

doi: 10.12029/gc20200115001

林锐华,尹青青,项新葵,梁锋,杨秀峰,王天晨,柳和清,周文俊,朱斌. 2023. 江西昆山钨钼铜多金属矿床辉钼矿 Re-Os 年代及其对成矿地球动力学演化的启示[J]. 中国地质, 50(4): 1176-1187.

Lin Ruihua, Yin Qingqing, Xiang Xinkui, Liang Feng, Yang Xiufeng, Wang Tianchen, Liu Heqing, Zhou Wenjun, Zhu Bin. 2023. Molybdenite Re-Os isotopic age of the Kunshan Mo-W-Cu polymetallic deposit in the Jiangxi Province and its evolution of metallogenic geodynamics[J]. Geology in China, 50(4): 1176-1187(in Chinese with English abstract).

江西昆山钨钼铜多金属矿床辉钼矿 Re-Os 年代及其对成矿地球动力学演化的启示

林锐华¹, 尹青青^{1,2}, 项新葵², 梁锋^{3,4}, 杨秀峰¹, 王天晨², 柳和清², 周文俊², 朱斌¹

(1. 中钢集团天津地质研究院有限公司, 天津 300181; 2. 江西省地质矿产勘查开发局九一六大队, 江西 九江 332100; 3. 中国地质科学院矿产资源研究所, 自然资源部成矿作用与资源评价重点实验室, 北京 100037; 4. 中国地质科学院地球深部探测中心, 北京 100037)

摘要:【研究目的】昆山钨钼铜多金属矿床行政区划属于江西修水县境内,大地构造位置位于江南造山带中段之九岭隆起东段。本次研究试图对昆山 W-Cu-Mo 多金属矿床成矿年龄进行精准约束,为该矿床成矿作用研究、成矿规律总结提供年代学证据,同时对该矿床成岩成矿关系、成矿物质来源作简要探讨,并对大湖塘钨多金属矿集区成矿期次进行划分。【研究方法】本文对昆山钨钼铜多金属矿床开展了辉钼矿 Re-Os 同位素年代学研究。【研究结果】实验获得的 10 件辉钼矿等时线年龄为(148.8±1.0) Ma, MSWD=0.42, Re-Os 加权平均年龄为(148.7±0.7) Ma, MSWD=0.10, 加权平均年龄与等时线年龄基本一致,因此本次所采集的样品 Re-Os 体系是封闭的。¹⁸⁷Re 和 ¹⁸⁷Os 沿等时线距离拉开的较远,表明本次定年数据较为可靠。昆山矿床成矿作用发生稍滞后于似斑状黑云母花岗岩侵位时限,与晚侏罗世这期岩浆活动有成因联系。昆山钨钼铜多金属矿床的成矿物质以壳源为主,考虑到存在较高 Re 两个样品($n \times 10^{-5}$),说明可能存在部分幔源的成矿物质参与了该矿床的形成。【结论】软流圈物质自晚侏罗世开始,沿着 NNE 向深断裂与先期(晋宁晚期)形成的 NEE 向古断裂的交汇部位上涌,通过热传导效应引起地壳物质发生部分熔融,于大湖塘地区形成了似斑状黑云母花岗岩(岩株)、细粒黑云母花岗岩(小岩株)、花岗斑岩(岩脉或岩枝)等一系列中酸性侵入岩。

关键词: 钨钼铜多金属矿床; Re-Os 年龄; 同位素; 成矿作用; 江南造山带; 矿产勘查工程; 昆山; 江西

创新点: (1) 采用辉钼矿 Re-Os 同位素年代学,对昆山 Mo-W-Cu 多金属矿床进行了成矿时代约束; (2) 依据辉钼矿石中 Re 的含量确定了成矿作用过程中有幔源物质的参与; (3) 总结归纳了大湖塘地区的两期成矿作用与成岩成矿地球动力学演化模式。

中图分类号: P588.12¹; P597.3 文献标志码: A 文章编号: 1000-3657(2023)04-1176-12

Molybdenite Re-Os isotopic age of the Kunshan Mo-W-Cu polymetallic deposit in the Jiangxi Province and its evolution of metallogenic geodynamics

LIN Ruihua¹, YIN Qingqing^{1,2}, XIANG Xinkui², LIANG Feng^{3,4}, YANG Xiufeng¹,

收稿日期: 2020-01-15; 改回日期: 2020-05-31

基金项目: 中国地质调查局项目(DD2016005234)、江西省地勘基金项目(20160010)和江西省地矿局项目(赣地矿字[2016]98号)联合资助。

作者简介: 林锐华,男,1982年生,高级工程师,长期从事金属固体矿产勘查与科学研究; E-mail: 53630996@qq.com。

通讯作者: 项新葵,男,1963年生,教授级高级工程师,长期从事固体矿产勘查、区域地质调查、科研及成矿预测工作;

E-mail: 1178852439@qq.com。

WANG Tianchen², LIU Heqing², ZHOU Wenjun², ZHU Bin¹

(1. Sinosteel Tianjin Geological Academy Ltd, Tianjin 300181, China; 2. No.916 Geological Party, Jiangxi Bureau of Geology and Mineral Exploration, Jiujiang 332100, Jiangxi, China; 3. MLR Key of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China; 4. China Deep Exploration Center, Chinese Academy of Geological Sciences, Beijing 100037, China)

Abstract: This paper is the result of mineral exploration engineering.

[Objective] Kunshan molybdenum polymetallic deposit is located in Xiushui County, Jiangxi Province, and belongs to eastern segment of the Jiuling uplift from mid-segment of the Jiangnan orogen. This study attempts to precisely constrain the metallogenic age of the Kunshan W-Cu-Mo polymetallic deposit, provide geochronological evidence for the study of mineralization and the summary of the metallogenic regularity of the deposit, study the metallogenic relationship of the deposit and the source of metallogenic material, and divide the metallogenic periods of the Dahutang tungsten polymetallic ore concentration area. **[Methods]** The Re-Os isotopic geochronology for the molybdenite from the Kunshan molybdenum polymetallic deposit was carried out in this paper. **[Results]** An isochron age of (148.8±1.0) Ma, and a weighted mean age of (148.7±0.7) Ma for 10 molybdenite samples were obtained, which were approximately simultaneous with each other, and the Re-Os system was closed accordingly. The points of ¹⁸⁷Re and ¹⁸⁷Os are far away along the isochron, which indicates that the geochronology data are reliable. Metallogenesis lags behind the emplacement of porphyritic-like biotitic granite in the Kunshan deposit, caused by Late Jurassic granitic magmatism. Metallogenic materials of the Kunshan molybdenum polymetallic deposit mainly came from crust materials, in addition, there are two samples with higher Re, it shows that partial mantle source metallogenic materials participated in the formation of the deposit. **[Conclusions]** The intrusion of asthenospheric materials began from the Late Jurassic epoch, through the intersection part of NNE deep faults and NEE ancient faults formed from Late Jinningian. Partial melting of crustal material was caused by the heat conduction effect, which forms a series of intermediate-acid intrusive rocks in the Dahutang area, such as porphyritic-like biotitic granite, fine-grained biotitic granite, and granite-porphphy.

Key words: Mo-W-Cu polymetallic deposit; Re-Os age; isotope; metallogenesis; Jiangnan orogen; mineral exploration engineering; Kunshan; Jiangxi Province

Highlights: (1) The molybdenite Re-Os isotope chronology of Kunshan Mo-W-Cu polymetallic deposit metallogenic epoch constraints; (2) Based on the content of Re in molybdenite ore, it is determined that mantle-derived materials are involved in the process of mineralization; (3) The two-stage mineralization and the evolution model of diagenetic geodynamics in the Dahutang area are summarized.

About the first author: LIN Ruihua, male, born in 1982, senior engineer, engaged in solid mineral exploration and scientific research; E-mail: 53630996@qq.com.

About the corresponding author: XIANG Xinkui, male, born in 1963, professor-level senior engineer, engaged in solid mineral exploration, regional geologic reconnaissance, scientific research and metallogenic prediction work; E-mail: 1178852439@qq.com.

Fund support: Supported by the project of China Geological Survey (No.DD2016005234), Geological Exploration Fund Program of Jiangxi Province (No.20160010) and Jiangxi Bureau of Geology and Mineral Exploration Program (No.[2016]98).

