- Townley B K, Godwin C I. Isotope characterization of lead in galena from ore deposits of the Aysén Region, Southern Chile. *Miner Deposita*, 2001, 36: 45–57
- Chang X Y, Zhu B Q. Isotope Geochemistry of the Dongchuan copper deposit, Yunnan, SW China: Stratigraphic chronology and application of lead isotopes in geochemical exploration. *Chin J Geochem*, 2002, 22: 244–252
- Jiang S Y, Yang T, Li L, et al. Lead and sulfur isotopic compositions of sulfides from the TAG hydrothermal field, Mid-Atlantic Ridge (in Chinese). *Acta Petrol Sin*, 2006, 22: 2597–2602 [蒋少涌, 杨涛, 李亮, 等. 大西洋洋中脊 TAG 热液区硫化物铅和硫同位素研究. 岩石学报, 2006, 20: 2597–2602]
- Deng X H, Chen Y J, Bagas L, et al. Isotope (S-Sr-Nd-Pb) constraints on the genesis of the ca. 850 Ma Tumen Mo-F deposit in the Qinling Orogen, China. *Precambrian Res*, 2015, 266: 108–118

- 17 Woodhead J, Volker F, McCulloch M. Routine lead isotope determinations using a ^{207}Pb - ^{204}Pb double spike: A long-term assessment of analytical precision and accuracy. *Analyst*, 1995, 120: 35–39
- 18 Todt W, Cliff R, Hanser A, et al. Evaluation of a ^{202}Pb - ^{205}Pb double spike for high-precision lead isotopic analyses. In: Basu A, Hart S, eds. *Earth Processes: Reading the Isotopic Code* (Geophysical Monograph, vol.95). Washington DC: AGU, 1996. 429–437
- 19 White W M, Albarede F, Telouk P. High-precision analysis of Pb isotope ratios by Multi-collector ICP-MS. *Chem Geol*, 2000, 167: 257–270
- 20 Elburg M, Vroon P, van der Wagt B, et al. Sr and Pb isotopic composition of five USGS glasses (BHVO-2G, BIR-1G, BCR-2G, TB-1G, NKT-1G). *Chem Geol*, 2005, 223: 196–207
- 21 He X X, Zhu X K, Yang C, et al. High-precision analysis of Pb isotope ratios using MC-ICP-MS (in Chinese). *Acta Geosci Sin*, 2005, 26(Suppl): 19–22 [何学贤, 朱祥坤, 杨淳, 等. 多接收器等离子体质谱(MC-ICP-MS)Pb 同位素高精度测定. *地球学报*, 2005, 26(增刊): 19–22]
- 22 Yuan H L, Chen K Y, Bao Z A, et al. Determination of lead isotope compositions of geological samples using femtosecond laser ablation MC-ICPMS. *Chin Sci Bull*, 2013, 58: 3914–3921 [袁洪林, 陈开运, 包志安, 等. 飞秒激光剥蚀多接收等离子体质谱准确分析地质样品中的铅同位素组成. *科学通报*, 2013, 58: 3440–3449]
- 23 Yuan H L, Yin C, Liu X, et al. High precision *in-situ* Pb isotopic analysis of sulfide minerals by femtosecond laser ablation multi-collector inductively coupled plasma mass spectrometry. *Sci China Earth Sci*, 2015, 58: 1713–1721 [袁洪林, 殷琮, 刘旭, 等. 飞秒激光剥蚀多接收等离子体质谱分析硫化物中 Pb 同位素组成研究. *中国科学: 地球科学*, 2015, 45: 1285–1293]
- 24 Chen K Y, Yuan H L, Bao Z A, et al. Accurate and precise *in situ* determination of lead isotope ratios in NIST, USGS, MPI-DING and CGSG reference glasses using femtosecond laser ablation MC-ICP-MS. *Geostand Geoanal Res*, 2014, 38: 5–21
- 25 Liu X J, Wang G Q, Castillo P R, et al. Highly precise Pb isotope analysis by ^{207}Pb - ^{204}Pb double spike method using TIMS (in Chinese). *Geochimica*, 2013, 42: 103–115 [刘希军, 王桂琴, Castillo P R, 等. 高精度铅同位素 ^{207}Pb - ^{204}Pb 双稀释剂 TIMS 测试方法. *地球化学*, 2013, 42: 103–115]
- 26 Jin L L, Jiang J F, Hu S H, et al. Determination of lead isotope ratio by dual gas flow-laser ablation-inductively coupled plasma-mass spectrometry (in Chinese). *Chin J Anal Chem*, 2007, 35: 191–195 [靳兰兰, 姜劲峰, 胡圣虹, 等. 双气流路-激光剥蚀电感耦合等离子体质谱测定铅同位素比值. *分析化学研究报告*, 2007, 35: 191–195]
