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# 湘西沃溪金锑钨矿床白钨矿、黑钨矿与磷灰石 U-Pb 定年及其地质意义\*

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**Abstract** The Xuefeng Uplift in western Hunan is an important Au-Sb-W mineralization belt in South China, while the Woxi deposit is the largest gold deposit with a unique element association of Au-Sb-W in this region. As the ore-forming elements and mineralization stages of the deposit are relatively complex, there has been a long dispute about its mineralization ages. In this study, geological characteristics of scheelite, wolframite and pyrite (the most important gold-bearing mineral) and stibnite in the Woxi deposit were observed in details, and U-Pb dating of scheelite, wolframite and apatite were conducted with a LA-ICP-MS method. The results show that the Woxi deposit was genetically related to several hydrothermal events happened during the Late Jurassic to Early Cretaceous. Among the dated minerals, the scheelite is the earliest, which has the intercept ages of  $149.0 \pm 12\text{Ma}$ ,  $144.8 \pm 1.7\text{Ma}$  and  $139.8 \pm 6.1\text{Ma}$ ; and the wolframite was formed slightly later than the scheelite, with the intercept ages of  $137.8 \pm 3.9\text{Ma}$ ,  $134.8 \pm 5.1\text{Ma}$ . Native gold and stibnite were mainly precipitated after the formation of scheelite and wolframite, and there was still a small amount of native gold occurred in the late quartz carbonate vein ( $125.8 \pm 5.6\text{Ma}$ ,  $123.8 \pm 4.6\text{Ma}$ ). Combined with the published geochronological data, two periods of mineralization are revealed in the Woxi deposit, i. e., the Caledonian intracontinental orogenesis and the Yanshanian extensional tectonic event, respectively. The fragments of earlier W-bearing quartz veins are usually in good collage and cemented by later Au-, Sb-bearing quartz veins, indicating that there was a succession of crack-seal processes which bring about hydraulic fracturing in the Woxi deposit. Such processes were conducive to the activation, migration, accumulation and precipitation of the ore-forming elements (especially gold) in the deposit.

**Key words** Scheelite; Wolframite; Xuefeng Uplift area; Woxi; LA-ICP-MS U-Pb dating

**摘要** 沃溪矿床位于湘西雪峰隆起区的转折部位,是该区金锑钨矿床的典型代表。该矿床成矿元素及成矿期次较为复杂,各成矿阶段的形成时代长期存在争议。本次研究在对沃溪矿床详细野外调查及岩相学观察的基础上,对深部中段矿体中的白钨矿、磷灰石及浅部中段矿体中的黑钨矿开展了 U-Pb 同位素分析。依据本次所获年龄数据,结合观察到的矿脉交切关系、矿物共生组合等特征,本文认为沃溪矿床除了加里东期成矿作用之外,还存在燕山期成矿作用。其中,白钨矿形成相对较早,成矿年龄为  $149.0 \pm 12\text{Ma}$ 、 $144.8 \pm 1.7\text{Ma}$ 、 $139.8 \pm 6.1\text{Ma}$ ;黑钨矿与白钨矿同时生成(或稍晚),成矿年龄为  $137.8 \pm 3.9\text{Ma}$ 、

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134.8 ± 5.1 Ma; 自然金、辉锑矿主要在白钨矿、黑钨矿形成以后通过沉淀而成,且自然金在晚阶段(125.8 ± 5.6 Ma、123.8 ± 4.6 Ma)石英-碳酸盐脉中仍有少量产出。综合已有年代学资料推测,沃溪矿床可能在经历了加里东期陆内造山成矿作用之后,还经受了燕山期伸展构造背景下深部流体不同程度的叠加改造作用。而该矿床发现的矿脉原地破裂后被后期矿物胶结等现象,则指示其矿脉的形成与液压致裂作用有关,这种作用导致矿脉反复裂开-愈合,有利于成矿元素(尤其是金)的活化迁移和再富集沉淀。

**关键词** 白钨矿; 黑钨矿; 雪峰隆起区; 沃溪; LA-ICP-MS U-Pb 定年  
**中图法分类号** P597.3; P618.67

华南是全球规模最大的钨成矿区,钨矿床主要集中产于南岭地区及江南古陆(冶金部南岭钨矿专题组, 1985; 华仁民等, 2010; 袁顺达, 2017; Yuan *et al.*, 2018, 2019; Mao *et al.*, 2019; 谢桂青等, 2021; Zhao *et al.*, 2022a, b)。江南古陆可分为东段江南钨矿带(毛景文等, 2020)和西南段雪峰隆起区(丘元禧等, 1998; 柏道远等, 2015; Hu *et al.*, 2017)。前者主要发育与花岗岩有关的斑岩-矽卡岩型钨矿床(仅东坪钨矿床为石英脉型),通常伴有 Mo、Cu、Pb、Zn 矿化,成矿时代为燕山期,又可分为 150 ~ 135 Ma 和 130 ~ 125 Ma 两个主成矿期(毛景文等, 2020)。后者以与岩浆活动无关的层控石英脉型钨矿床为主(包正相, 1987),其次为与花岗岩有关的矽卡岩型(张龙升等, 2020; 吕沅峻等, 2021)、斑岩型钨矿(陕亮等, 2019),并常伴有大量 Au、Sb 矿化。这些钨矿床主要形成于加里东期(如沃溪、西安、杨家山; 万嘉敏, 1986; 彭建堂等, 2003; 胡瑞忠等, 2007; 张志远等, 2021)以及印支期(如大溶溪、渣滓溪、杏枫山、木瓜园; 王永磊等, 2012; 张龙升等, 2014; 陕亮等, 2019; 黄建中等, 2020; 吕沅峻等, 2021)。最近研究发现雪峰隆起区还存在燕山期的钨成矿活动(Dai *et al.*, 2022; Li *et al.*, 2022; Tang *et al.*, 2022; 李彬等, 2022),有人提出这些矿床可能与岩浆活动有关(Li *et al.*, 2022)。

沃溪金锑钨矿床位于雪峰隆起区的转折部位,是该区唯一产出白钨矿和黑钨矿都具有经济价值的矿床(祝亚男等, 2014),也是该区唯一同时发育金、锑、钨成矿且均达到工业开采品位和规模的矿床。截止到 2020 年,沃溪矿床共计获得黄金储量 40.746 t, 平均品位为 3.49 ~ 8.05 g/t; 锑 15.69 万 t; 钨矿 5.5 万 t(湖南省自然资源厅, 2020<sup>①</sup>)。沃溪矿床由于成矿元素组合较特殊,成矿具有明显的多期、多阶段性,其成矿时代一直颇受关注,不同学者相继采取不同的测试方法开展了年代学工作,例如白钨矿 Sm-Nd 等时线法(402 ± 6 Ma; 彭建堂等, 2003)、石英<sup>40</sup>Ar-<sup>39</sup>Ar 快中子活化法最小视年龄(420 ± 20 Ma 和 414 ± 19 Ma; 彭建堂等, 2003)、与辉锑矿共生石英中的流体包裹体 Rb-Sr 等时线法(144.8 ± 11.7 Ma; 史明魁等, 1993)、黑钨矿及其共生磷灰石 LA-ICP-MS U-Pb 年龄(约 130 ~ 150 Ma; Dai *et al.*, 2022; Li *et al.*, 2022; 李彬等, 2022)。这些矛盾的成矿年龄制约了对该矿床成因、成矿作用以及雪峰隆起区金锑钨成矿事件的进一步认识。

矿石矿物测年是厘定成矿时代最可靠、有效的手段

(Yuan *et al.*, 2008, 2011)。白钨矿和黑钨矿是钨矿床中最重要两种钨矿石矿物,对其直接开展定年研究可以获得更加精确可靠的钨成矿年龄。由于白钨矿和黑钨矿的部分样品中具有较高且变化范围较大的 Sm/Nd 值,是进行 Sm-Nd 定年的良好对象,前人利用此方法开展了大量年代学研究工作,并成功地获得了各类钨矿床的成矿年龄(李华芹等, 1992; 彭建堂等, 2006, 2021; Guo *et al.*, 2018)。同时,也有不少学者利用同位素稀释-热电质谱法(ID-TIMS)对黑钨矿进行 U-Pb 定年(Frei *et al.*, 1998; Romer and Lüders, 2006)。但上述两种主要的定年方法也存在局限性,具体表现在:(1)部分白钨矿、黑钨矿中的 Sm/Nd 变化很小,使得 Sm-Nd 同位素定年的应用在很大程度上受到限制(Peng and Frei, 2004);(2)无法剔除黑钨矿中常见的富 U、富普通铅的包裹体,从而严重影响分析结果(Yang *et al.*, 2020)。随着现代分析技术的发展,原位微区同位素测年因与传统的整体分析方法相比,具有高空间分辨率、高效率等优点而被广泛应用,其中最常用的是含 U 副矿物 U-Pb 测年,如锆石(Cocherie and Robert, 2008)、独居石(Wing *et al.*, 2003)、金红石(Kooijman *et al.*, 2010)、榍石(Aleinkoff *et al.*, 2002)、磷灰石(O'Sullivan *et al.*, 2020)、锡石(Yuan *et al.*, 2011)等。近年来,国内外学者相继建立了黑钨矿(Tang *et al.*, 2020; Yang *et al.*, 2020)、白钨矿激光微区原位分析方法(Poitrenaud *et al.*, 2020; Tang *et al.*, 2022),为精确厘定钨矿成矿年代学提供了技术支撑。

本文对沃溪矿床进行了详细的野外调研及岩相学研究,在此基础上,利用 LA-ICP-MS U-Pb 同位素定年方法分别对白钨矿及共生磷灰石、黑钨矿开展精确的年代学测试工作,以确定该矿床的成矿时代,并结合雪峰隆起区及其邻区金锑钨矿床的年代学资料,以期对该区金锑钨矿床成矿规律取得更加明确的认识。

## 1 区域地质背景

雪峰隆起区位于扬子地块与华夏板块之间,是江南古陆的西南段,该隆起自南而北由 NNE 向逐渐转变为 EW 向,呈向北西凸出的弧形展布,北西以慈利-保靖断裂为界,南东与

① 湖南省自然资源厅. 2020. 湖南省金矿概述. [http://zrzyt.hunan.gov.cn/zrzyt/xxgk/kxpj2017/202004/t20200405\\_4898557.html](http://zrzyt.hunan.gov.cn/zrzyt/xxgk/kxpj2017/202004/t20200405_4898557.html)