1 引言

2012年江西省地质矿产勘查开发局916大队于大湖塘钨多金属矿集区石门寺钨铜钼多金属矿床取得WO₃金属量取得突破之后,打破了江西“南钨北铜”的分布格局,并成就了其迄今为止世界级第二大钨矿的地位,学者们从多种地质维度采用了多种实

验方法对其开展了一系列研究,并取得了丰硕的成果。项新葵等(2012a,2013a,b,c)对石门寺矿床的地质特征进行了总结,约束了各类成矿条件。黄兰椿和蒋少涌(2012,2013)对狮尾洞矿床似斑状白云母花岗岩和富钨花岗斑岩成因进行了探讨(Huang and Jiang, 2014)。项新葵等(2015a,b,c)对石门寺矿床同构造花岗斑岩成因及流体迁移规律进行了总结。

随着Re-Os同位素测年技术被应用于本区,先后获得了一系列成矿年龄数据,如石门寺矿床成矿年龄(139.2 ± 1.0)Ma(Mao et al., 2013)、(143.7 ± 1.2)Ma(丰成友等, 2012)和(149.6 ± 1.4)Ma(项新葵等, 2013a);狮尾洞矿床成矿年龄(140.9 ± 3.6)Ma(丰成友等, 2012);昆山矿床成矿年龄(151.0 ± 1.3)Ma(张明玉等, 2016);梅子坑矿床成矿年龄(148.9 ± 4.4)Ma(张志辉等, 2013)等。这些研究作为研究大湖塘钨多金属矿集区成矿作用、金属矿质来源、年代学格架搭建、地球动力学演化提供了重要支撑。

成矿年龄时限精准约束是认识成矿规律的基石,是建立成矿(找矿)地质勘查模型的重要参考资料,是反演成矿动力学演化和搭建年代学格架的基础资料(杨斌等, 2021;丰晓路等, 2022)。本文通过详细研究昆山钨钨铜多金属矿床基础资料,运用辉钨矿Re-Os同位素测年方法,试图对其成矿年龄进行精准约束,为该矿床成矿作用研究、成矿规律总结提供年代学证据,同时对该矿床成岩成矿关系、成矿物质来源作简要探讨,并对大湖塘钨多金属矿集区成矿期次进行划分,对该区成岩成矿地球动力学演化规律进行进一步总结。

2 成矿地质背景

昆山钨钨铜多金属矿床行政区划属于江西修水县境内,大地构造位置位于江南造山带中段之九岭隆起东段(图1),东邻鄱阳凹陷,修水—武宁滑覆拗褶带以南,九岭南缘推覆构造带北侧(杨明桂和王昆, 1994;项新葵等, 2012a, b)。成矿区隶属于江南地块钨铜(金、钨等多金属)成矿带(项新葵等, 2013c)。自古元古代以来,九岭隆起经历了扬子结晶基底的形成,随后其褶皱的隆升运动主要发生于古生代时期,至燕山期,则以板内构造运动(挤压—伸展)为主,伴随多期岩浆活动,并诱发一系列金属成矿作用(杨明桂和王昆, 1994;林黎等, 2006a, b;张志辉等, 2021)。双桥山群安乐林组(中新元古界)在矿区内大面积出露(图1),为一套含变余结构的粉(细)砂岩、千枚岩和板岩的火山—碎屑岩沉积建造。控制区内岩浆岩带和矿体展布的断裂主要有两组,一组呈近E-W向展布,另外一组为NE—NNE向。区内岩浆活动主要为晋宁期(花岗闪长岩)和燕山期(似斑状黑云母花岗岩、细粒白云母花

岗岩、细粒二云母花岗岩、花岗斑岩)。晋宁期花岗闪长岩于九岭地区呈规模较大的岩基产出,主要出露于矿区西部(项新葵等, 2015a, b)。燕山期中酸性花岗岩出露较少,多呈岩株、岩脉(岩枝)侵入于花岗闪长岩岩基和双桥山群地层中(项新葵等, 2013b, c, 2015b, 2017)。

3 矿床地质特征

昆山钨钨铜多金属矿床大面积出露的地层为以泥砂质浅变质岩和火山碎屑岩为主的双桥山群(图1),仅少数地段被白垩系红层覆盖(林黎等, 2006b;张明玉等, 2016, 2018a)。晋宁期黑云母花岗闪长岩作为九岭地区的花岗岩基,隐伏于矿床深部,仅于西部和东南部地区部分出露(叶少贞等, 2016;张明玉, 2016)。燕山期花岗斑岩在区内出露数量较多,矿床北部、中部、南部均有花岗斑岩脉分布。区内隐伏燕山期似斑状黑云母花岗岩(图2),似斑状黑云母花岗岩主要呈岩株产出,为本区的主要成矿岩体,未出露地表,经钻孔验证,其侵入高度最高至650 m海拔附近(图2)。昆山钨钨铜多金属矿床区断裂主要分为两类,一类为成矿前断裂,成群成组呈带状分布,并被(含矿)石英脉不同程度的充填,主要呈NEE、NE、NWW向展布;另一类为规模较小的成矿后断裂,以切断(含矿)石英脉为特征,延伸距离较为有限(汪国华等, 2015;王西荣等, 2016;张明玉等, 2018b)。

区内围岩蚀变现象较为普遍,主要包括云英岩化、硅化和绿泥石化等,基本呈线性分布。其中,云英岩化仅于脉壁间或近矿围岩中的小(或微小)裂隙中较为发育;硅化遍布整个矿区,主要发育部位为矿体两侧($n\sim n\times 10$)cm范围内。本矿床矿石矿物较丰富,其中辉钨矿、黑钨矿、黄铜矿占主导,白钨矿和黄铁矿次之。矿石结构主要为自形—半自形、他形粒状和交代残余等结构;矿石构造包含细脉状、浸染状、鳞片状构造等(叶少贞等, 2016)。

昆山矿床工业矿体类型主要为含Mo、Wu、Cu矿质的热液充填于先期断裂形成的石英脉型矿体,Mo和Wu共生、交替沉淀,呈近EW向分布(叶少贞等, 2015),沿倾向(较陡)深部延伸较远(图2)。Mo—Wu矿体呈透镜状或薄层状,分支复合现象较为普遍,其产状与石英脉体走向(一般 $65^\circ\sim 80^\circ$)、倾

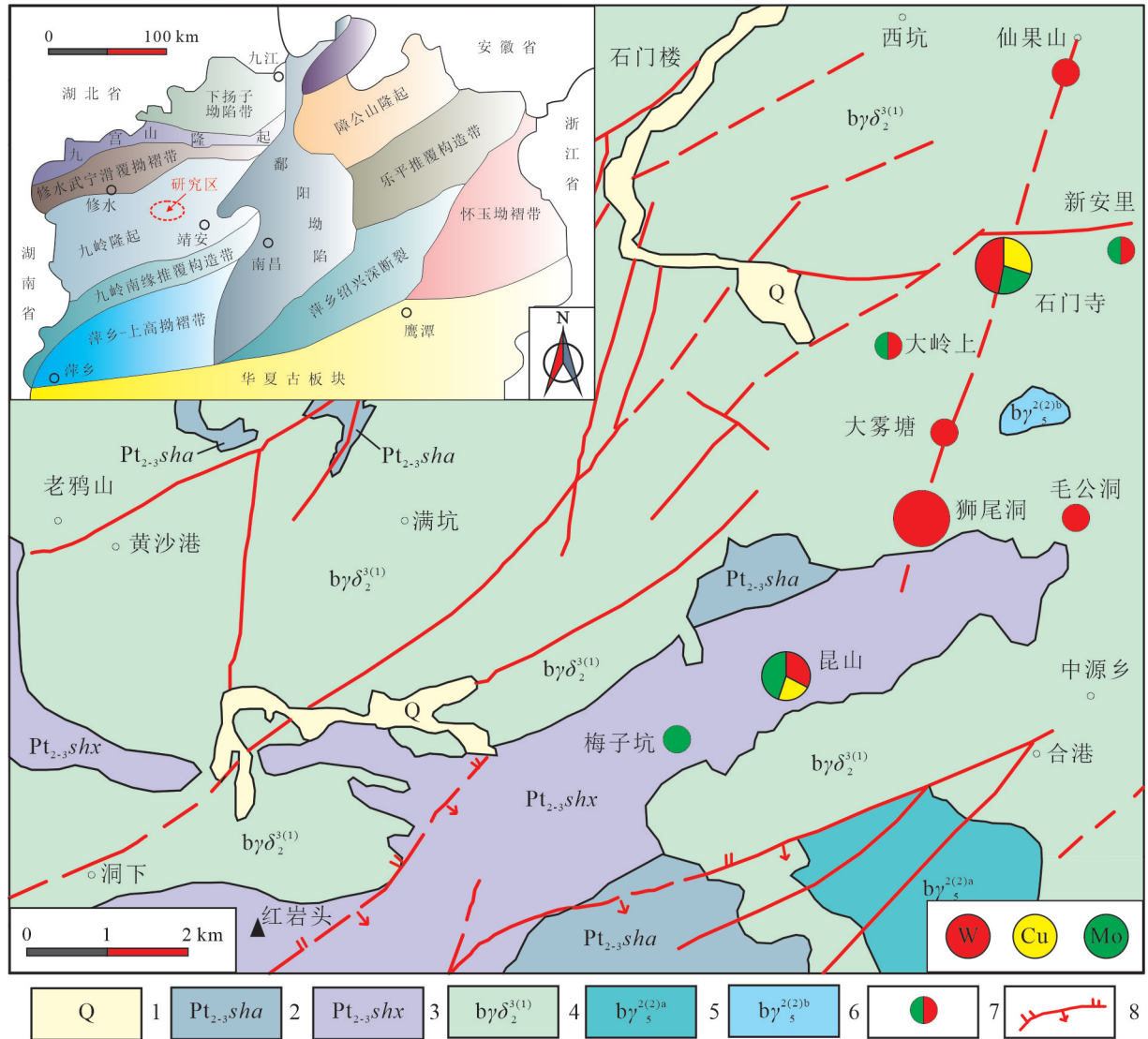


图1 江西九岭成矿带地质略图(据项新葵等, 2012a, b修改)