- 27 Chen K Y, Fan C, Yuan H L, et al. High-precision *in-situ* analysis of the lead isotopic composition in copper using femtosecond laser ablation MC-ICP-MS and the application in ancient coins (in Chinese). *Spectrosc Spect Anal*, 2013, 33: 1342–1349 [陈开运, 范超, 袁洪林, 等. 飞秒激光剥蚀-多接收电感耦合等离子质谱原位微区分析青铜中铅同位素组成——以古铜钱币为例. *光谱学与光谱分析*, 2013, 33: 1342–1349]
- 28 Fernández B, Clavier F, Péchéryan C, et al. Direct analysis of solid samples by fs-LA-ICP-MS. *TrAC-Trend Anal Chem*, 2007, 26: 951–966
- 29 Koch J, Günther D. Review of the State-of-the-Art of Laser Ablation Inductively Coupled Plasma Mass Spectrometry. *Appl Spectrosc*, 2011, 65: 115–162
- 30 Horn I, von Blanckenburg F, Schoenberg R, et al. *In situ* iron isotope ratio determination using UV-femtosecond laser ablation with application to hydrothermal ore formation processes. *Geochim Cosmochim Acta*, 2006, 70: 3677–3688
- 31 Sangster D F. Isotopic studies of ore-leads in the Hanson Lake-Flin Flon-Snow Lake mineral belt Saskatchewan, Manitoba. *Can J Earth Sci*, 1972, 9: 500–512
- 32 Ohmoto H, Rye R O. Hydrogen and oxygen isotopic compositions of fluid inclusions in the Kuroko deposits, Japan. *Econ Geol*, 1974, 69: 947–953
- 33 Large R, Doyle M, Raynond O, et al. Evaluation of the role of Cambrian granites in the genesis of world class VHMS deposits in Tasmania. *Ore Geol Rev*, 1996, 10: 215–230
- 34 Zaw K, Gemmell J B, Large R R, et al. Evolution and source of ore fluids in the stringer system, Hellyer VHMS deposit, Tasmania, Australia: Evidence from fluid inclusion microthermometry and geochemistry. *Ore Geol Rev*, 1996, 10: 251–278
- 35 Hou Z Q, Zaw K, Li Y H, et al. Possible contribution of magmatic fluid to the active hydrothermal system in the JADE field, Okinawa trough: Evidence from fluid inclusions and oxygen and Helium isotopes. *Int Geol Rev*, 2005, 47: 420–437
- 36 Hou Z Q, Zaw K, Rona P, et al. Geology, fluid inclusions, and oxygen isotope geochemistry of the Baiyinchang Pipe-style volcanic-hosted massive sulfide Cu deposit in Gansu Province, northwestern China. *Econ Geol*, 2008, 103: 269–292
- 37 Allen R L, Tornos F, Peter J M. A thematic issue on the geological setting and genesis of volcanogenic massive sulfide (VMS) deposits. *Miner Deposita*, 2011, 46: 429–430
- 38 Hollis S P, Yeats C J, Wyche S, et al. A review of volcanic-hosted massive sulfide (VHMS) mineralization in the Archaean Yilgarn Craton, Western Australia: Tectonic, stratigraphic and geochemical associations. *Precambrian Res*, 2015, 260: 113–135
- 39 Xu Y H, Zhao T P, Chen W. Origin of felsic volcanic rocks associated with VMS-type deposits in the Er'langping Group, East Qinling: Implications for ore-forming setting (in Chinese). *Acta Petrol Sin*, 25: 399–412 [徐勇航, 赵太平, 陈伟. 东秦岭二郎坪群长英质火山岩成因及其对 VMS 型矿床成矿环境的制约. *岩石学报*, 2009, 25: 399–412]
- 40 Lee B, Zhu L M, Zhang G W, et al. Geological characteristics, metallogenic background, and genesis of the Tongyu VHMS copper deposit in the west part of the North Qinling, Shaanxi Province. *Sci China Earth Sci*, 2010, 53: 1460–1485 [李桦, 朱赖民, 张国伟, 等. 北秦岭西部陕西铜峪 VHMS 型铜矿床矿化地质特征、成矿背景与矿床成因. *中国科学: 地球科学*, 2010, 40: 970–995]