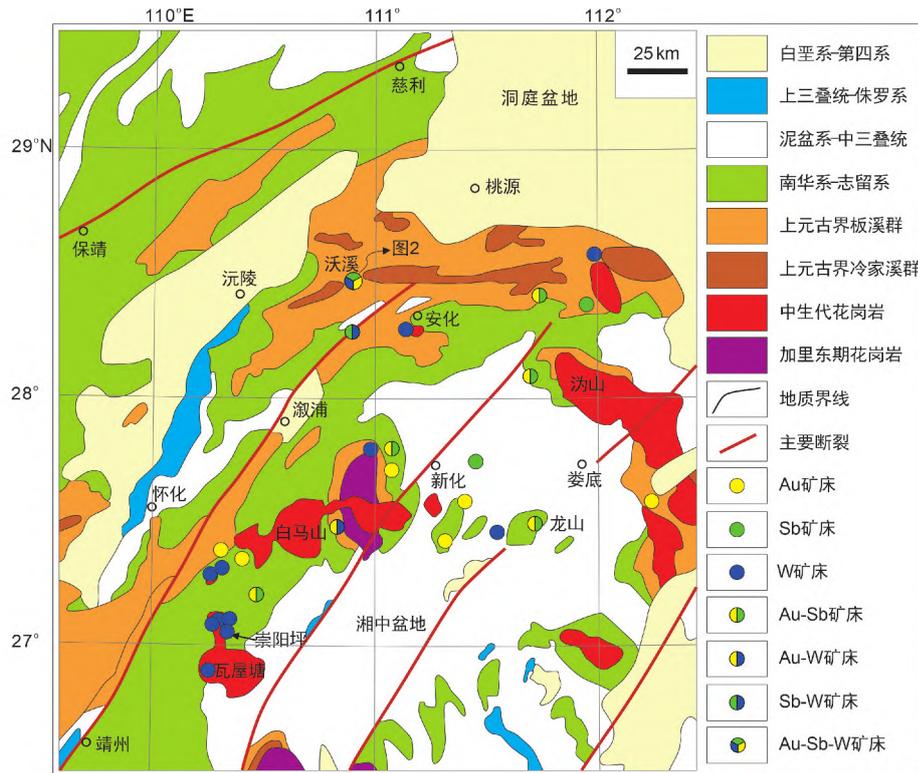


图1 雪峰隆起区地质简图(据柏道远等, 2015 改绘)

Fig. 1 Geological sketch map of Xuefeng Uplift area (modified after Bai *et al.*, 2015)

湘中盆地相接(图1)(柏道远等, 2015)。区内主要出露新元古界和寒武系及少量泥盆系、石炭-二叠系和白垩系地层。其中, 上元古界冷家溪群和板溪群是重要的金、锑、钨赋矿层位, 主要由一套巨厚的浅变质海相沉积粘土岩、碎屑岩组成, 局部夹镁铁质火山岩。雪峰隆起区经历了武陵(晋宁)、加里东、印支、燕山等多期次的构造运动, 主要发育 NE 向的褶皱和断裂。岩浆活动以溆浦-靖州断裂为界, 两侧差异显著; 该断裂以东分布大量加里东期和印支期花岗岩, 以西则无花岗岩发育(图1)。

区内广泛分布金、锑、钨矿床, 如大溶溪钨矿床、沃溪金锑钨矿床、符竹溪金(锑)矿床、西安金钨矿床、渣滓溪锑钨矿床、合仁坪金矿床等, 且多数金、锑、钨矿床中常伴生少量白钨矿或钨矿化(罗献林, 1990; 何永森等, 2013), 如西冲金锑矿床(牛贺才和马东升, 1992)、符竹溪金(锑)矿床(潘灿军等, 2015)等。这些矿床几乎都产于上元古界冷家溪群和板溪群的浅变质岩中, 矿体层控特征明显, 主要受断裂影响, 成矿与岩浆活动无直接关系(包正相, 1987; 罗献林, 1990)。近十年来, 随着勘查工作的深入, 在雪峰隆起区相继发现了许多与花岗岩有关的钨矿床, 如杨家山、上茶山、寨溪山、沙溪、牛角界石英脉型钨矿床(孔令兵等, 2014; 梁玉明, 2015; 苏康明等, 2016; 李永德等, 2017), 杏枫山、大溶溪砂卡岩型钨矿床(彭建堂, 2019; 张龙升等, 2020), 以及木瓜园斑岩型钨矿床(李洪英等, 2019; 陕亮等, 2019)。这些与花岗岩有关的钨矿床, 除杨家山钨矿床形成于加里东期外,

其余均为印支期。

## 2 矿床地质特征

沃溪矿区范围内未见岩浆岩, 主要出露上元古界冷家溪群和板溪群的浅变质岩。其中, 板溪群不整合于冷家溪群之上, 可划分为马底驿组 and 上覆的五强溪组, 两组地层以沃溪断层为界呈断层接触(图2a, b)。矿区内次级层间断裂受褶皱影响, 与沃溪断层呈“入”字型构造相交(图2a), 均发育于马底驿组紫红色绢云母板岩中, 具有多期活动的特征, 这些断裂控制了矿脉的形态与规模。赋矿围岩发育广泛的蚀变作用, 常见硅化、绢云母化、黄铁矿化、碳酸盐化和绿泥石化, 另有白云母化、叶蜡石化、伊利石化等(邵靖邦等, 1989; 中国人民武装警察部队黄金指挥部, 1996)。蚀变围岩局部破碎呈角砾分布于石英脉中, 角砾见黄铁矿化, 大小不等, 基本在 1~40cm 之间, 多呈分选性差的棱角状、次棱角状, 大部分角砾间具有良好的拼合性, 显示其为原位破裂(图3a)。自东向西, 沃溪矿区可划分为上沃溪、十六棚公、粟家溪、鱼儿山和红岩溪 5 个矿段(图2a), 钨的矿物相亦由白钨矿转变为黑钨矿。

### 2.1 矿体特征

沃溪矿床的矿体均产于沃溪断层下盘马底驿组的绢云

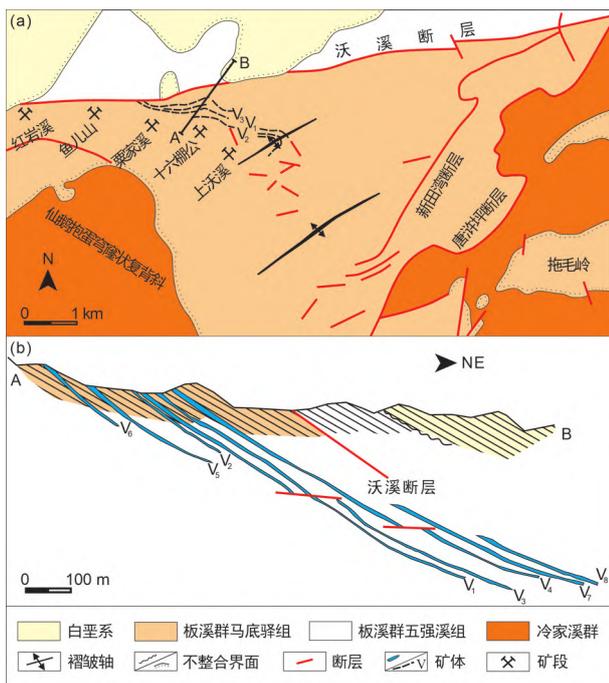


图2 沃溪矿区地质简图(a)及剖面图(b)(据中国人民武装警察部队黄金指挥部, 1996 改绘)

Fig. 2 Sketch map of the Woxi deposit district (a) and cross section A-B through the Woxi deposit (b) (modified after The Gold Headquarter of the Chinese People's Armed Police Force, 1996)

母板岩中,由含矿石英脉和蚀变板岩组成。按其产出形态,矿脉可分为层脉、网脉及节理脉。其中,层脉是沃溪矿床最重要的含矿脉体,占总储量70%以上。

层脉又称主脉,是充填于次级层间断裂中的含矿石英脉,产状平缓且与赋矿围岩基本一致(图3a-f),沿倾斜方向可延伸数百米甚至大于2km。少数层脉由近平行的数条含白钨矿石英脉组成(图3b),大部分层脉由多个含金锑钨的石英条带(石英±白钨矿/黑钨矿±黄铁矿±自然金±辉锑矿)组成(图3c, d)。层脉沿走向倾斜可呈尖灭再现,尖灭地段为石英细脉带、含矿蚀变板岩或断层泥线连接(图3f);局部层脉构造变形强烈,可发育石香肠构造或强烈的揉皱变形(图3d),或见早期形成的石英脉呈角砾状分布于辉锑矿脉中(图3e)。

网脉为充填于层脉两侧羽状或网状裂隙中的含矿石英细脉带,以含金、钨矿为主(图3g, h),一般出现在层脉的下盘,倾斜延伸可达数百米,常与层脉一起形成厚大的矿脉带。这些网脉在不同方向上普遍存在相互切割现象(图3g, h),表明该区可能存在多阶段矿化。

节理脉主要是指与层脉呈锐角相交的支脉,常产于层脉下盘的切层节理裂隙中(图3f),形态复杂多变(图3i),通常规模较小但品位较富。局部节理脉中可同时发育金锑钨矿化(图3f)。

## 2.2 矿物组成及生成顺序

沃溪矿床中金属矿物以白钨矿、黑钨矿、黄铁矿、自然金、辉锑矿为主,还可见少量毒砂、闪锌矿、方铅矿、硫锑铅矿等;脉石矿物主要为石英、绢云母、白云母、高岭石、方解石、绿泥石,以及少量的铁白云石、菱铁矿、磷灰石、金红石等。

根据矿脉穿插关系与矿物共生组合特征,可将沃溪矿床的成矿过程划分为4个阶段(梁金城等, 1981; 罗献林等, 1984; 刘亚军, 1992):

(I) 石英-碳酸盐阶段(早):主要矿物为石英、方解石、白云石,无明显矿化,两侧围岩蚀变微弱。

(II) 石英-白钨矿阶段:为钨的主要成矿期,由大量石英、白钨矿、黑钨矿、碳酸盐及少量磷灰石、毒砂、黄铁矿、菱铁矿和菱镁矿等组成。其中,白钨矿为主要的钨矿物相,黑钨矿通常仅在西部矿段出现(中国人民武装警察部队黄金指挥部, 1996; 祝亚男等, 2014)。含白钨矿石英脉很少单独产出,常与硫化物、自然金石英脉一起呈复脉出现,且含钨石英脉很容易破碎呈角砾状(图4a)或形成串珠状石香肠(梁金城等, 1981)。白钨矿常呈块状(图4b)、脉状(图4c)、浸染状(图4d)、条带状(图4e)产于石英脉中,多被晚阶段石英-硫化物脉、石英-碳酸盐脉切割(图4a-d)。黑钨矿常呈浸染状、条带状(图4f)、细脉状(图4g)产于石英脉及围岩中,局部与毒砂关系密切。较宽的黑钨矿石英脉中常见围岩残余条带以及拼合性较好的围岩角砾(图4f),较细的黑钨矿则往往交错成网脉状(图4g),反映该区黑钨矿可能存在多阶段矿化。