1—第四系;2—安乐林组;3—修水组;4—黑云母花岗闪长岩(晋宁期);5—似斑状黑云母花岗岩(燕山期);6—细粒黑云母花岗岩(燕山期);7—矿床;8—断层

Fig.1 Regional geological sketch maps of Jiuling mineralization belt, Jiangxi (modified from Xiang Xinkui et al., 2012a, b)

1—Quaternary; 2—Anlelin Formation; 3—Xiushui Formation; 4—Biotite granodiorite (Jingningian); 5—Porphyritic biotitic granite (Yanshanian); 6—Fine-grained biotitic granite (Yanshanian); 7—Ore deposit; 8—Fault

向(以南倾为主)相耦合(张明玉等, 2016)(图2)。钼矿体厚度一般3~26 m,有的厚达60 m以上,Mo品位一般介于0.06%~0.32%,平均品位0.11%;钨矿体厚度1.4~6.3 m,有的厚达44 m;WO₃品位0.12%~1.02%,平均品位为0.30%(汪国华等, 2015)。

4 分析方法

4.1 样品分解和蒸馏分离Os

首先将待测定辉钼矿样品进行准确称重,加

入至Carius管,然后配置乙醇和液氮黏稠体,用来保温盛好样品的Carius管(-50~-80℃)。利用适量HCl溶液将¹⁹⁰Os和¹⁸⁵Re稀释剂导入Carius管底部位置,再加入4~5 mL浓度为16 mol/L的HNO₃溶液,当Carius管底部冷冻固结后,加热密封,置入不锈钢套管内保存,待其恢复室内温度后,便均匀加热至200℃保温存放24 h。将Carius管开口,在冰水浴中升温后,加入1.5倍样品体积的超纯水,把连接两根Teflon管的胶头固定于Carius管顶

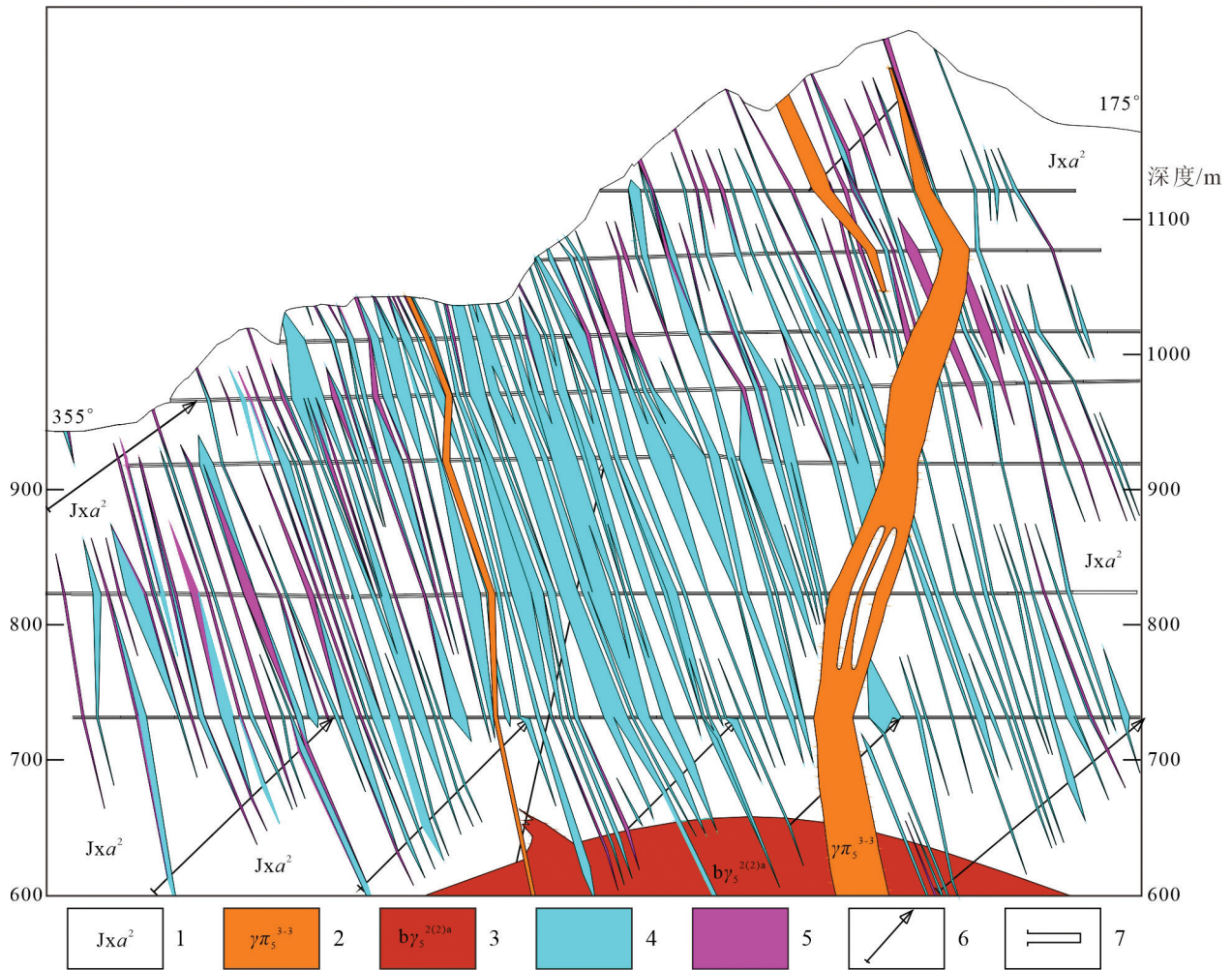


图2 昆山钼钨铜多金属矿床0线勘探SE—NW向剖面图(据叶少贞等, 2015, 2016修改)

1—双桥山群安乐林组中段; 2—燕山期花岗斑岩; 3—燕山期似斑状黑云母花岗岩; 4—钼矿体; 5—钨矿体; 6—钻孔; 7—平洞

Fig.2 Geological section along the NE-SW trending explosion line of Kunshan Mo-W-Cu polymetallic deposit (modified from Ye Shaozhen et al., 2015, 2016)

1-The middle member of Anlelin Formation; 2-Granite-porphyrity of Yanshanian period; 3-Porphyritytic biotitic granite of Yanshanian period; 4-Molybdenum orebody; 5-Tungsten orebody; 6-Drilling; 7-Adit

部位置, 将 Carius 管放置于电加热蒸笼中, 利用 100℃ 恒温蒸汽持续加热 40~60 min。通过以上操作获得的水吸收液(吸附 OsO_4) 便可以通过实验测试获得其 Os 同位素比值, 为方便下一步萃取分离 Re, 需将蒸馏获得的残液导入至 Teflon 烧杯中。详细步骤参见文献(Du et al., 2007; 屈文俊等, 2008; 李超等, 2009)。

4.2 萃取分离 Re 和质谱测定

将残液在电热板上烘至近干后, 再少量水烘至近干。碱化过程中需加入 4~10 mL、浓度为 10 mol/L 的 NaOH 溶液, NaOH 溶液用量视沉淀量多少来调节。为使样品达到碱性条件, 可对样品溶液进行微