- 41 Han D W. Alteration-mineralization zoning and metallogeny of Tongyu copper deposit in Meixian, Shaanxi Province (in Chinese). *Northwestern Geol*, 1982, 2: 38–48 [戴文哈. 陕西眉县铜峪铜矿床矿化蚀变分带及成矿作用. *西北地质*, 1982, 2: 38–48]
- 42 Ning X C. Study on structural system of Tongyu copper ore field (in Chinese). *Northwestern Geol*, 1984, 2: 1–14 [宁晰春. 铜峪铜矿田构造体系分析. *西北地质*, 1984, 2: 1–14]
- 43 Zhang X Y, Li Y L, Hu M Z, et al. Geology of the Tongyu copper deposit in Shaanxi Province and research of unconventional methods for mining (in Chinese). *Geol Shaanxi*, 2013, 31: 27–32 [张旭宇, 李引芳, 胡敏智, 等. 陕西铜峪铜矿床地质特征及非常规采矿方法的探索与实践. *陕西地质*, 2013, 31: 27–32]
- 44 Xiong X, Zhu L M, Li B, et al. Zircon U-Pb geochronology and geochemical characteristics of the volcanic host rocks from the Tongyu VHMS copper deposit in the western North Qinling Orogen and their geological significance. *Acta Geol Sin*, 2015, 89: 1926–1946
- 45 Zhang G W, Zhang B R, Yuan X C, et al. Qinling Orogenic Belt and Continent Dynamics (in Chinese). Beijing: Science Press, 2001. 1–855 [张国伟, 张本仁, 袁学诚, 等. 秦岭造山带与大陆动力学. 北京: 科学出版社, 2001. 1–855]
- 46 Song Z J, Zhang W J, An S Y. The characteristics of volcanic rocks and its environment formed in graben zone of northern part of the North Qinling orogen, in early Paleozoic era (in Chinese). In: Institute of Geology and Mineral Resources, Xi'an. Academy of Geological Sciences Institute, China, 1988, 24: 51–63 [宋子季, 张维吉, 安三元. 北秦岭北部早古生代断陷带古海相火山岩特征及其形成环境. *中国地质科学院西安地质矿产研究所文集*, 1988, 24: 51–63]
- 47 Zhang W J. Basic characteristics evolvement of the north Qinling (in Chinese). In: 45th Anniversary Symposium for the Establishment of Department of Geology, Northwest University (the second volume). Xi'an: Northwest University Publishing House, 1987. 312–320 [张维吉. 北秦岭地质构造演化基本特征. 见: 西北大学地质系成立四十五周年学术报告会论文集(下册). 西安: 西北大学出版社, 1987. 312–320]
- 48 Yan Q R, Wang Z Q, Chen J L, et al. Tectonic setting and SHRIMP age of volcanic rocks in the Xieyuguan and Caotangou Groups: Implications for the North Qinling orogenic belt (in Chinese). *Acta Geol Sin*, 2007, 81: 488–500 [闫全人, 王宗起, 陈隽璐, 等. 北秦岭斜峪关群和草滩沟群火山岩成因的地球化学和同位素约束、SHRIMP 年代及其意义. *地质学报*, 2007, 81: 488–500]
- 49 Thirlwall M F. Multicollector ICP-MS analysis of Pb isotopes using a ^{207}Pb - ^{204}Pb double spike demonstrates up to 400 ppm/amu systematic errors in TI-normalization. *Chem Geol*, 2002, 184: 255–279
- 50 Bodet F, Schärer U. Pb isotope systematics and time-integrated Th/U of SE-Asian continental crust recorded by single K-feldspar grains in large rivers. *Chem Geol*, 2001, 177: 265–285
- 51 Andrew A, Godwin C I, Sinclair A J, et al. Mixing line isochrones: A new interpretation of galena lead isotope data from southeastern British Columbia. *Econ Geol*, 1984, 79: 919–932
- 52 Defant M J, Xu J F, Kepezhinskis P, et al. Adakites: Some variations on a theme (in Chinese). *Acta Petrol Sin*, 2002, 18: 129–141 [Defant M J, 许继峰, Kepezhinskis P, 等. 埃达克岩: 关于其成因的一些不同观点. *岩石学报*, 2002, 18: 129–141]
- 53 Thieblemont D, Stein G, Lescuyer J L. Epithermal and porphyry deposits: The adakitic connection. *Earth Planet Sci Lett*, 1997, 329: 243–250
- 54 Yan C H, Xu Y H, Peng Y, et al. Geological-geochemical characteristics and genesis of massive sulfide deposits in Er'langping Group of East Qinling (in Chinese). *Miner Deposits*, 2008, 27: 4–27 [燕长海, 徐勇航, 彭翼, 等. 东秦岭二郎坪群火山岩中火山成因块状硫化物矿床地质地球化学特征及其成因讨论. *矿床地质*, 2008, 27: 4–27]
- 55 Wan B, Zhang L C. Sr-Nd-Pb isotope geochemistry and tectonic setting of Devonian polymetallic metallogenic belt on the Southern margin of Altaid, Xinjiang (in Chinese). *Acta Petrol Sin*, 2006, 22: 145–152 [万博, 张连昌. 新疆阿尔泰山南缘泥盆纪多金属成矿带 Sr-Nd-Pb 同位素地球化学与构造背景讨论. *岩石学报*, 2006, 22: 145–152]
- 56 Dong Y P, Zhang G W, Hauzenberger C, et al. Palaeozoic tectonics and evolutionary history of the Qinling orogen: Evidence from geochemistry and geochronology of ophiolite and related volcanic rocks. *Lithos*, 2011, 122: 39–56
- 57 Sillitoe R H. Characteristics and controls of the largest porphyry copper-gold and epithermal gold deposits in the circum-Pacific region. *Aust J Earth Sci*, 1997, 44: 373–388
- 58 Gibson S A, Thompson R N, Leonardos O H, et al. The Late Cretaceous impact of the mantle plume: Evidence from large volume mafic potassic magmatism in SE Brazil. *J Petrol*, 36: 189–229
- 59 Métrich N, Schiano P, Clocchiatti R, et al. Transfer of sulfur in subduction settings: An example from Batan Island (Luzon volcanic arc, Philippines). *Earth Planet Sci Lett*, 1999, 167: 1–14
- 60 Wyborn D, Sun S S. Sulphur-undersaturated magmatism: A key factor for generating magma-related copper-gold deposits. *AGSO Res News-lett*, 1994, 21: 7–8