(III) 石英-硫化物-自然金阶段:该阶段以广泛分布的黄铁矿、辉锑矿以及自然金为特征,此外还有少量毒砂、闪锌矿、方铅矿和硫盐矿物等生成,脉石矿物主要为石英、绢云母、绿泥石、高岭石等。黄铁矿是最重要的载金矿物,往往以不同粒径大小的自形-半形晶产出,主要呈浸染状(图4b-d)、细脉状(图4b-d)、网脉状(图4h)及条带状(图4e, i)产于石英脉与蚀变围岩中。自然金常呈星散状、小圆球状、链状、片状、不规则粒状及树枝状(张振儒等, 1978; 中国人民武装警察部队黄金指挥部, 1996),主要赋存于黄铁矿和少量石英、辉锑矿、铁白云石的晶粒内、晶隙间,或产于黄铁矿裂隙内(图5-图7)。辉锑矿通常呈不规则状充填于石英裂隙中(图4h);或呈致密块状产出,内含大小不一的石英角砾(图4a, i)。早阶段含白钨矿石英脉角砾被晚阶段石英-硫化物胶结(图5a),白钨矿被黄铁矿-辉锑矿脉切割、错断(图5b),自然金与黄铁矿共生(图5c),局部黄铁矿被辉锑矿交代形成残余结构(图5a),指示白钨矿形成最早,黄铁矿(和自然金)形成较晚,辉锑矿形成最晚。

(IV) 石英-碳酸盐阶段(晚):主要由石英、碳酸盐类矿物及绿泥石组成,偶见少量的自然金、黄铁矿(图6a, b)。这些矿物常呈不规则网脉穿插于先形成的矿物裂隙中,或形成于晶洞内。

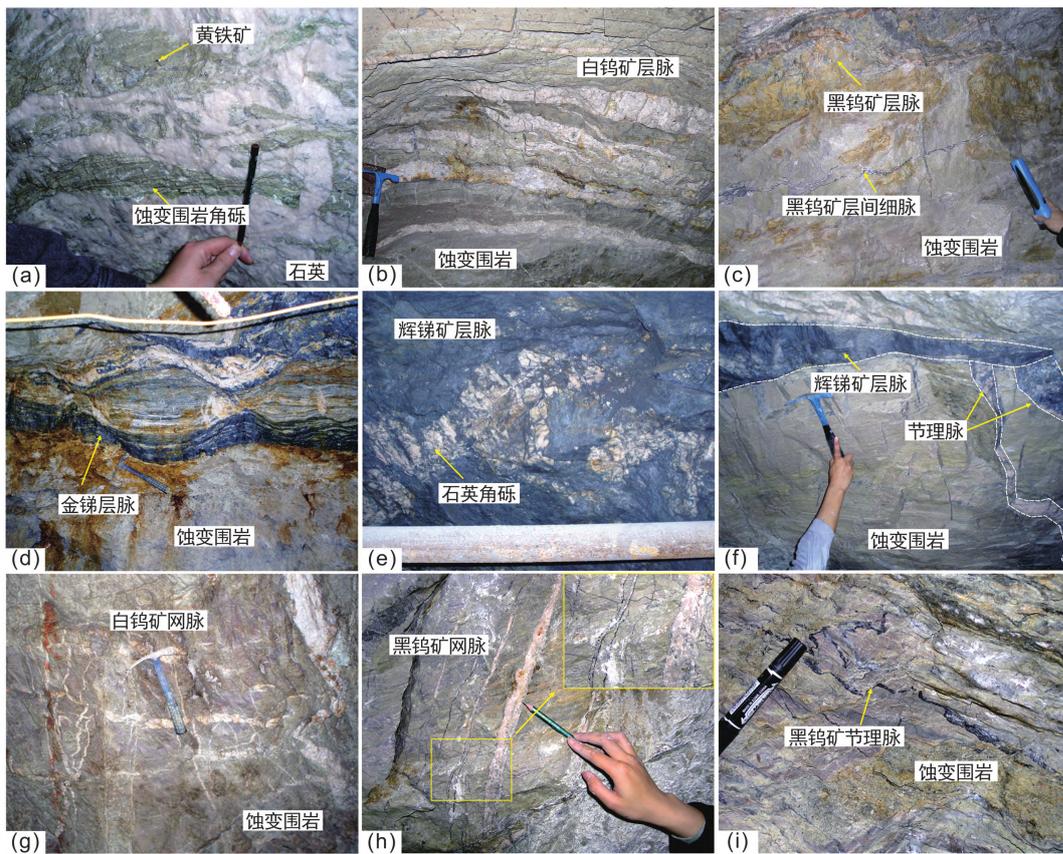


图3 沃溪矿床蚀变围岩、金锑钨矿脉的野外产出特征

(a) 蚀变围岩呈角砾状分布于石英脉中; (b) 白钨矿层脉; (c) 条带状黑钨矿层脉及层间细脉; (d) 条带状金锑矿脉的香肠构造; (e) 早阶段石英脉呈角砾状分布于块状辉锑矿脉; (f) 层状辉锑矿脉的尖灭现象及辉锑矿节理脉; (g) 白钨矿网脉; (h) 黑钨矿网脉; (i) 不规则状黑钨矿节理脉

Fig. 3 Field characteristics of the Woxi deposit

(a) brecciated host rocks in quartz vein; (b) quartz-scheelite bedding veins; (c) bedding veins of banded quartz-wolframite; (d) boudinage of banded stibnite-gold-quartz vein; (e) brecciated quartz vein in massive stibnite; (f) A pinch-out bedding-parallel vein and two discordant veins; (g) quartz-scheelite veinlets intersected at nearly right angles; (h) quartz-wolframite veinlets intersected at nearly right angles; (i) quartz-wolframite irregular veinlets

### 3 样品特征及分析方法

#### 3.1 样品特征

样品 WX-34-4 采自十六棚公矿段  $V_7$  矿脉 34 中段, 其中白钨矿主要与磷灰石、黄铁矿共生, 矿物普遍发育裂隙, 裂隙由晚阶段铁白云石-石英脉充填 (图 6a), 并有少量硫酸 (如硫锑铅矿, 可见其交代早阶段黄铁矿) 以及自然金产出 (图 6b)。

样品 WX-23-3 采自十六棚公矿段  $V_4$  矿脉 23 中段, 其中白钨矿与磷灰石共生, 发育碎裂结构 (图 7a)。白钨矿被晚阶段石英-白云母-高岭石-黄铁矿-自然金细脉切穿 (图 7a, b), 自然金常见赋存于该细脉中细粒黄铁矿的晶粒内 (图 7c)、裂隙中 (图 7d), 或直接产于该细脉中 (图 7b, e)。

样品 YRS-1910-2 采自鱼儿山矿段  $V_6$  矿脉主脉下盘顺

层支脉 (标高 450m), 白钨矿呈条带状产于石英脉中, 与磷灰石共生, 脉两侧围岩见细粒黄铁矿条带 (图 4e)。

黑钨矿样品均采自鱼儿山矿段  $V_1$  矿脉及其近下盘 (标高 -75m)。样品 YRS-40 中黑钨矿碎裂结构较发育, 裂隙主要被方解石、菱铁矿和少量高岭石充填 (图 8a)。样品 YRS-1904 中黑钨矿碎裂结构较发育 (图 8b), 黑钨矿脉两侧围岩发育黄铁矿化和毒砂化, 脉中则发育菱铁矿。与样品 YRS-40 不同, YRS-1904 中菱铁矿通常垂直于脉壁向中心生长形成梳状构造, 内部可见黑钨矿的交代残余结构; 仅少数菱铁矿充填于黑钨矿裂隙中 (图 8b)。

样品 YRS-1902-2 中黑钨矿碎裂结构发育, 裂隙多被高岭石、斜长石和白云母充填。局部见毒砂呈细粒浸染状产于黑钨矿晶粒间及裂隙中 (图 8c)。该样品与样品 YRS-1904 分别采自同一取样点的矿脉中部和其近下盘处。

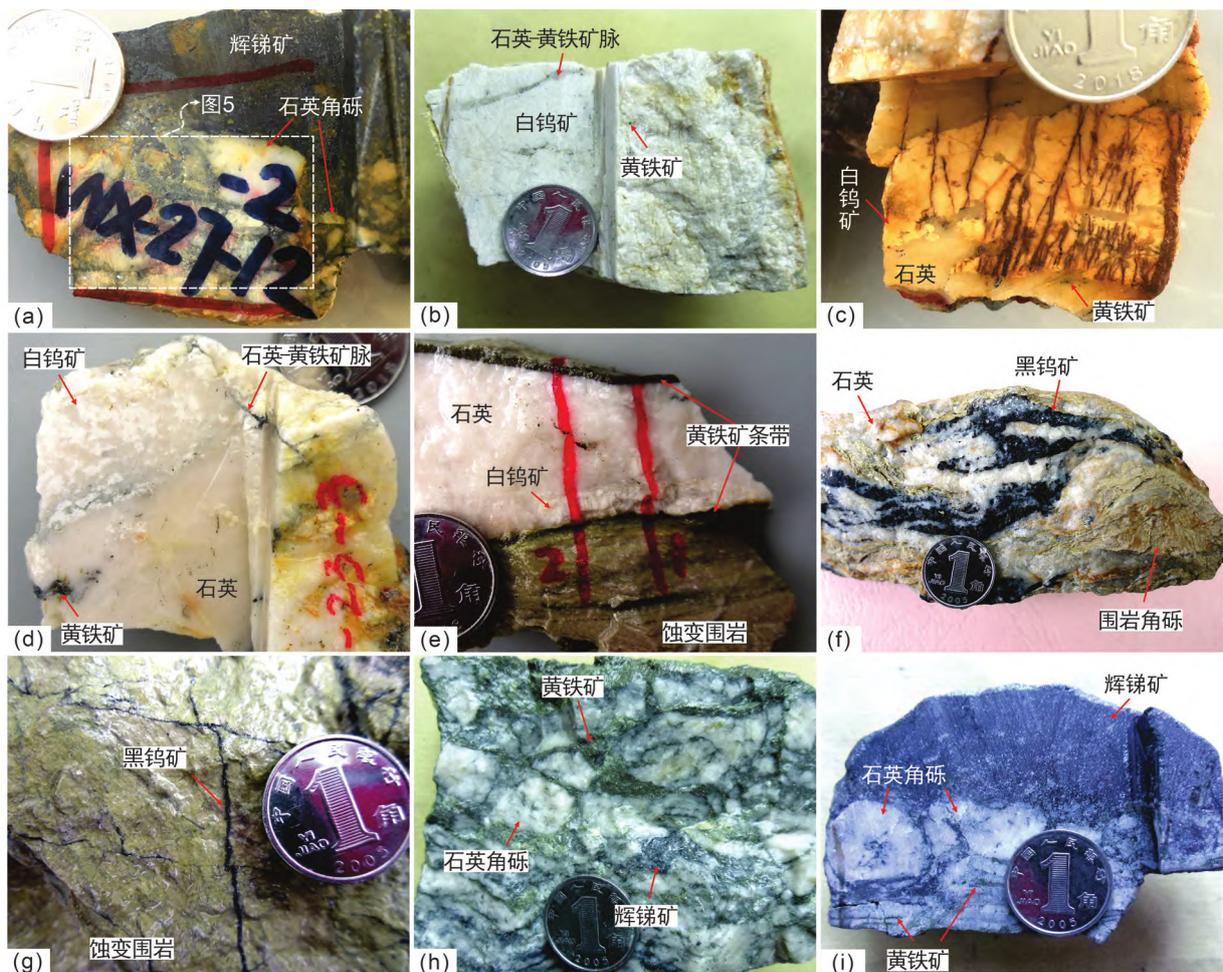


图4 沃溪矿床的主要矿石构造特征

(a) 含白钨矿石英角砾分布于块状辉锑矿中; (b-d): 块状(b)、脉状(c)、浸染状(d)白钨矿被晚阶段石英-黄铁矿脉切割; (e) 条带状白钨矿及黄铁矿; (f) 黑钨矿条带及围岩角砾分布于石英脉中; (g) 相互交错的黑钨矿细脉; (h) 网状状黄铁矿和辉锑矿胶结破碎的早阶段石英角砾; (i) 早阶段石英角砾分布于块状辉锑矿中