加热, 再置入 Teflon 离心管中, 在振荡萃取 Re 之前, 先加入 4~10 mL 二甲基酮, 持续离心振荡约 1 min 后, 将上层二甲基酮转移至盛有少量水的 Teflon 烧杯中, 为促进样品溶液中二甲基酮挥发, 将其加热 50℃ 附近, 持续 30~60 min, 并继续加热升温至 120℃ 烘干。为分离残余的 Os, 再次烘干之前, 需滴入适量 30% 的 H_2O_2 溶液和浓度较高的 HNO_3 溶液。将烘干的残渣用适量硝酸溶解稀释后, 用于测定 Re 同位素比值的样品溶液便制备完成。将上述分离的 Os 和 Re 两组样品通过 X-series ICP-MS 测定。详细步骤参见文献(杜安道, 2012; 周利敏等, 2012; 王礼兵等, 2013)。

5 分析结果

为避免辉钼矿 Re-Os 同位素因失耦影响定年数据准确性,本次在辉钼矿采集过程中遵循“多取样,细磨碎”的原则(Stein et al., 2003; Selby and Creaser, 2004)。用于本次研究的 10 件样品均采自昆山钼钨铜多金属矿床 PD920 平硐内(采集间距 10 m 以上),采样时主要从辉钼矿较富集的地段采集,所采集的辉钼矿样品不同程度的伴生少量黄铁矿或黄铜矿,辉钼矿单矿物分选后每件样品重量都大于 1 g,考虑到测试数据 Re-Os 等时线上分布过于集中而引起等时线年龄误差变大的情况,在 PD920 平硐采样过程中每个样品采集位置均距离较远,并分别于不同的石英脉矿体采集样品,以达到 Re 含量或 Re/Os 比值变化较大要求。实验测试由国家地质测试中心完成,通过 Isoplot 程序分别对 10

组 $^{187}\text{Re}-^{187}\text{Os}$ 年龄数据(表 1)做等时线,并计算出年龄加权平均值(图 3)。年龄数据介于 $(148.0\pm 2.4)\sim(149.6\pm 2.4)$ Ma,分布比较集中。在 $^{187}\text{Re}-^{187}\text{Os}$ 等时线图上数据分布近似一条直线,且 ^{187}Re 和 ^{187}Os 沿等时线距离拉开的较远(图 3),因此等时线年龄 (148.8 ± 1.0) Ma (MSWD=0.42) 较为可靠。模式年龄加权平均值为 (148.7 ± 0.7) Ma (MSWD=0.10)。本次测得的辉钼矿 $^{187}\text{Re}-^{187}\text{Os}$ 等时线年龄与加权平均年龄基本一致,考虑到统计学 MSWD 指标,选取加权平均年龄 (148.7 ± 0.7) Ma (MSWD=0.10) 作为本区辉钼矿的形成年龄。

6 讨论

6.1 成矿时限厘定

昆山矿床精细成矿年龄报道较少(张明玉等, 2016),为进一步针对本区成矿年龄进行有效精准

表 1 昆山钼钨铜多金属矿床辉钼矿 Re-Os 同位素模式年龄及含量

Table 1 Re-Os isotopic model age and contents of molybdenite in the Kunshan Mo-W-Cu polymetallic deposit

样品编号	Re/ 10^{-6}		普 Os/ 10^{-9}		$^{187}\text{Re}/10^6$		$^{187}\text{Os}/10^9$		模式年龄/Ma	
	测定值	不确定度	测定值	不确定度	测定值	不确定度	测定值	不确定度	测定值	不确定度
KS6-1	10.26	0.080	0.091	0.038	6.448	0.053	16.06	0.100	149.3	2.1
KS6-3	25.72	0.250	0.019	0.019	16.16	0.150	40.21	0.300	149.1	2.3
KS6-7	10.12	0.080	0.018	0.120	6.360	0.048	15.73	0.120	148.3	2.1
KS6-8	5.794	0.042	0.018	0.022	3.642	0.026	9.021	0.082	148.5	2.3
KS6-9	7.971	0.058	0.018	0.027	5.010	0.037	12.40	0.090	148.3	2.1
KS6-10	8.022	0.058	0.018	0.027	5.042	0.036	12.46	0.120	148.2	2.3
KS6-11	5.059	0.041	0.018	0.025	3.179	0.026	7.847	0.077	148.0	2.4
KS6-13	43.51	0.470	0.010	0.022	27.35	0.290	68.23	0.420	149.6	2.4
KS6-15	2.947	0.019	0.059	0.017	1.852	0.012	4.603	0.033	149.0	2.1
KS6-16	3.307	0.024	0.000	0.012	2.078	0.015	5.165	0.037	149.0	2.1

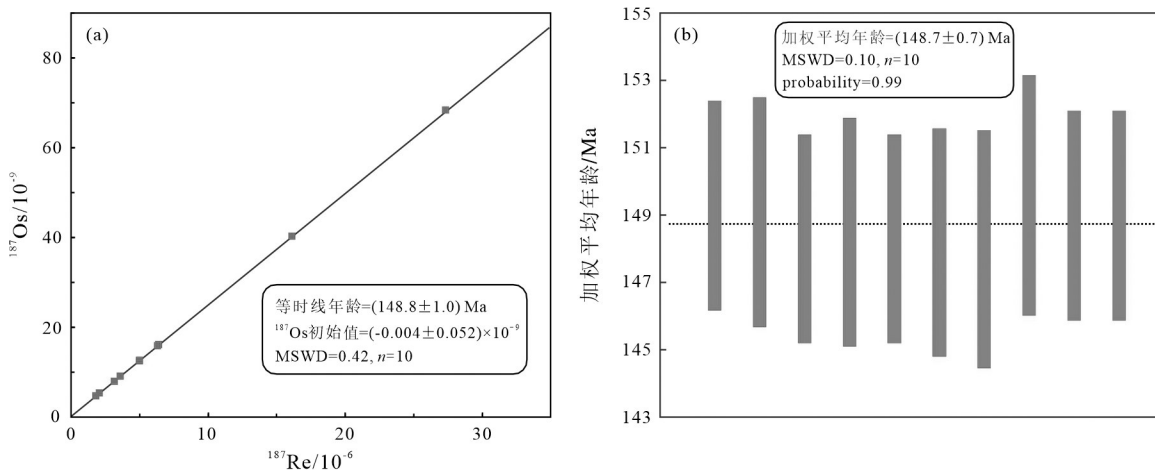


图 3 昆山钼钨铜多金属矿床 PD920 平硐中辉钼矿 Re-Os 同位素等时线年龄(a)和加权平均年龄(b)

Fig.3 Re-Os isochrone (a) and the weighted average (b) ages of molybdenite in PD920 adit of Kunshan Mo-W-Cu polymetallic deposit

厘定。通过实验获得的10件辉钼矿等时线年龄为 (148.8 ± 1.0) Ma (MSWD=0.42); Re-Os加权平均年龄为 (148.7 ± 0.7) Ma (MSWD=0.10)。其加权平均年龄与等时线年龄基本一致,因此本次所采集的样品Re-Os体系是封闭的,在采集足量的辉钼矿样品以满足实验测试条件的基础上, ^{187}Re 和 ^{187}Os 沿等时线距离拉开的较远,表明本次定年数据较为可靠。由于本次用于定年的辉钼矿样品采自于辉钼矿、黑钨矿、黄铜矿共生的含石英脉,因此MSWD值较小的Re-Os加权平均年龄 (148.7 ± 0.7) Ma (MSWD=0.10),可以直接代表昆山钨铜多金属矿床的成矿年龄,该矿床为晚侏罗世岩浆期后热液活动的产物。

6.2 成岩成矿关系

总结认识规模较大的客观成岩成矿事件是以较为丰富的精细定年数据为基础的(丰成友等, 2012; 黄兰椿和蒋少涌, 2012, 2013; 项新葵等, 2013a, 2015c; 张明玉, 2016; 张明玉等, 2016; 江丽, 2017)。项新葵等(2012a, b, 2013c, 2017)认为大湖塘钨多金属矿集区燕山期岩浆活动具有多期多次性,从似斑状黑云母花岗岩→细粒黑云母花岗岩→花岗斑岩(成矿期)→花岗斑岩(成矿后),岩石粒度粒径具有递减变细的特点,侵位顺序由早到晚(项新葵等, 2012a, b, 2013a, b, c, 2015a, b, c, 2017)。昆山矿床似斑状黑云母花岗岩、花岗斑岩的锆石单矿物U-Pb年龄分别为 (151.7 ± 1.3) Ma、 (136.6 ± 2.5) Ma(张明玉, 2016),侵入时间由早到晚,时空关系上,基本符合矿集区内岩浆侵位规律。昆山矿床燕山期至少存在两期成岩作用,第一期是152 Ma前后的晚侏罗世(以似斑状黑云母花岗岩为代表)(张明玉, 2016),略早于成矿 (148.7 ± 0.7) Ma,暗示昆山矿床成矿作用发生稍滞后于似斑状黑云母花岗岩侵位时限,因此昆山钨铜多金属矿床为典型的岩浆期后热液矿床,与晚侏罗世岩浆活动有成因联系;第二期岩浆活动为137 Ma前后的早白垩世(以花岗斑岩为代表)(张明玉, 2016),滞后于成矿 (148.7 ± 0.7) Ma约12 Ma,表明第二期岩浆活动可能不具有成矿意义,经过野外地质调查发现,早白垩世花岗斑岩产出状态主要为岩枝或岩脉,与围岩的接触关系截然,未见明显热液矿化蚀变现象,切穿似斑状黑云母花岗岩和Mo-W-Cu工业矿体,对矿体形态