补充材料

表 S1 铜峪铜矿床铅同位素组成

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***In-situ* microanalysis of Pb isotopic compositions using fsLA-MC-ICP-MS for the Tongyu copper deposit in the North Qinling Orogen and its geological significance**

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Pb isotopes are considered an ideal tool for identifying material sources and tectonic settings of various petrogeneses and mineralizations. A high precision method for *in-situ* Pb isotopic analysis by femtosecond laser-ablation multi-collector inductively coupled plasma mass spectrometry (fsLA-MC-ICP-MS) was first established in China by the State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University. This new method has been used to measure Pb isotopic compositions for inclusions, minerals, glasses, metals, etc., because of its negligible element fractionation and well-corrected mass discrimination. However, Pb isotopic studies on typical deposits using fsLA-MC-ICP-MS have until now rarely been reported globally. The Tongyu copper deposit in the Shaanxi Province, China is one of the most important VHMS deposits with industrial value and is also a typical example of mineralization associated with subduction and metallogenesis during the Caledonian orogeny in the western part of the North Qinling Orogen. Previous studies of this deposit have focused mainly on geological features and ore-forming ages, but detailed isotopic geochemical studies on the ore-forming material sources and tectonic settings were lacking.

In this study, *in-situ* microanalyses of Pb isotopic compositions for ore sulfides and feldspar of the volcanic host rocks, Meigou pluton, and pyroclastic rock from the Tongyu copper deposit were carried out by using the fsLA-MC-ICP-MS method. The Pb isotopic compositions of sulfides are in good agreement with those of the volcanic host rocks, indicating that the ore-forming materials and the volcanic host rocks share a common source. In the Pb isotope diagram of tectonic evolutions, most samples of the sulfides and volcanic host rocks plot near the mantle or orogenic Pb evolution lines, reflecting a mixed mantle-lower crust Pb source. The Meigou pluton samples in the mine district have higher Pb isotopic ratios than the sulfides and volcanic host rocks, showing a similar trend to them, and mainly plot near the orogenic Pb evolution line. Samples of the pyroclastic rock plot near the upper crust evolution line and far from fields of the ores, volcanic host rocks, and Meigou pluton. Therefore, ore-forming materials of the deposit have a common source with the volcanic host rocks, rather than the Meigou pluton and pyroclastic rock. From the $\Delta\gamma$ - $\Delta\beta$ diagram, most ores, volcanic host rocks, and Meigou pluton samples fall in the field of subduction Pb related to magmatism, and approach or overlap ores from those of the East Qinling Orogen and polymetallic metallogenic belt of the southern margin of Altai in Xinjiang, both of which were formed in an island arc environment. This further supports the position that diagenetic and metallogenetic processes for the Tongyu copper deposit bear a close relationship to the subduction-related mixing of crust and mantle. Considering the volcanic host rocks and Meigou pluton from the Tongyu copper deposit yielded LA-ICP-MS zircon U-Pb ages of 436 ± 4 to 440 ± 5 Ma, which correspond to the ca. 440 Ma northward subduction event of the Palaeo-Qinling oceanic crust, we propose that The Tongyu copper deposit was formed in an island arc environment related to the northward subduction of the Shangdan oceanic crust in the Early Palaeozoic.

Tongyu copper deposit, femtosecond laser-ablation, lead isotope, ore-forming materials, island arc environment

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