Fig. 4 Photographs of hand specimen samples from the Woxi deposit

(a) brecciated scheelite-quartz vein in massive stibnite; (b-d): massive (b), vein (c) and disseminated (d) structure, with quartz and pyrite filled in the fracture of scheelite; (e) banded scheelite and pyrite; (f) banded wolframite and brecciated host rocks in quartz vein; (g) intersected wolframite veinlets; (h) mesh-vein structure, with pyrite and stibnite filled in the mesh fissures of early stage veins; (i) brecciated quartz vein in massive stibnite

### 3.2 分析方法

所选样品分别利用透反射光、阴极发光、扫描电子显微镜、矿物自动分析系统(TIMA)进行观察、分析、照相,以确定矿物共生关系和内部结构,并使测试点避开包裹体和裂纹。白钨矿、黑钨矿以及磷灰石 U-Pb 微区定年均在中国科学院地球化学研究所矿床地球化学国家重点实验室完成。分析仪器为相干 GeoLasPro 193nm ArF 激光剥蚀系统和热电 Element XR 磁质谱(SF-ICP-MS),脉冲频率 6Hz,激光束斑为 32 $\mu\text{m}$ ,激光能量密度 4J/cm<sup>2</sup>,分析点背景信号和样品剥蚀信号分别为 20s 和 30s。测试同位素包括:<sup>202</sup>Hg、<sup>204</sup>Pb、<sup>206</sup>Pb、<sup>207</sup>Pb、<sup>208</sup>Pb、<sup>232</sup>Th 和 <sup>238</sup>U。黑钨矿和白钨矿以黑钨矿 YGX 为

主标样、磷灰石以 OD306 为主标样进行同位素分馏校正,同位素比值及年龄误差均为 1 $\sigma$ 。矿物 U、Pb 含量采用 NIST612 进行简单校正。黑钨矿 NM/KA (Tang *et al.*, 2020) 和清湖磷灰石 QH (~160Ma) 分别为年龄监控样。分析数据利用 Isoplot 软件获得 Tera-Wasserburg 图解上的下交点年龄 (Ludwig, 2003)。详细的实验条件、仪器参数和具体方法详见文献 Thompson *et al.* (2016) 和 Tang *et al.* (2020; 2022)。

## 4 分析结果

### 4.1 磷灰石

样品 YRS-1910-2 中与白钨矿共生的磷灰石一共 29 个

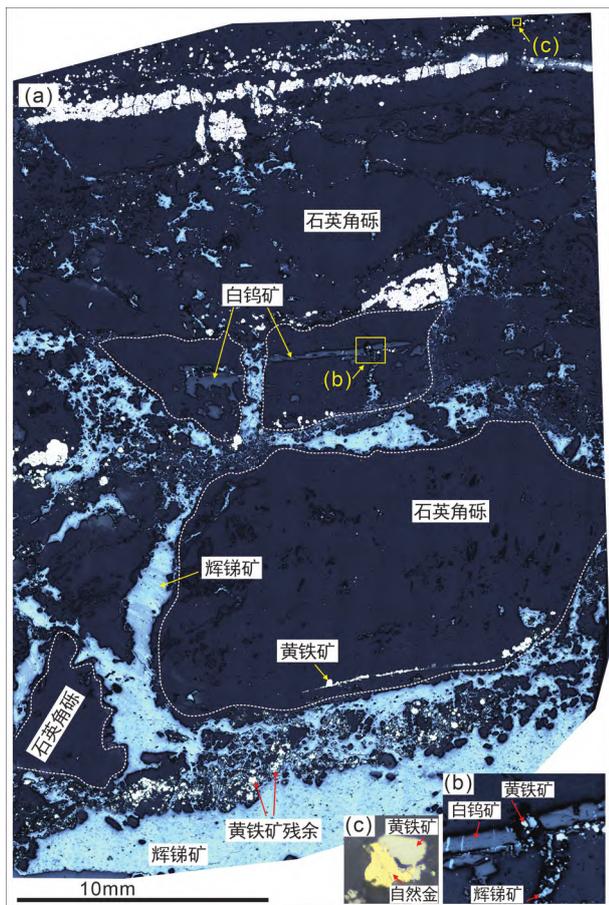


图5 样品 WX-27-12 的反光显微镜下图像

(a) 含白钨矿石英角砾被黄铁矿、辉锑矿切割、胶结, 辉锑矿中见黄铁矿交代残余结构; (b) 白钨矿被黄铁矿、辉锑矿切割; (c) 黄铁矿与自然金共生

Fig. 5 Microscope photos of Sample WX-27-12 from the Woxi deposit

(a) brecciated scheelite-quartz vein cemented by pyrite and stibnite, and metasomatic relict texture of pyrite; (b) scheelite cut by pyrite-stibnite vein; (c) native gold coexist with pyrite

有效测点(表1), 其中, U 含量为  $1.35 \times 10^{-6} \sim 473 \times 10^{-6}$  (平均  $76.2 \times 10^{-6}$ ),  $^{238}\text{U}/^{206}\text{Pb}$  的比值变化范围为 1.2134 ~ 42.907 (平均 18.017),  $^{207}\text{Pb}/^{206}\text{Pb}$  的比值变化范围为 0.0672 ~ 0.7262 (平均 0.4594), 获得下交点年龄为  $144.8 \pm 1.7\text{Ma}$  (MSWD = 1.19) (图 9a)。

样品 WX-34-4 中与白钨矿共生的磷灰石一共 22 个有效测点(表1), 其中, U 含量为  $0.19 \times 10^{-6} \sim 14.1 \times 10^{-6}$  (平均  $3.75 \times 10^{-6}$ ),  $^{238}\text{U}/^{206}\text{Pb}$  的比值变化范围为 0.0943 ~ 23.968 (平均 9.4132),  $^{207}\text{Pb}/^{206}\text{Pb}$  的比值变化范围为 0.4316 ~ 0.8403 (平均 0.6752), 获得下交点年龄为  $139.8 \pm 6.1\text{Ma}$  (MSWD = 0.95) (图 9b)。

样品 WX-23-3 中与白钨矿共生的磷灰石一共 16 个有效测点(表1), 其中, U 含量为  $0.11 \times 10^{-6} \sim 15.1 \times 10^{-6}$  (平均  $3.84 \times 10^{-6}$ ),  $^{238}\text{U}/^{206}\text{Pb}$  的比值变化范围为 0.0097 ~ 24.212

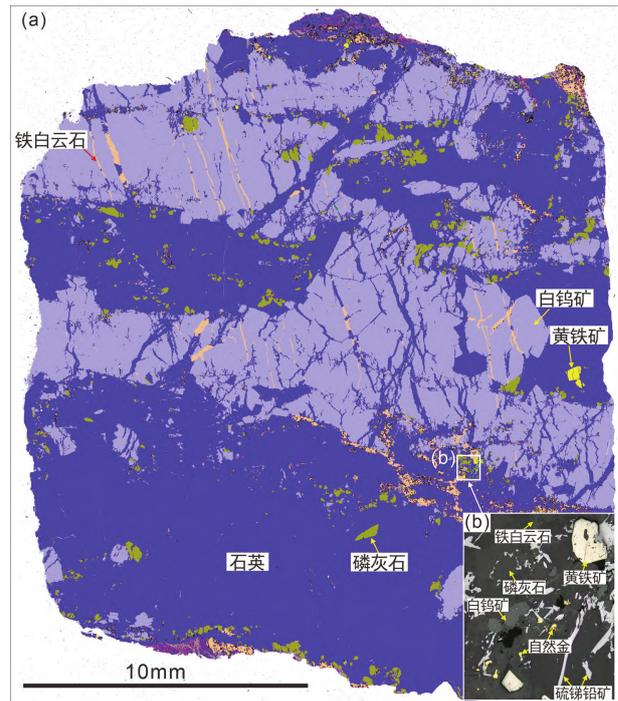


图6 样品 WX-34-4 的 TIMA 图像(a) 和反光显微镜下图像(b)

Fig. 6 TIMA (a) and microscope (b) photos of Sample WX-34-4 from the Woxi deposit

(平均 5.5149),  $^{207}\text{Pb}/^{206}\text{Pb}$  的比值变化范围为 0.3899 ~ 0.8518 (平均 0.7420), 获得下交点年龄为  $149.0 \pm 12\text{Ma}$  (MSWD = 0.39) (图 9c)。

#### 4.2 白钨矿

样品 WX-34-4 中与磷灰石共生的白钨矿一共 18 个有效测点(表1), 其中, U 含量为  $2.50 \times 10^{-6} \sim 6.09 \times 10^{-6}$  (平均  $3.87 \times 10^{-6}$ ),  $^{238}\text{U}/^{206}\text{Pb}$  的比值变化范围为 4.6217 ~ 40.952 (平均 19.331),  $^{207}\text{Pb}/^{206}\text{Pb}$  的比值变化范围为 0.1693 ~ 0.8173 (平均 0.5533), 获得下交点年龄为  $125.8 \pm 5.6\text{Ma}$  (MSWD = 0.96) (图 9d)。