造成一定的破坏,为成矿后花岗斑岩。

6.3 成矿物质来源

Re-Os同位素组成不仅在约束成矿作用时限方面发挥重要作用,而且可以反演成矿物质初始来源的深度,进一步示踪不同深度混源的程度。Re元素化学性质表现为分散元素和不相容元素,在地壳中表现为强烈亏损,结晶为独立的自然矿物较为困难(涂光炽等, 2004)。壳源→壳幔混源→幔源,辉钼矿中Re相差一个数量级,即 $n \times 10^{-6} \rightarrow n \times 10^{-5} \rightarrow n \times 10^{-4}$ 呈现递增趋势(Mao et al., 1999; Stein et al., 2001)。单一矿种的钼金属矿床Re一般波动较小,并且较多矿种的钼多金属矿床而言,Re表现更低(叶会寿等, 2006)。当然,有时在同一个矿床中,也存在辉钼矿Re波动范围较大的情况(代军治等, 2007)。辉钼矿中Re高低通常与成矿主岩不均一的源物质组成,经历部分熔融作用后,在岩浆期后热液成矿演化过程中,析出挥发份的能力有关(Selby and Creaser, 2001),期间,成矿主岩的差异性演化,通常会导致Cu(或W)多金属矿床中辉钼矿Re显著高于Mo多金属矿床对应的含量(Berzina et al., 2005)。

昆山钨铜多金属矿床中辉钼矿Re为 $2.95 \times 10^{-6} \sim 43.51 \times 10^{-6}$,仅KS6-3和KS6-13两个样品Re稍高(分别为 25.72×10^{-6} 和 43.51×10^{-6}),其他8个样品Re较低(平均 6.69×10^{-6}),综合以上分析结果,认为昆山钨铜多金属矿床的成矿物质以壳源为主,考虑到存在较高Re两个样品($n \times 10^{-5}$),说明可能存在部分幔源的成矿物质参与了该矿床的形成。这一结果与张明玉等(2018a)获得的Hf同位素认识一致,作为昆山矿床成矿主岩的似斑状黑云母花岗岩,其20个锆石原位Hf同位素测点 $\epsilon_{\text{Hf}}(t)$ 值介于-8.8~4.48,存在两个大于0(0.03和4.48)的测点,表明似斑状黑云母花岗岩以壳源为主,并存在少量幔源物质参与其形成。昆山钨铜多金属矿床含石英脉和黑钨矿氧同位素研究表明,12件石英 $\delta^{18}\text{O}_{\text{V-SMOW}}$ 值介于11.2‰~16.9‰,平均为12.5‰;黑钨矿 $\delta^{18}\text{O}_{\text{V-SMOW}}$ 值为6.2‰~8.1‰,平均为7.1‰,显示成矿流体为再平衡岩浆水,因此本区成矿流体应为成矿主岩母岩浆演化晚期分异而成,因此昆山矿床属于岩浆期后热液矿床,成矿物质来源相应继承了成矿主岩的源区特征,说明本区辉钼矿Re-Os同位素体系对昆山矿床成矿物质来源的示踪较为可靠。

表2 大湖塘钨铜钼多金属矿集区成矿定年结果汇总

Table 2 A summary of mineralization ages of Dahutang W-Cu-Mo polymetallic ore-concentrated area

矿床名称	测试对象	测试方法	成岩、成矿年龄/Ma	数据来源
石门寺	辉钼矿	Re-Os法	139.2±1.0	等时线年龄(Mao et al., 2013)
	辉钼矿	Re-Os法	143.7±1.2	等时线年龄(丰成友等, 2012)
	辉钼矿	Re-Os法	149.6±1.4	等时线年龄(项新葵等, 2013a)
狮尾洞	辉钼矿	Re-Os法	140.9±3.6	等时线年龄(丰成友等, 2012)
昆山	辉钼矿	Re-Os法	148.7±0.7	等时线年龄(本文)
	辉钼矿	Re-Os法	151.0±1.3	等时线年龄(张明玉, 2016)
梅子坑	辉钼矿	Re-Os法	148.9±4.4	加权平均年龄(张志辉等, 2013)

6.4 地球动力学演化

昆山矿床所属的大湖塘钨铜钼多金属矿集区已报道了一批与成矿相关的年代学数据(表2), 总结后推测本区燕山期成矿事件至少存在两期。其中第一期晚侏罗世成矿事件时限为 151.0~148.7 Ma, 昆山辉钼矿 Re-Os 等时线年龄(151.0±1.3) Ma (张明玉, 2016), 梅子坑辉钼矿 Re-Os 加权平均年龄(150.0±1.0)Ma(张志辉等, 2013), 石门寺辉钼矿 Re-Os 等时线年龄(149.6±1.2) Ma (项新葵等, 2013a), 本次研究测得的昆山辉钼矿 Re-Os 加权平均年龄(148.7±0.7)Ma; 第二期早白垩世成矿事件(140.9±3.6) Ma(丰成友等, 2012), 石门寺辉钼矿

Re-Os 等时线年龄件时限约为 143.7~139.2 Ma, 石门寺、狮尾洞辉钼矿 Re-Os 等时线年龄分别为 (143.7 ± 1.2) Ma、(139.2 ± 1.0) Ma (Mao et al., 2013)。项新葵等(2015c)将江南造山带中段的“挤压-伸展旋回”时限约束为 146~135 Ma, 因此本区第一期晚侏罗世成矿事件(151.0~148.7 Ma)形成于碰撞挤压(陆内造山)环境, 为“挤压成矿”; 第二期早白垩世成矿事件(143.7~139.2 Ma)发生于陆内挤压向伸展转换的背景, 为“挤压至伸展过渡成矿”。大湖塘矿集区在伸展拉张转换之前便已有成矿作用发生, 说明伸展拉张引发的地壳减薄环境对本区的成矿作用发生不是所必需的。结合上述区域成矿

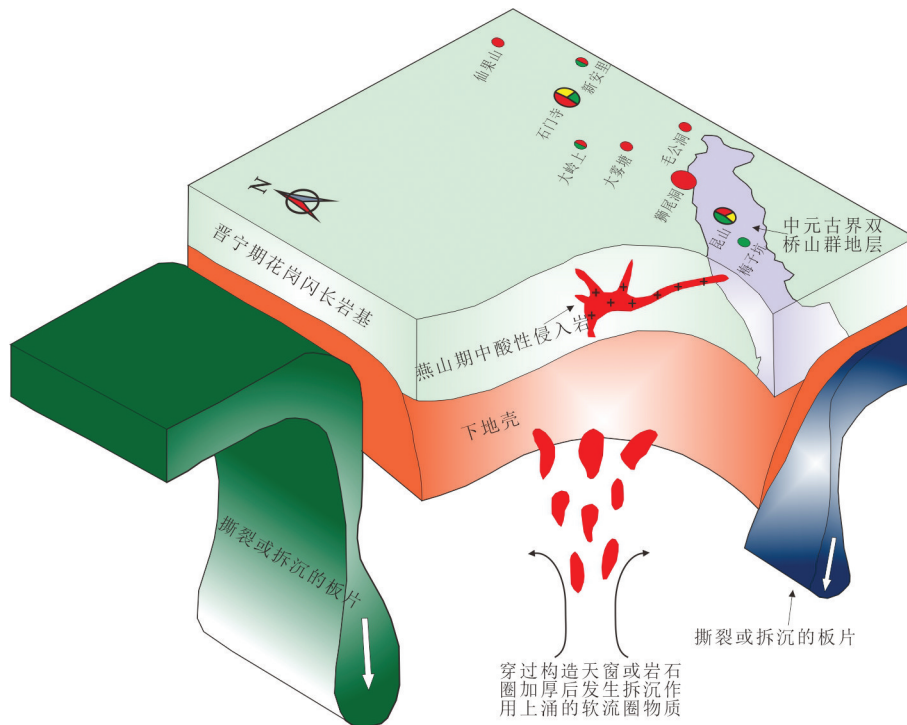


图4 大湖塘钨多金属矿集区成岩成矿地球动力学演化模式图

Fig.4 The geodynamical evolution pattern diagrams of ore-and rock-forming in W-Cu-Mo polymetallic ore-concentrated area

作用时限及构造旋回演化特征,本文推测热源供给途径有两种可能性,第一种诱发软流圈上涌途径,早侏罗世 Izanagi 板块(高浮力块体,如海山岛链、无震海岭等)俯冲至九岭地区时俯冲角度发生转换,诱发俯冲板片出现裂缝而撕裂,从而打开构造天窗(Mao et al., 2011);第二种诱发软流圈上涌途径,在陆内造山作用产生的碰撞挤压应力场控制下,引发岩石圈加厚而产生拆沉((项新葵等, 2015c)。通过以上途径之一导致在该地区形成一系列 NNE 向壳幔相互作用强烈的低压带,软流圈物质自晚侏罗世开始,沿着 NNE 向深断裂与先期(晋宁晚期)形成的 NEE 向古断裂的交汇部位上涌,通过热传导效应引起地壳物质发生部分熔融,于大湖塘地区形成了似斑状黑云母花岗岩(岩株)、细粒黑云母花岗岩(小岩株)、较早期花岗斑岩(岩脉或岩枝)等一系列中酸性侵入岩(图4)。当它们侵位于新元古界双桥山群地层时,则发生第一期成矿作用,即以石英脉型为主的 Mo-W-Cu 多金属矿床(如昆山矿床、梅子坑矿床,图4);当它们侵位于晋宁期黑云母花岗闪长岩时,第一期和第二期成矿作用均有发生,形成“一区三型”W-Cu-Mo 多金属矿床(项新葵等, 2015a),即石英脉型、云英岩型(或细脉浸染型)和热液隐爆角砾岩型(如石门寺、新安里、大岭上等矿床,图4)。

7 结 论

(1)本次测得的辉钼矿 Re-Os 加权平均年龄(148.7±0.7) Ma (MSWD=0.10),可以直接代表昆山钨钼铜多金属矿床的成矿年龄,该矿床为晚侏罗世岩浆期后热液活动的产物。

(2)昆山钨钼铜多金属矿床属于典型的岩浆期后热液矿床,成矿物质来源相应继承了成矿主岩的源区特征。成矿物质以壳源为主,可能存在部分幔源的成矿物质参与了该矿床的形成。

(3)大湖塘钨多金属矿集区燕山期成矿事件至少存在两期,第一期晚侏罗世成矿事件时限为 151.0~148.7 Ma,第二期早白垩世成矿事件时限为 143.7~139.2 Ma。

(4)当燕山期中酸性侵入岩侵位于新元古界双桥山群地层时,则发生第一期成矿作用,即以石英脉型为主的 Mo-W-Cu 多金属矿床;当侵位于晋宁

期黑云母花岗闪长岩时,第一期和第二期成矿作用均有发生,形成石英脉型、云英岩型和热液隐爆角砾岩型 W-Cu-Mo 多金属矿床。

致谢: 本文一些观点和结论的凝练曾向杨明桂教授请教与讨论,他们提出了许多宝贵意见;本文取得的进展基于大湖塘地区近年实施的诸多矿产地质调查与勘查项目及相关研究成果。在此谨致谢意!

References

- Berzina A N, Sotnikov V I, Economou-Eliopoulos M, Eliopoulos D G. 2005. Distribution of rhenium in molybdenite from porphyry Cu-Mo and Mo-Cu deposits of Russia (Siberia) and Mongolia[J]. *Ore Geology Reviews*, 26(1): 91-113.
- Dai Junzhi, Mao Jingwen, Du Andao, Xie Guiqing, Bai Jie, Yang Fuquan, Qu Wenjun. 2007. Re-Os dating of molybdenite from the Xiaojiaingzi Mo (Fe) deposit in Western Liaoning and its geological significance[J]. *Acta Geologica Sinica*, 81(7): 917-923 (in Chinese with English abstract).
- Du A D, Wu S, Sun D, Wang S, Qu W, Markey H S R, Morgan J, Malinovsky D. 2007. Preparation and certification of Re-Os dating reference materials: Molybdenites HLP and JDC[J]. *Geostandards and Geoanalytical Research*, 28(1): 41-52.
- Du Andao, Qu Wenjun, Wang Denghong, Li Chao. 2012. Re-Os Method and its Application in Ore Deposit Science[M]. Beijing: Geological Publishing House, 15-178 (in Chinese).
- Feng Chengyou, Zhang Dequan, Xiang Xinkui, Li Daxin, Qu Hongying, Liu Jiannan, Xiao Ye. 2012. Re-Os isotopic dating of molybdenite from the Dahutang tungsten deposit in northwestern Jiangxi Province and its geological implication[J]. *Acta Petrologica Sinica*, 28(12): 3858-3868 (in Chinese with English abstract).
- Feng Xiaolu, Cheng Zhiguo, Liu Zhao, Zhang Yan. 2022. Metallogenic age of the Caojiatun Mo deposit in the Southern Great Xing'an Range: Evidence from molybdenite Re-Os isotopic dating[J]. *Geology in China*, 49(2): 667-668 (in Chinese with English abstract).
- Huang Lanchun, Jiang Shaoyong. 2012. Zircon U-Pb geochronology, geochemistry and petrogenesis of the porphyry-like muscovite granite in the Dahutang tungsten deposit, Jiangxi Province[J]. *Acta Petrologica Sinica*, 28(12): 3887-3900 (in Chinese with English abstract).
- Huang Lanchun, Jiang Shaoyong. 2013. Geochronology, geochemistry and petrogenesis of the tungsten-bearing porphyritic granite in the Dahutang tungsten deposit, Jiangxi Province[J]. *Acta Petrologica Sinica*, 29(12): 4323-4335 (in Chinese with English abstract).
- Huang L C, Jiang S Y. 2014. Highly fractionated S-type granites from the giant Dahutang tungsten deposit in Jiangnan Orogen, Southeast