#### 4.3 黑钨矿

样品 YRS-1902-2 和 YRS-1904 中黑钨矿一共 13 个有效测点(表1), 其中, U 含量为  $0.11 \times 10^{-6} \sim 82.2 \times 10^{-6}$  (平均  $10.1 \times 10^{-6}$ ),  $^{238}\text{U}/^{206}\text{Pb}$  的比值变化范围为 0.7978 ~ 45.028 (平均 14.791),  $^{207}\text{Pb}/^{206}\text{Pb}$  的比值变化范围为 0.0980 ~ 0.8758 (平均 0.6207), 获得下交点年龄为  $137.8 \pm 3.9\text{Ma}$  (MSWD = 1.12) (图 9e)。

样品 YRS-40 中黑钨矿一共 25 个有效测点(表1), 其中, U 含量为  $0.67 \times 10^{-6} \sim 82.7 \times 10^{-6}$  (平均  $11.2 \times 10^{-6}$ ),  $^{238}\text{U}/^{206}\text{Pb}$  的比值变化范围为 1.1384 ~ 32.517 (平均 13.551),  $^{207}\text{Pb}/^{206}\text{Pb}$  的比值变化范围为 0.3443 ~ 0.8842 (平

表1 沃溪矿床磷灰石、白钨矿与黑钨矿的 LA-ICP-MS U-Pb 同位素数据

Table 1 LA-ICP-MS U-Pb isotope data of apatite, scheelite and wolframite from the Woxi deposit

测点号	Total Pb ( $\times 10^{-6}$ )	U	$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{238}\text{U}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{206}\text{Pb}$		rho
			比值	$1\sigma$	比值	$1\sigma$	比值	$1\sigma$	比值	(%)	比值	(%)	
样品 WX-34-4 磷灰石													
-1	0.91	4.81	0.5916	0.0159	5.2563	0.1900	0.0651	0.0016	15.359	2.4762	0.5916	2.6957	0.6849
-2	1.11	7.79	0.5166	0.0132	3.8499	0.1236	0.0548	0.0012	18.235	2.1391	0.5166	2.5492	0.6660
-3	0.78	8.07	0.4316	0.0137	2.4309	0.0954	0.0417	0.0011	23.967	2.5999	0.4316	3.1771	0.6625
-5	1.26	6.46	0.5920	0.0147	5.2545	0.1663	0.0651	0.0014	15.359	2.0744	0.5920	2.4764	0.6554
-6	1.82	4.41	0.7217	0.0167	11.817	0.3933	0.1208	0.0035	8.2760	2.8603	0.7217	2.3117	0.8594
-7	23.9	0.85	0.8263	0.0083	896.15	23.868	7.8373	0.1323	0.1276	1.6877	0.8263	1.0071	0.6337
-9	5.66	1.97	0.7829	0.0147	48.331	1.4232	0.4501	0.0088	2.2216	1.9556	0.7829	1.8747	0.6641
-10	6.88	0.19	0.8261	0.0121	1210.9	56.015	10.608	0.4384	0.0943	4.1323	0.8261	1.4695	0.8933
-11	0.71	3.72	0.6092	0.0243	5.6409	0.2609	0.0698	0.0024	14.328	3.4248	0.6092	3.9858	0.7405
-13	1.23	0.27	0.8297	0.0249	149.29	5.8190	1.3488	0.0457	0.7414	3.3913	0.8297	2.9963	0.8700
-14	0.76	2.47	0.6780	0.0213	8.6638	0.2866	0.0960	0.0025	10.416	2.6304	0.6780	3.1385	0.7952
-15	0.85	0.21	0.8331	0.0246	132.31	5.3219	1.1829	0.0405	0.8454	3.4276	0.8331	2.9536	0.8522
-16	2.23	14.1	0.4579	0.0112	3.1684	0.1094	0.0500	0.0009	20.012	1.7759	0.4579	2.4423	0.5145
-19	0.67	1.69	0.7035	0.0299	11.124	0.5157	0.1212	0.0060	8.2537	4.9908	0.7035	4.2552	1.0765
-20	0.98	0.24	0.8403	0.0320	130.03	5.4304	1.2149	0.0603	0.8231	4.9624	0.8403	3.8061	1.1883
-22	0.75	2.67	0.6441	0.0235	8.1655	0.4532	0.0945	0.0047	10.584	4.9962	0.6441	3.6539	0.9002
-23	1.11	3.63	0.6637	0.0209	9.1967	0.3404	0.1037	0.0032	9.6444	3.1171	0.6637	3.1437	0.8420
-24	1.50	6.26	0.6033	0.0182	6.4839	0.2585	0.0805	0.0027	12.426	3.3575	0.6033	3.0211	0.8421
-25	0.63	2.58	0.6065	0.0357	6.6648	0.3313	0.0849	0.0041	11.785	4.7946	0.6065	5.8787	0.9646
-26	1.03	0.32	0.8196	0.0299	99.165	3.7819	0.9231	0.0344	1.0833	3.7220	0.8196	3.6493	0.9759
-27	0.85	5.00	0.5607	0.0260	4.7127	0.1937	0.0634	0.0023	15.772	3.5987	0.5607	4.6401	0.8756
-28	2.20	4.81	0.7165	0.0155	14.401	0.5717	0.1485	0.0053	6.7351	3.5639	0.7165	2.1604	0.8977
样品 YRS-1910-2 磷灰石													
-1	3.14	27.6	0.4248	0.0155	3.0906	0.1583	0.0518	0.0015	19.317	2.8829	0.4248	3.6525	0.5628
-2	3.60	26.5	0.4570	0.0169	3.9920	0.2548	0.0609	0.0024	16.428	3.9482	0.4570	3.6923	0.6186
-3	3.09	18.8	0.4835	0.0183	4.1106	0.1848	0.0615	0.0016	16.265	2.5361	0.4835	3.7813	0.5642
-4	3.78	29.5	0.4250	0.0182	2.9564	0.1245	0.0504	0.0010	19.848	1.9509	0.4250	4.2833	0.4632
-5	6.87	14.7	0.6232	0.0196	13.097	0.7217	0.1500	0.0055	6.6650	3.6435	0.6232	3.1463	0.6612
-6	12.8	56.4	0.5401	0.0153	6.0851	0.2928	0.0812	0.0028	12.313	3.4339	0.5401	2.8242	0.7136
-7	6.80	49.2	0.4750	0.0127	3.7012	0.1395	0.0561	0.0010	17.822	1.7585	0.4750	2.6700	0.4665
-8	7.07	34.6	0.5280	0.0130	5.1041	0.1745	0.0700	0.0012	14.289	1.7135	0.5280	2.4705	0.5012
-9	7.55	2.74	0.7243	0.0169	82.508	3.1632	0.8241	0.0207	1.2134	2.5169	0.7243	2.3387	0.6565
-10	4.46	43.5	0.4112	0.0104	2.4960	0.0801	0.0441	0.0006	22.678	1.4059	0.4112	2.5395	0.4383
-11	7.52	44.6	0.5009	0.0125	4.3696	0.1378	0.0634	0.0009	15.776	1.3803	0.5009	2.4927	0.4378
-12	2.57	3.94	0.6691	0.0191	19.492	0.8911	0.2121	0.0070	4.7155	3.3224	0.6691	2.8555	0.7267
-13	1.69	6.57	0.5631	0.0179	8.5433	0.6332	0.1073	0.0062	9.3216	5.7370	0.5631	3.1742	0.7740
-14	4.12	102	0.1838	0.0070	0.7156	0.0347	0.0280	0.0005	35.688	1.9385	0.1838	3.8145	0.3997
-15	16.7	473	0.1465	0.0072	0.5456	0.0307	0.0270	0.0005	37.031	1.8308	0.1465	4.9256	0.3250
-16	2.72	7.15	0.6149	0.0176	12.457	0.6712	0.1472	0.0065	6.7916	4.3899	0.6149	2.8607	0.8147
-17	7.67	233	0.1433	0.0044	0.5140	0.0178	0.0263	0.0004	38.083	1.4617	0.1433	3.0402	0.4229
-18	2.74	1.35	0.7052	0.0184	58.926	2.0256	0.6096	0.0107	1.6404	1.7581	0.7052	2.6087	0.5114
-19	7.63	250	0.1251	0.0074	0.4461	0.0331	0.0250	0.0004	40.047	1.5242	0.1251	5.9317	0.2053
-20	1.80	3.37	0.6599	0.0208	15.589	1.0068	0.1712	0.0089	5.8407	5.1692	0.6599	3.1575	0.8004
-21	2.99	83.5	0.1796	0.0076	0.7065	0.0403	0.0280	0.0005	35.718	1.9491	0.1796	4.2570	0.3415
-22	6.39	16.5	0.6512	0.0136	11.675	0.4252	0.1301	0.0031	7.6843	2.4124	0.6512	2.0915	0.6624