- China: Geochronology, petrogenesis and their relationship with W-mineralization[J]. *Lithos*, 202-203: 207-226.
- Jiang Li. 2017. The Geochemical Characteristics and Diagenetic Ages of Granitic Rock of Kunshan Molybdenum Copper Deposit, Jiangxi Province[D]. Nanchang: East China Institute of Technology (in Chinese with English abstract).
- Li Chao, Qu Wenjun, Du Andao. 2009. Decoupling of Re and Os and migration model of ^{187}Os in coarse-grained molybdenite[J]. *Mineral Deposits*, 28(5): 707-712 (in Chinese with English abstract).
- Lin Li, Yu Zhongzhen, Luo Xiaohong, Ding Shaohui. 2006a. The metallogenic prognosis of Dahutang tungsten ore field in Jiangxi[J]. *Journal of East China Institute of Technology*, (S1): 139-142 (in Chinese with English abstract).
- Lin Li, Zhan Gangle, Yu Xiaoping. 2006b. Geological characteristics and ore-search prospect of Dahutang tungsten (tin) orefield in Jiangxi[J]. *Resources Survey and Environment*, 27(1): 25-32 (in Chinese with English abstract).
- Mao J W, Zhang Z C, Zhang Z H, Du A D. 1999. Re-Os isotopic dating of molybdenites in the Xiaoliugou W (Mo) deposit in the northern Qilian mountains and its geological significance[J]. *Geochimica et Cosmochimica Acta*, 63(11/12): 1815-1818.
- Mao J W, Xie G Q, Duan C, Franco P, Dazio L, Chen Y C. 2011. A tectono-genetic 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(1): 294-314.
- Mao Z H, Cheng Y B, Liu J J, Yuan S D, Wu S H, Xiang X K, Luo X H. 2013. Geology and molybdenite Re-Os age of the Dahutang granite-related veinlets-disseminated tungsten ore field in the Jiangxin Province, China[J]. *Ore Geology Reviews*, 53: 422-433.
- Qu Wenjun, Du Andao, Ren Jing. 2008. Influence of H_2O_2 on the signal intensity of rhenium, ssmium and Re-Os age in the process of dissolution for pyrite[J]. *Chinese Journal of Analytical Chemistry*, 36(2): 223-226 (in Chinese with English abstract).
- Selby D, Creaser R A. 2001. Re-Os geochronology and systematics in molybdenite from the Endako porphyry molybdenum deposit, British Columbia, Canada[J]. *Economic Geology*, 96(1): 197-204.
- Selby D, Creaser R A. 2004. Macroscale NTIMS and microscale LA-MC-ICP-MS Re-Os isotopic analysis of molybdenite: Testing spatial restrictions for reliable Re-Os age determinations, and implications for the decoupling of Re and Os within molybdenite[J]. *Geochimica et Cosmochimica Acta*, 68(19): 3897-3908.
- Stein H, Markey R, Morgan J, Hannah J, Scherstén A. 2001. The remarkable Re-Os chronometer in molybdenite: How and why it works[J]. *Terra Nova*, 13(6): 479-486.
- Stein H, Scherstén A, Hannah J, Markey R. 2003. Subgrain-scale decoupling of Re and ^{187}Os and assessment of laser ablation ICP-MS spot dating in molybdenite[J]. *Geochimica et Cosmochimica Acta*, 67(19): 3673-3686.
- Tu Guangzhi, Gao Zhenmin, Hu Ruizhong. 2004. Dispersed Element Geochemistry and Ore-forming Mechanism[M]. Beijing: Geological Publishing House, 27-86 (in Chinese).
- Wang Guohua, Liao Chuanmao, Zhang Yong. 2015. Geological characteristic and ore genesis of the Kunshan molybdenite-tungsten polymetallic deposit, northern Jiangxi Province[J]. *Heilongjiang Science and Technology Information*, (21): 7-8 (in Chinese with English abstract).
- Wang Libing, Qu Wenjun, Li Chao, Zhou Limin, Du Andao, Zu Bo. 2013. Method study on the separation and enrichment of rhenium measured by negative thermal ionization mass spectrometry[J]. *Rock and Mineral Analysis*, 32(3): 402-408 (in Chinese with English abstract).
- Wang Xirong, Pan Jiayong, Li Shaoxia, Wang Jiabin. 2016. Study on metallogenic series of ore deposits during Yanshanian metallogenic period and discussion on ore prospecting in Dahutang ore-deposit-clustered area[J]. *Contributions to Geology and Mineral Resources Research*, 31(2): 206-212 (in Chinese with English abstract).
- Xiang Xinkui, Chen Maosong, Zhan Guonian, Qian Zhenyi, Li Hui, Xu Jianhua. 2012a. Metallogenic geological conditions of Shimensi tungsten-polymetallic deposit in north Jiangxi province[J]. *Contributions to Geology and Mineral Resources Research*, 27(2): 143-155 (in Chinese with English abstract).
- Xiang Xinkui, Liu Xianmu, Zhan Guonian. 2012b. Discovery of Shimensi super-large tungsten deposit and its prospecting significance in Dahutang area, Jiangxi Province[J]. *Resources Survey and Environment*, 33(3): 141-151 (in Chinese with English abstract).
- Xiang Xinkui, Wang Peng, Sun Deming, Zhong Bo. 2013a. Re-Os isotopic age of molybdenite from the Shimensi tungsten polymetallic deposit in northern Jiangxi Province and its geological implications[J]. *Geological Bulletin of China*, 32(11): 1824-1831 (in Chinese with English abstract).
- Xiang Xinkui, Wang Peng, Sun Deming, Zhong Bo. 2013b. Isotopic geochemical characteristics of the Shimensi Tungsten-polymetallic deposit in northern Jiangxi province[J]. *Acta Geoscientica Sinica*, 34(3): 263-271 (in Chinese with English abstract).
- Xiang Xinkui, Wang Peng, Zhan Guonian. 2013c. Geological characteristics of Shimensi tungsten polymetallic deposit in northern Jiangxi province[J]. *Mineral Deposits*, 32(6): 1171-1187 (in Chinese with English abstract).
- Xiang Xinkui, Yin Qingqing, Feng Chengyou, Wang Hui, Liu Nanqing, Yu Zhendong. 2015a. Elements and fluids migration regularity of granodiorite alteration zones in the Shimensi tungsten polymetallic deposit in northern Jiangxi and their constrain on mineralization[J]. *Acta Geologica Sinica*, 89(7): 1273-1287 (in

- Chinese with English abstract).
- Xiang Xinkui, Yin Qingqing, Sun Deming, Zhong Bo. 2015b. Petrogenesis of Yanshanian granites in Shimensi, northern Jiangxi Province: Sr–Nd isopleth evidence[J]. *Geology of Jiangxi*, 16(2): 79–87 (in Chinese with English abstract).
- Xiang Xinkui, Yin Qingqing, Sun Keke, Chen Bin. 2015c. Origin of the Dahutang syn– collisional granite– porphyry from mid– segment of the Jiangnan orogen, China: Zircon U– Pb geochronology, geochemical and Nd– Hf isotopic constraints[J]. *Acta Petrologica et Mineralogica*, 34(5): 581–600 (in Chinese with English abstract).
- Xiang Xinkui, Yin Qingqing, Zhan Guonian, Qu Kai, Liu Xing, Tan Rong, Zhong Bo. 2017. Metallogenic conditions and ore– prospecting of Shimensi tungsten ore section in the north of Dahutang area in Jiangxi Province[J]. *Journal of Jilin University (Earth Science Edition)*, 47(3): 645–658 (in Chinese with English abstract).
- Yang Bin, Zhao Lei, Chen Zhengle, Mo Huohua, Lu Jie, Tan You. 2021. U–Pb and Re–Os dating of the Jianlong Cu–W deposit in Xingguo County of southern Jiangxi Province: Constraint on its petrogenetic and metallogenetic ages[J]. *Geology in China*, 48(2): 495–506 (in Chinese with English abstract).
- Yang Minggui, Wang Kun. 1994. The geological tectonic framework and the crustal evolution in Jiangxi Province[J]. *Jiangxi Geology*, (4): 239–251 (in Chinese with English abstract).
- Ye Huitao, Mao Jingwen, Li Yongfeng, Guo Bojian, Zhang Changqing, Liu Wangjun, Yan Quanren, Liu Guoyin. 2006. SHRIMP zircon U–Pb and molybdenite Re–Os dating for the superlarge Donggou porphyry Mo deposit in East Qinling, China, and its geological implication[J]. *Acta Geologica Sinica*, 80(7): 1078–1088 (in Chinese with English abstract).
- Ye Shaozhen, Wang Guohua, Gan Jinjun, Liao Chuanmao, Pen Huai'an, Li Minze, Wu Huoxing, Zha Zhiqiang, Huang Jiexiang, Chen Dekang. 2015. New progress in prospecting in the middle of Jiuling metallogenic belt of northern region of Jiangxi[J]. *China Molybdenum Industry*, 39(2): 16–22 (in Chinese with English abstract).
- Ye Shaozhen, Xia Jiehua, Xu Jun, Chen Wenhua, Wang Guohua. 2016. Geological characteristics of Kunshan W–Mo–Cu deposit in Jiuling metallogenic belt in Northern Jiangxi[J]. *China Tungsten Industry*, 31(4): 7–13 (in Chinese with English abstract).
- Zhang Mingyu. 2016. *Genesis and Metallogenic Model of Kunshan W–Mo–Cu Deposit in Dahutang Area, Northern Jiangxi Province*[D]. Beijing: China University of Geosciences (in Chinese with English abstract).
- Zhang Mingyu, Feng Chengyou, Li Daxin, Wang Hui, Zhou Jianhou, Ye Shaozhen, Wang Guohua. 2016. Geochronological study of the Kunshan W–Mo–Cu deposit in the Dahutang area, Northern Jiangxi Province and its geological significance[J]. *Geotectonica et Metallogenia*, 40(3): 503–516 (in Chinese with English abstract).
- Zhang Mingyu, Feng Chengyou, Li Daxin, Wang Hui, Zhou Jianhou, Ye Shaozhen, Wang Guohua. 2018a. Geochemical and Hf isotopes of granites in the Kunshan W–Mo–Cu deposit, northern Jiangxi Province[J]. *Acta Geologica Sinica*, 92(1): 77–93 (in Chinese with English abstract).
- Zhang Mingyu, Feng Chengyou, Wu Guang, Wang Hui, Wu Yu, Han Meimei, Wu Wenheng. 2018b. Fluid inclusion study and stable isotope characteristics of the Kunshan W–Mo–Cu deposit in the Dahutang area, northern Jiangxi Province, China[J]. *Acta Petrologica Sinica*, 34(9): 2615–2631 (in Chinese with English abstract).
- Zhang Zhihui, Zhang Da, Wu Ganguo, Luo Ping, Chen Xihua, Di Yongjun, Lü Liangji. 2013. Re–Os isotopic age of molybdenite from the Meizikeng molybdenite deposit in Northern Jiangxi Province and its geological significance[J]. *Journal of Jilin University (Earth Science Edition)*, 43(6): 1851–1863 (in Chinese with English abstract).
- Zhang Zhihui, Zhang Da, He Xiaolong, Hu Bojie, Zhu Xinyou, Du Zezhong, Jia Wenbin, Gong Xiaodong. 2021. Biotite granodiorite age of Jiuling complex in Jiangxi Province and its limitation on the collision and splicing time of the Yangtze and Cathay plates[J]. *Geology in China*, 48(5): 1562–1579 (in Chinese with English abstract).
- Zhou Limin, Gao Bingyu, Wang Libing, Li Chao, Qu Wenjun, Hou Zengqian, Du Andao. 2012. Improvements on the separation method of osmium by direct distillation in Carius tube[J]. *Rock and Mineral Analysis*, 31(3): 413–418 (in Chinese with English abstract).