续表 1

Continued Table 1

测点号	Total Pb ( $\times 10^{-6}$ )	U	$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{238}\text{U}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{206}\text{Pb}$		rho
			比值	$1\sigma$	比值	$1\sigma$	比值	$1\sigma$	比值	(%)	比值	(%)	
-23	7.40	11.0	0.6716	0.0137	19.404	0.5767	0.2100	0.0030	4.7629	1.4395	0.6716	2.0364	0.4843
-24	7.41	325	0.0672	0.0017	0.2160	0.0071	0.0233	0.0002	42.907	1.0471	0.0672	2.4705	0.3197
-26	5.85	185	0.1109	0.0056	0.3955	0.0200	0.0261	0.0005	38.338	1.7333	0.1109	5.0356	0.3436
-27	2.28	1.95	0.7134	0.0201	33.787	1.1427	0.3460	0.0060	2.8899	1.7484	0.7134	2.8135	0.5170
-28	3.32	2.00	0.7262	0.0172	50.584	1.8919	0.5058	0.0123	1.9770	2.4314	0.7262	2.3635	0.6501
-29	4.37	10.6	0.6531	0.0169	12.027	0.4147	0.1341	0.0026	7.4576	1.9229	0.6531	2.5942	0.5577
-30	4.72	146	0.1460	0.0056	0.5241	0.0259	0.0257	0.0004	38.975	1.5447	0.1460	3.8448	0.3126
样品 WX-23-3 磷灰石													
-1	44.6	0.97	0.8347	0.0132	1566.9	50.154	13.670	0.3426	0.0732	2.5064	0.8347	1.5851	0.7831
-2	39.5	1.51	0.8481	0.0165	902.24	27.822	7.7753	0.1773	0.1286	2.2803	0.8481	1.9429	0.7395
-3	8.91	0.51	0.8518	0.0147	590.06	21.051	5.1048	0.1663	0.1959	3.2577	0.8518	1.7244	0.9131
-4	7.15	15.1	0.7136	0.0107	15.539	0.5342	0.1578	0.0039	6.3352	2.4568	0.7136	1.5025	0.7147
-5	6.18	12.5	0.7260	0.0116	15.913	0.4489	0.1600	0.0033	6.2494	2.0422	0.7260	1.6034	0.7239
-6	8.58	5.78	0.8042	0.0125	49.332	1.5387	0.4457	0.0095	2.2436	2.1361	0.8042	1.5498	0.6848
-7	2.81	2.53	0.7797	0.0162	38.985	1.5078	0.3682	0.0127	2.7162	3.4497	0.7797	2.0729	0.8920
-11	0.79	4.62	0.4876	0.0228	3.3097	0.1545	0.0507	0.0017	19.737	3.4275	0.4876	4.6849	0.7344
-12	0.35	0.54	0.7652	0.0470	18.806	0.9367	0.1938	0.0087	5.1601	4.4737	0.7652	6.1388	0.8982
-13	0.47	1.44	0.6733	0.0257	9.3956	0.4984	0.1050	0.0047	9.5272	4.4786	0.6733	3.8174	0.8443
-14	0.59	0.79	0.7856	0.0325	22.228	0.8674	0.2171	0.0066	4.6060	3.0565	0.7856	4.1345	0.7832
-18	322	0.94	0.8250	0.0208	11397	378.24	102.58	2.9539	0.0097	2.8795	0.8250	2.5156	0.8677
-21	0.69	0.71	0.7901	0.0325	29.775	1.1469	0.2876	0.0091	3.4769	3.1524	0.7901	4.1147	0.8185
-22	0.52	0.11	0.8247	0.0526	132.70	8.1735	1.2838	0.0905	0.7789	7.0512	0.8247	6.3800	1.1448
-28	0.99	12.0	0.3899	0.0188	2.2598	0.1619	0.0413	0.0018	24.212	4.2390	0.3899	4.8154	0.5917
-29	1.89	1.52	0.7727	0.0240	37.627	1.3817	0.3586	0.0089	2.7884	2.4842	0.7727	3.1102	0.6765
样品 WX-34-4 白钨矿													
-15	4.47	4.52	0.8173	0.0166	37.139	8.9326	0.3246	0.0085	4.6217	2.6274	0.8173	2.0261	0.1092
-05	3.44	4.00	0.7791	0.0126	31.970	7.6611	0.3007	0.0052	4.9885	1.7299	0.7791	1.6187	0.0722
-03	3.13	4.47	0.7748	0.0150	27.338	6.6171	0.2605	0.0105	5.7574	4.0384	0.7748	1.9407	0.1668
-30	1.70	2.68	0.7374	0.0163	22.254	5.3476	0.2235	0.0059	6.7104	2.6525	0.7374	2.2088	0.1104
-06	2.25	4.58	0.7093	0.0215	17.416	4.1747	0.1710	0.0029	8.7743	1.7085	0.7093	3.0335	0.0713
-18	1.46	5.07	0.6141	0.0214	8.8465	2.1237	0.1079	0.0023	13.904	2.1729	0.6141	3.4813	0.0905
-27	0.93	3.64	0.6296	0.0233	8.1896	1.9747	0.0972	0.0029	15.431	2.9339	0.6296	3.7010	0.1217
-20	1.21	4.50	0.6286	0.0260	7.9283	1.9065	0.0958	0.0030	15.664	3.1130	0.6286	4.1345	0.1295
-14	1.54	6.09	0.6247	0.0171	8.2522	2.0008	0.0956	0.0029	15.689	3.0854	0.6247	2.7401	0.1273
-22	0.59	2.55	0.6100	0.0217	6.7269	1.6202	0.0841	0.0024	17.842	2.8960	0.6100	3.5524	0.1202
-02	0.72	3.43	0.5416	0.0211	5.9262	1.4268	0.0834	0.0024	17.993	2.9162	0.5416	3.8956	0.1211
-29	0.63	3.32	0.5311	0.0220	5.1323	1.2382	0.0749	0.0025	20.040	3.2804	0.5311	4.1475	0.1360
-12	0.71	4.11	0.5232	0.0210	4.5798	1.1038	0.0668	0.0020	22.464	2.9233	0.5232	4.0168	0.1213
-11	0.63	4.82	0.4616	0.0187	3.5637	0.8629	0.0564	0.0015	26.603	2.6562	0.4616	4.0584	0.1097
-28	0.32	3.31	0.2875	0.0221	1.5913	0.3893	0.0439	0.0015	34.166	3.3300	0.2875	7.6929	0.1361
-26	0.26	3.06	0.2863	0.0208	1.4234	0.3496	0.0418	0.0020	35.899	4.8689	0.2863	7.2662	0.1982
-23	0.19	2.50	0.2335	0.0236	1.0137	0.2527	0.0371	0.0018	40.453	4.8503	0.2335	10.103	0.1945
-25	0.22	2.99	0.1693	0.0186	0.8508	0.2169	0.0366	0.0017	40.952	4.5809	0.1693	10.988	0.1797
样品 YRS-1904 黑钨矿													
-1	1.20	0.32	0.8758	0.0253	328.96	11.080	0.9164	0.0278	0.8948	3.0327	0.8758	2.8853	0.9004
-4	2.26	13.3	0.5881	0.0115	13.458	0.2615	0.0550	0.0009	14.902	1.5509	0.5881	1.9575	0.7981

续表 1

Continued Table 1

测点号	Total Pb ( $\times 10^{-6}$ )	U	$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{238}\text{U}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{206}\text{Pb}$		rho
			比值	$1\sigma$	比值	$1\sigma$	比值	$1\sigma$	比值	(%)	比值	(%)	
-5	0.22	4.66	0.2048	0.0149	1.9193	0.1433	0.0232	0.0008	35.376	3.5715	0.2048	7.2559	0.4783
-8	0.65	15.7	0.2370	0.0098	2.2624	0.0815	0.0235	0.0005	34.936	1.9999	0.2370	4.1361	0.5551
-13	0.73	5.12	0.5683	0.0265	10.818	0.4794	0.0461	0.0017	17.798	3.5838	0.5683	4.6611	0.8088
-14	0.48	0.23	0.8709	0.0398	169.67	8.2579	0.4939	0.0241	1.6601	4.8877	0.8709	4.5681	1.0042
-16	0.65	0.16	0.8738	0.0357	353.13	14.615	1.0278	0.0438	0.7978	4.2648	0.8738	4.0874	1.0305
-20	1.00	6.04	0.6017	0.0169	12.923	0.4555	0.0518	0.0014	15.837	2.6118	0.6017	2.8047	0.7410
样品 YRS-1902-2 黑钨矿													
-3	1.83	82.2	0.0980	0.0037	0.7544	0.0342	0.0182	0.0003	45.027	1.7902	0.0980	3.7956	0.3953
-7	0.53	0.47	0.8604	0.0371	108.40	5.4370	0.3128	0.0131	2.6218	4.2029	0.8604	4.3100	0.8379
-9	0.50	2.42	0.6781	0.0403	17.192	0.9883	0.0626	0.0029	13.089	4.5927	0.6781	5.9485	0.7990
-17	0.08	0.11	0.7458	0.1200	39.689	4.2570	0.1243	0.0106	6.5966	8.5573	0.7458	16.095	0.7978
-18	0.29	0.23	0.8663	0.0661	91.967	4.8553	0.2982	0.0146	2.7500	4.9026	0.8663	7.6261	0.9286
样品 YRS-40 黑钨矿													
-15	2.90	0.90	0.8842	0.0254	60.166	11.652	0.5015	0.0115	1.3959	2.2834	0.8842	2.8718	0.1179
-7	2.07	1.21	0.8520	0.0271	30.398	5.9076	0.2650	0.0082	2.6420	3.0878	0.8520	3.1787	0.1589
-17	4.17	5.68	0.8001	0.0157	13.172	2.5442	0.1203	0.0024	5.8206	2.0214	0.8001	1.9667	0.1046
-29	0.83	1.37	0.7661	0.0352	10.057	1.9827	0.0990	0.0039	7.0733	3.9850	0.7661	4.5965	0.2021
-3	0.24	0.82	0.6567	0.0481	4.1487	0.8298	0.0498	0.0023	14.049	4.6402	0.6567	7.3174	0.2320
-5	0.31	2.01	0.6021	0.0547	2.5868	0.5571	0.0334	0.0024	20.932	7.1650	0.6021	9.0872	0.3327
-1	0.97	6.71	0.5643	0.0254	2.2778	0.4470	0.0304	0.0010	23.016	3.2382	0.5643	4.5007	0.1650
-6	0.19	1.53	0.4204	0.0632	1.2116	0.2533	0.0256	0.0015	27.338	5.8749	0.4204	15.030	0.2811
-10	0.86	8.44	0.4353	0.0185	1.4385	0.2845	0.0242	0.0008	28.927	3.1476	0.4353	4.2460	0.1592
-28	0.94	11.3	0.3815	0.0171	1.2026	0.2410	0.0224	0.0006	31.205	2.7779	0.3815	4.4845	0.1386
-19	5.10	69.0	0.3443	0.0065	1.0180	0.1966	0.0215	0.0004	32.517	1.7358	0.3443	1.8765	0.0899
-20	4.51	2.52	0.8255	0.0144	32.136	6.2205	0.2844	0.0073	2.4610	2.5796	0.8255	1.7491	0.1333
-14	2.71	0.69	0.8468	0.0212	70.599	13.652	0.6149	0.0152	1.1384	2.4721	0.8468	2.4997	0.1278
-21	3.02	1.04	0.8477	0.0192	52.476	10.206	0.4562	0.0146	1.5344	3.2060	0.8477	2.2614	0.1649
-23	6.08	1.88	0.8350	0.0132	58.944	11.429	0.5151	0.0144	1.3588	2.8018	0.8350	1.5771	0.1445
-25	2.67	1.51	0.8393	0.0197	32.393	6.3532	0.2825	0.0109	2.4781	3.8729	0.8393	2.3482	0.1975
-9	1.45	2.03	0.7513	0.0311	11.541	2.3178	0.1151	0.0066	6.0820	5.7175	0.7513	4.1351	0.2847
-24	0.85	1.35	0.7362	0.0278	10.587	2.0636	0.1082	0.0035	6.4709	3.2791	0.7362	3.7793	0.1682
-13	2.01	4.71	0.7010	0.0191	7.2088	1.3977	0.0756	0.0018	9.2618	2.3942	0.7010	2.7186	0.1235
-18	3.83	18.1	0.5849	0.0103	3.5429	0.6851	0.0441	0.0010	15.864	2.1980	0.5849	1.7652	0.1137
-26	0.26	0.67	0.6950	0.0847	5.3827	1.0968	0.0667	0.0044	10.498	6.6465	0.6950	12.188	0.3262
-4	0.35	1.57	0.5485	0.0372	2.9672	0.5925	0.0421	0.0016	16.640	3.7932	0.5485	6.7874	0.1900
-27	0.70	3.95	0.5532	0.0468	2.9668	0.5889	0.0436	0.0016	16.067	3.7664	0.5532	8.4615	0.1898
-16	4.91	49.0	0.3918	0.0083	1.4581	0.2851	0.0268	0.0008	26.149	2.8272	0.3918	2.1193	0.1446
-22	7.68	82.7	0.3940	0.0056	1.3674	0.2639	0.0251	0.0004	27.856	1.5934	0.3940	1.4231	0.0826