附中文参考文献

- 代军治, 毛景文, 杜安道, 谢桂青, 白杰, 杨富全, 屈文俊. 2007. 辽西肖家营子钨(铁)矿床 Re–Os 年龄及其地质意义[J]. *地质学报*, 81(7): 917–923.
- 杜安道, 屈文俊, 王登红, 李超. 2012. 铼–钨法及其在矿床学中的应用[M]. 北京: 地质出版社, 15–178.
- 丰成友, 张德全, 项新葵, 李大新, 瞿泓滢, 刘建楠, 肖晔. 2012. 赣西北大湖塘钨矿床辉钨矿 Re–Os 同位素定年及其意义[J]. *岩石学报*, 28(12): 3858–3868.
- 丰晓路, 程志国, 刘钊, 张岩. 2022. 大兴安岭南段曹家屯钨矿床成矿时代: 来自辉钨矿 Re–Os 年龄的证据[J]. *中国地质*, 49(2): 667–668.
- 黄兰椿, 蒋少涌. 2012. 江西大湖塘钨矿床似斑状白云母花岗岩锆石 U–Pb 年代学、地球化学及成因研究[J]. *岩石学报*, 28(12): 3887–3900.
- 黄兰椿, 蒋少涌. 2013. 江西大湖塘富钨花岗岩斑岩年代学、地球化学特征及成因研究[J]. *岩石学报*, 29(12): 4323–4335.
- 江丽. 2017. 江西昆山钨铜矿床岩浆岩地球化学特征及成岩时代[D]. 南昌: 东华理工大学.

- 李超, 屈文俊, 杜安道. 2009. 大颗粒辉钼矿 Re-Os 同位素失耦现象及 187Os 迁移模式研究[J]. 矿床地质, 28(5): 707-712.
- 林黎, 余忠珍, 罗小洪, 丁少辉. 2006a. 江西大湖塘钨矿田成矿预测[J]. 东华理工学院学报, (S1): 139-142.
- 林黎, 占岗乐, 喻晓平. 2006b. 江西大湖塘钨(锡)矿田地质特征及远景分析[J]. 华东地质, 27(1): 25-32.
- 屈文俊, 杜安道, 任静. 2008. 过氧化氢在黄铁矿的溶解过程中对铼-钨信号强度及年龄的影响[J]. 分析化学, 36(2): 223-226.
- 涂光炽, 高振敏, 胡瑞忠. 2004. 分散元素地球化学及成矿机制[M]. 北京: 地质出版社, 27-86.
- 汪国华, 廖传茂, 张勇. 2015. 赣北昆山钨钼铜多金属矿床地质特征及成因探讨[J]. 黑龙江科技信息, (21): 7-8.
- 王礼兵, 屈文俊, 李超, 周利敏, 杜安道, 俎波. 2013. 负离子热表面电离质谱法测量铼的化学分离方法研究[J]. 岩矿测试, 32(3): 402-408.
- 王西荣, 潘家永, 李绍侠, 王佳鑫. 2016. 大湖塘矿集区燕山成矿阶段矿床成矿系列研究及找矿问题探讨[J]. 地质找矿论丛, 31(02): 206-212.
- 项新葵, 陈茂松, 詹国年, 钱振义, 李辉, 许建华. 2012a. 赣北石门寺矿区钨多金属矿床成矿地质条件[J]. 地质找矿论丛, 27(2): 143-155.
- 项新葵, 刘显沐, 詹国年. 2012b. 江西省大湖塘石门寺矿区超大型钨矿的发现及找矿意义[J]. 资源调查与环境, 33(3): 141-151.
- 项新葵, 王朋, 孙德明, 钟波. 2013a. 赣北石门寺钨多金属矿床辉钼矿 Re-Os 同位素年龄及其地质意义[J]. 地质通报, 32(11): 1824-1831.
- 项新葵, 王朋, 孙德明, 钟波. 2013b. 赣北石门寺钨多金属矿床同位素地球化学研究[J]. 地球学报, 34(3): 263-271.
- 项新葵, 王朋, 詹国年. 2013c. 赣北石门寺超大型钨多金属矿床地质特征[J]. 矿床地质, 32(6): 1171-1187.
- 项新葵, 尹青青, 丰成友, 王辉, 刘南庆, 余振东. 2015a. 赣北石门寺钨多金属矿床花岗岩闪长岩蚀变带元素、流体迁移规律及其对成矿作用的制约[J]. 地质学报, 89(7): 1273-1287.
- 项新葵, 尹青青, 孙德明, 钟波. 2015b. 赣北石门寺矿区燕山期花岗岩成因的 Sr-Nd 同位素制约[J]. 江西地质, 16(2): 79-87.
- 项新葵, 尹青青, 孙克克, 陈斌. 2015c. 江南造山带中段大湖塘同构造花岗岩斑岩的成因——锆石 U-Pb 年代学、地球化学和 Nd-Hf 同位素制约[J]. 岩石矿物学杂志, 34(5): 581-600.
- 项新葵, 尹青青, 詹国年, 曲凯, 刘行, 谭荣, 钟波. 2017. 江西大湖塘北区石门寺矿段钨成矿条件与找矿预测[J]. 吉林大学学报(地球科学版), 47(3): 645-658.
- 杨斌, 赵磊, 陈正乐, 莫火华, 鲁捷, 谭友. 2021. 赣南兴国县见龙铜钨矿床 U-Pb 和 Re-Os 同位素定年: 对成岩成矿时代的限定[J]. 中国地质, 48(2): 495-506.
- 杨明桂, 王昆. 1994. 江西省地质构造格架及地壳演化[J]. 江西地质, (4): 239-251.
- 叶会寿, 毛景文, 李永峰, 郭保健, 张长青, 刘王君, 闫全人, 刘国印. 2006. 东秦岭东沟超大型斑岩钼矿 SHRIMP 锆石 U-Pb 和辉钼矿 Re-Os 年龄及其地质意义[J]. 地质学报, 80(7): 1078-1088.
- 叶少贞, 汪国华, 千金军, 廖传茂, 彭淮安, 李民泽, 吴火星, 查志强, 黄家翔, 陈德康. 2015. 赣北九岭成矿带昆山钨钼铜矿区找矿新进展[J]. 中国钨业, 39(2): 16-22.
- 叶少贞, 夏节华, 徐军, 陈文华, 汪国华. 2016. 赣北九岭成矿带昆山钨钼铜矿床地质特征[J]. 中国钨业, 31(4): 7-13.
- 张明玉, 丰成友, 李大新, 王辉, 周建厚, 叶少贞, 汪国华. 2016. 赣北大湖塘地区昆山 W-Mo-Cu 矿床侵入岩锆石 U-Pb、辉钼矿 Re-Os 年代学及地质意义[J]. 大地构造与成矿学, 40(3): 503-516.
- 张明玉. 2016. 赣北大湖塘地区昆山 W-Mo-Cu 矿床成因及成矿模式[D]. 北京: 中国地质大学(北京).
- 张明玉, 丰成友, 李大新, 王辉, 周建厚, 叶少贞, 汪国华. 2018a. 赣北昆山钨钼铜矿床花岗岩地球化学及 Hf 同位素研究[J]. 地质学报, 92(1): 77-93.
- 张明玉, 丰成友, 武广, 王辉, 吴玉, 韩梅梅, 武文恒. 2018b. 赣北大湖塘地区昆山钨-钼-铜矿床流体包裹体研究和稳定同位素特征[J]. 岩石学报, 34(9): 2615-2631.
- 张志辉, 张达, 吴淦国, 罗平, 陈锡华, 狄永军, 吕良冀. 2013. 赣北梅子坑钨矿床辉钼矿 Re-Os 同位素年龄及其地质意义[J]. 吉林大学学报(地球科学版), 43(6): 1851-1863.
- 张志辉, 张达, 贺晓龙, 胡攀捷, 祝新友, 杜泽忠, 贾文彬, 巩小栋. 2021. 江西九岭杂岩体中黑云母花岗岩闪长岩年龄及对扬子和华夏板块碰撞拼合时间限定[J]. 中国地质, 48(5): 1562-1579.
- 周利敏, 高炳宇, 王礼兵, 李超, 屈文俊, 侯增谦, 杜安道. 2012. Carius 管直接蒸馏快速分离钨方法的改进[J]. 岩矿测试, 31(3): 413-418.