均 0.6503), 这些测点在 Tera-Wasserburg 图解上可分别获得两个下交点年龄, 即  $134.8 \pm 5.1\text{Ma}$  ( $\text{MSWD} = 0.61$ ) (图 9f) 和  $123.8 \pm 4.6\text{Ma}$  ( $\text{MSWD} = 0.95$ ) (图 9g)。

## 5 讨论

### 5.1 成矿时代

#### 5.1.1 磷灰石年龄

前文已述, 本次研究所选取的磷灰石均与白钨矿共生,

尽管样品 WX-23-3 中部分磷灰石的分布与晚阶段石英-白云母-高岭石-黄铁矿细脉有关(图 7), 但磷灰石 CL 图像表明, 所选磷灰石测试区域未受后期热液事件改造(图 9h, i)。并且磷灰石 U-Pb 同位素体系的封闭温度(约为  $350 \sim 550^\circ\text{C}$ , Chew and Spikings, 2015; 或  $620^\circ\text{C}$ , Krogstad and Walker, 1994) 远高于沃溪矿床晚阶段辉钨矿和石英中流体包裹体的最高均一温度(Zhu and Peng, 2015), 故磷灰石 U-Pb 体系不会受晚阶段热液事件影响。因此, 本文所获得的磷灰石 U-Pb 年龄, 可以代表与其共生的白钨矿成矿年龄, 即沃溪矿床

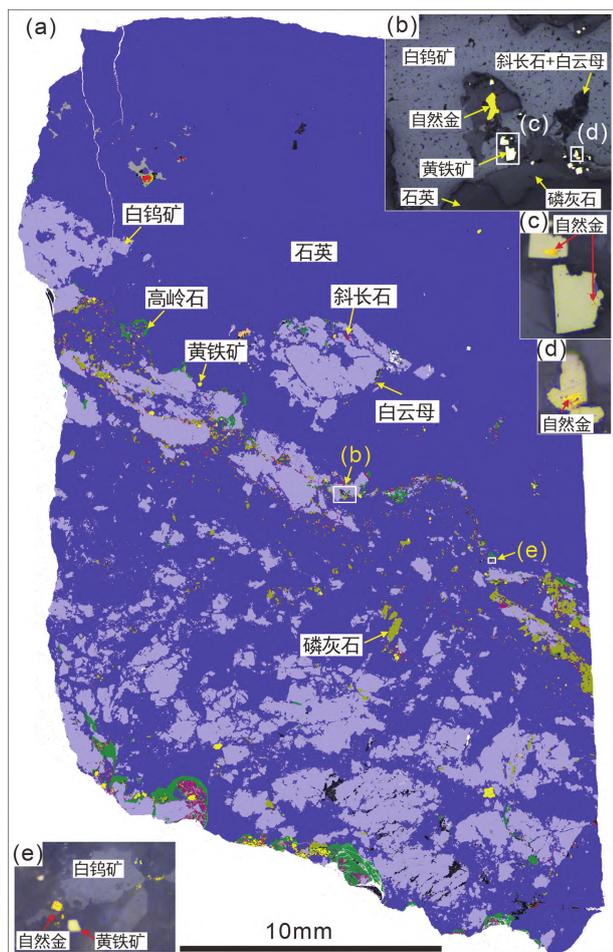


图7 样品 WX-23-3 的 TIMA 图像(a) 及反光显微镜下图像(b-e)

Fig. 7 IMA (a) and microscope (b-e) photos of Sample WX-23-3 from the Woxi deposit

中白钨矿形成于  $149.0 \pm 12\text{Ma}$  (样品 WX-23-3)、 $144.8 \pm 1.7\text{Ma}$  (样品 YRS-1910-2)、 $139.8 \pm 6.1\text{Ma}$  (样品 WX-34-4), 白钨矿成矿作用主要发生于晚侏罗世。

### 5.1.2 白钨矿年龄

样品 WX-34-4 中白钨矿年龄为  $125.8 \pm 5.6\text{Ma}$ , 而与其共生的磷灰石(图6)年龄却为  $139.8 \pm 6.1\text{Ma}$ , 这似乎与地质事实相悖。白钨矿 U-Pb 同位素体系的封闭温度较高( $480 \sim 510^\circ\text{C}$ , Wintzer *et al.*, 2022), 晚阶段低温热液活动事件不会导致沃溪白钨矿 U-Pb 体系开放。Han *et al.* (2020) 研究发现, 白钨矿形成之后容易受到后期热液改造而使其结构与成分发生变化。样品 WX-34-4 中白钨矿的 CL 图显示, 白钨矿颗粒的成分总体分布均匀, 但局部存在一些暗色细脉, 可能指示白钨矿遭受了晚阶段热液的改造作用。该样品白钨矿年龄较磷灰石年轻的原因可能是: 晚期石英-碳酸盐阶段, 热液交代先形成的白钨矿造成白钨矿中 Pb 丢失, 受改造后的白钨矿的年龄( $125.8 \pm 5.6\text{Ma}$ ) 实际上反映的是晚阶段热液

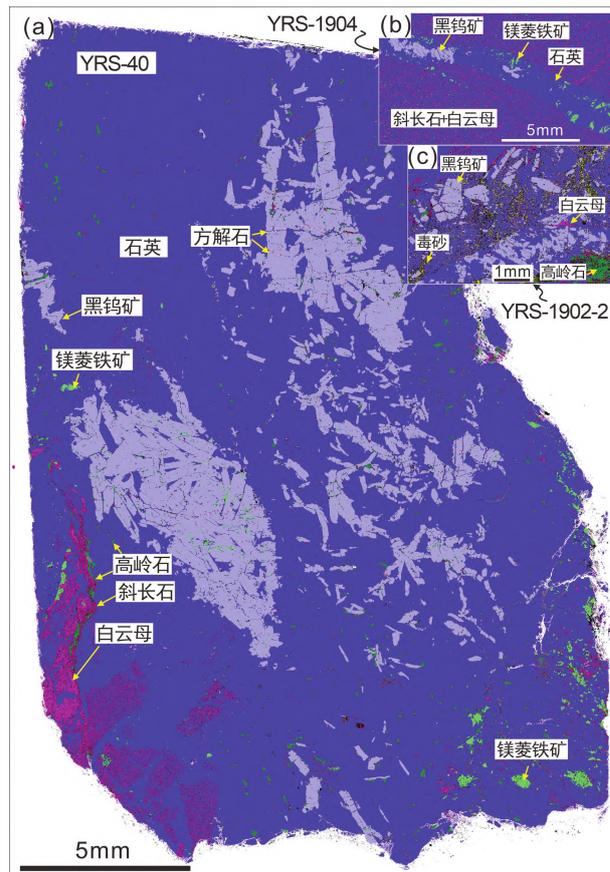


图8 样品 YRS-40(a)、YRS-1904(b) 及 YRS-1902-2(c) 的 TIMA 图像

Fig. 8 TIMA photos of samples YRS-40 (a), YRS-1904 (b) and YRS-1902-2 (c) from the Woxi deposit

活动事件的时代。与样品 WX-34-4 采自同一条矿脉( $V_7$ ) 的另一样品 WX-27-12 中白钨矿的 CL 图像及年龄也指示沃溪白钨矿可能存在不同世代(Tang *et al.*, 2022; 该文中沃溪矿床白钨矿样品由本文第一作者提供)。

因此, 样品 WX-34-4 中白钨矿的形成时间应与共生的磷灰石一致, 为  $139.8 \pm 6.1\text{Ma}$ ; 这与本次测试的另一同白钨矿共生的磷灰石年龄  $144.8 \pm 1.7\text{Ma}$  (样品 YRS-1910-2), 以及前人报道该矿床的白钨矿年龄  $144.3 \pm 2.2\text{Ma}$ 、 $142.7 \pm 2.4\text{Ma}$  (Tang *et al.*, 2022) 在误差范围内基本一致。本次白钨矿所测年龄  $125.8 \pm 5.6\text{Ma}$  可能代表了晚期石英-碳酸盐阶段热液活动事件的年龄。

### 5.1.3 黑钨矿年龄

本次测试的黑钨矿年龄为  $137.8 \pm 3.9\text{Ma}$  和  $134.8 \pm 5.1\text{Ma}$ , 以及较年轻的  $123.8 \pm 4.6\text{Ma}$ 。由于受黑钨矿中 Fe 的影响, CL 图像未能良好地显示黑钨矿的多世代性。但显微照片显示黑钨矿脉被晚阶段石英-碳酸盐脉切割, 黑钨矿颗粒亦普遍发育裂隙(图7a-c), 表明黑钨矿遭受晚阶段热液活动的影响。黑钨矿 U-Pb 同位素体系封闭温度很高( $900 \sim 1000^\circ\text{C}$ , Yang *et al.*, 2020), 远高于沃溪矿床晚阶段流体的

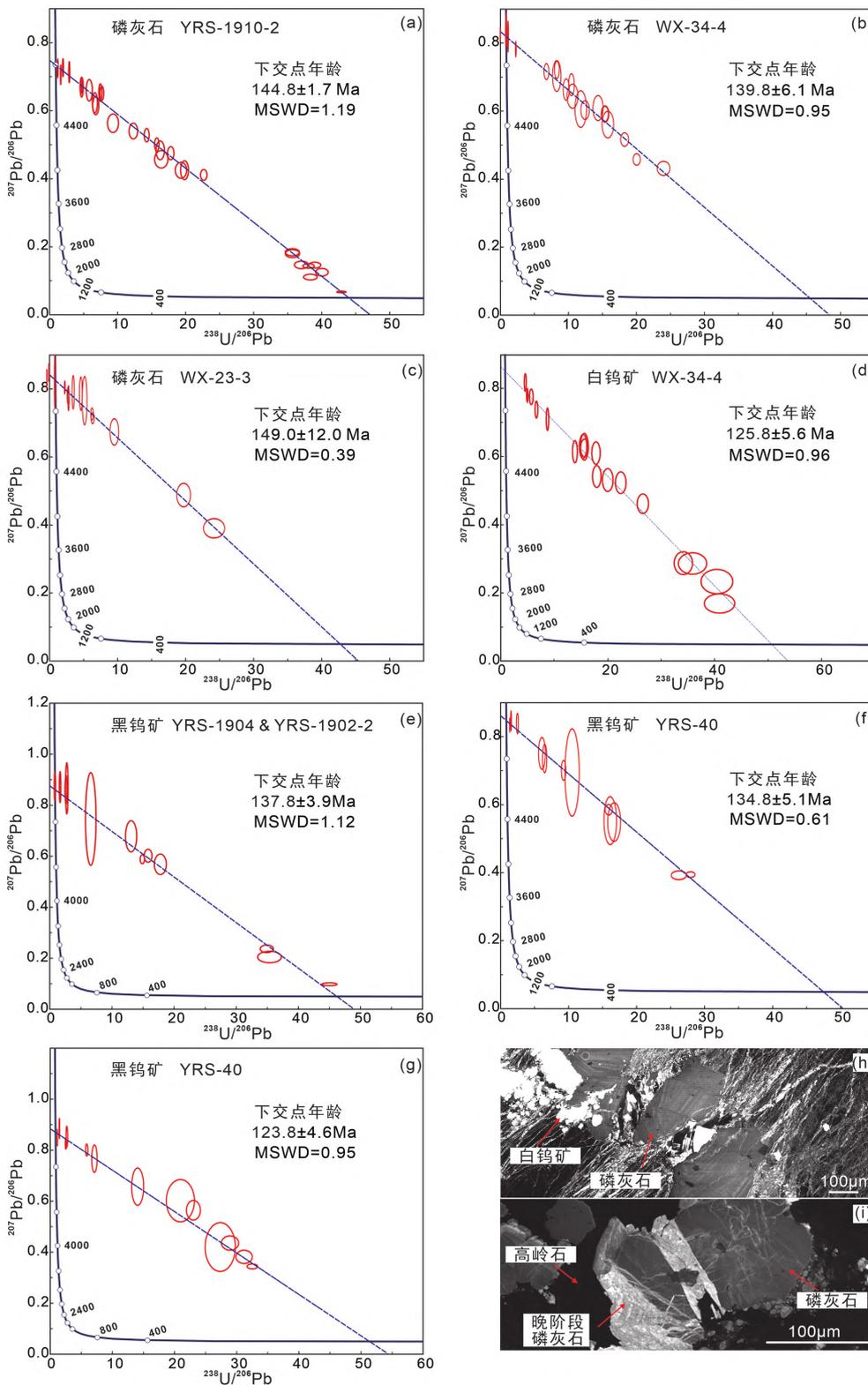


图9 沃溪矿床磷灰石(a-c)、白钨矿(d)、黑钨矿(e-g)的Tera-Wasserburg图解及与白钨矿共生磷灰石(h)和与高岭石共生晚阶段磷灰石(i)的CL图像

Fig. 9 Tera-Wasserburg diagram of apatite (a-c), scheelite (d) and wolframite (e-g) and CL photos of apatite which coexisted with scheelite (h) and kaolinite (i) from the Woxi deposit

温度,可排除发生由温度引起的黑钨矿 U-Pb 体系开放。样品 YRS-40 中黑钨矿的年龄  $123.8 \pm 4.6\text{Ma}$  与样品 WX-34-4 中白钨矿的年龄  $125.8 \pm 5.6\text{Ma}$  十分相近,这两个样品中的黑钨矿、白钨矿均发育大量裂隙并分别被镁菱铁矿与方解石(图 7a)、铁白云石(图 5a)充填,故推测黑钨矿的年轻年龄可能同样指示了晚阶段碳酸盐热液活动事件。因此,本文所获得的年龄  $137.8 \pm 3.9\text{Ma}$  和  $134.8 \pm 5.1\text{Ma}$  为沃溪黑钨矿的形成时间,黑钨矿在晚侏罗世发生沉淀后遭受晚阶段( $123.8 \pm 4.6\text{Ma}$ )热液活动改造。

综上所述,本次所获得的沃溪矿床各阶段矿物的年龄与其在野外、镜下所呈现的穿插、共生关系相一致。白钨矿( $149.0 \sim 139.8\text{Ma}$ )、黑钨矿( $137.8 \sim 134.8\text{Ma}$ )形成较早,手标本及显微镜下常见含白钨矿石英角砾被黄铁矿(自然金)-辉锑矿胶结(图 4a),石英-白钨矿脉被石英-黄铁矿-(辉锑矿)脉(图 4b-d、图 5a)、黄铁矿-自然金-高岭石脉(图 7a)以及含金碳酸盐脉(图 6a)切割,黑钨矿脉被毒砂-高岭石脉(图 8c)、辉锑矿脉(李彬等, 2022)以及碳酸盐脉(图 8a)切割,揭示金、锑成矿晚于钨。自然金主要与黄铁矿(图 5b、图 7b-d)共生,少量与辉锑矿(Zhu and Peng, 2015; 邓昌州等, 2022)和碳酸盐矿物(图 6b)共生,表明金成矿主要发生在钨大量沉淀( $149.0 \sim 134.8\text{Ma}$ )之后,且直到晚期碳酸盐阶段( $125.8 \sim 123.8\text{Ma}$ )仍有少量自然金生成。

## 5.2 地质意义

### 5.2.1 液致裂作用

本次工作获得的成矿年龄表明沃溪矿床在晚侏罗世-早白垩世发生金-锑-钨热液成矿作用,形成了以白钨矿、黑钨矿、黄铁矿(自然金)、辉锑矿为主要矿石矿物的石英脉。沃溪矿床中广泛发育分支复合的层脉(图 3b)、多方向张性节理脉(图 3f-i),以及条带状构造(图 3d)、角砾状构造(图 3a, e)等宏观地质现象以及显微镜下白钨矿、黑钨矿普遍发育的碎裂结构(图 6a、图 7a、图 8)等微观岩相学特征,指示矿脉的形成与液致裂作用有关,后期热液活动促使早期形成的矿脉反复张裂并被新生的矿物胶结(Ramsay, 1980; Weatherley and Henley, 2013)。前人研究发现,当有足够大的应力和足够量的流体时,液致裂作用就会反复发生,甚至在仅 7.5mm 宽的脉中记录了 500 次以上的裂开-愈合过程(Ramsay, 1980)。沃溪矿床的流体包裹体岩相学及均一温度、盐度等特征也反映,由断层闸机制产生的流体压力骤变可能是成矿的关键(Zhu and Peng, 2015)。这种由压力波动造成的裂开-愈合多期成矿作用在脉状金矿床中普遍发育(Sibson *et al.*, 1988),在雪峰隆起区及其邻区的金锑矿床中亦有报道并被认为与成矿关系密切(李玉坤等, 2016; 刘守林等, 2017)。因此,沃溪矿床含矿石英脉可能在液致裂的作用下,在晚侏罗世-早白垩世经历了反复裂开-愈合过程。这种过程不仅导致早期形成的矿物(如白钨矿、黑钨矿)发生碎裂、压溶等作用,而且有利于成矿元素(尤其是金)不断地

从围岩及早期形成的矿物中活化出来再次迁移富集沉淀。

### 5.2.2 雪峰隆起区加里东期和燕山期 Au-Sb-W 成矿作用

前人对雪峰隆起区广泛发育的金锑钨矿床的地质特征、矿床成因及成矿时代等进行过大量研究。其中,就成矿时代方面,部分学者认为该区广泛存在加里东期、印支期和燕山期成矿事件(包正相, 1987; 王甫仁等, 1993; 彭建堂和戴塔根, 1998)。另一部分学者则认为,该区燕山期金成矿( $152 \sim 130\text{Ma}$ )并非普遍发育,而是主要分布于同期雪峰冲断带东南部构造岩浆隆起带的东部,与伸展环境下的花岗质岩浆活动有关(柏道远等, 2021)。然而,沃溪矿床发育燕山期( $149.0 \sim 123.8\text{Ma}$ , 本文)成矿作用且矿区范围内未见同期岩浆岩出露,表明雪峰隆起区燕山期成矿事件与同期岩浆活动之间并不存在必然的时空联系。前人研究亦表明,雪峰隆起区的金锑钨矿床主要产于韧-脆性变形带中,构造控矿作用明显(包正相, 1987; 牛贺才和马东升, 1992; 王甫仁等, 1993),区内大部分断裂均具有多期活动特征,如杨坤光等(2006)通过石英 ESR 定年,发现安化-溆浦断裂在  $156.9 \sim 90.6\text{Ma}$  时期内活动强烈。这些同期的断裂活动、岩浆侵入有利于金锑钨等元素的活化、运移和聚积,它们与同期的成矿作用均是对相同构造事件的不同响应。

近年来大量年龄数据进一步证实雪峰隆起区及其邻区普遍发育燕山期金锑钨热液成矿事件,如板溪(辉锑矿和毒砂 Rb-Sr 等时线法: $129.4 \pm 2.4\text{Ma}$ , 辉锑矿 Sm-Nd 等时线法: $130.4 \pm 1.9\text{Ma}$ , Li *et al.*, 2018)、金井(毒砂 Re-Os 等时线法: $174 \pm 15\text{Ma}$ , 王加昇等, 2011)、半坡(方解石 Sm-Nd 等时线法: $130.5 \pm 3.0\text{Ma}$ , 肖宪国, 2014)、锡矿山(方解石 Sm-Nd 等时线法: $155.5 \pm 1.1\text{Ma}$  和  $124.1 \pm 3.7\text{Ma}$ , 彭建堂等, 2002; 方解石和辉锑矿 Sm-Nd 等时线法: $156.3 \pm 12\text{Ma}$ , Hu *et al.*, 1996)、龙山(白云母 Ar-Ar 法: $162.5 \pm 1.8$  和  $161.1 \pm 1.2\text{Ma}$ , 张志远等, 2018)、黄金洞(白钨矿 Sm-Nd 等时线法: $129.7 \pm 7.4\text{Ma}$ , 周岳强等, 2021; 石英流体包裹体 Rb-Sr 等时线法: $152 \pm 13\text{Ma}$ , 董国军等, 2008)、大岩(白云母 Ar-Ar 法: $130.3 \pm 1.4\text{Ma}$ , Xu *et al.*, 2017)等。这些金锑钨矿床成矿时代可大致分为  $155 \sim 135\text{Ma}$  和  $131 \sim 123\text{Ma}$  两个时期,可能与江南钨矿带的两期钨成矿( $150 \sim 135\text{Ma}$  和  $130 \sim 125\text{Ma}$ ) (毛景文等, 2020)具有相似的动力学背景,与中晚侏罗世古太平洋板块向华南大陆俯冲及早白垩世( $\sim 137\text{Ma}$ )俯冲板片后撤或转向(Jia *et al.*, 2004; 张岳桥等, 2012; Yuan *et al.*, 2015; Zhao *et al.*, 2018; Mao *et al.*, 2021a, b)两期构造事件密切相关。

值得注意的是,沃溪矿床深部中段(23、34 中段)矿体中白钨矿及共生磷灰石形成时间约为  $149.0 \sim 139.8\text{Ma}$ ,浅部中段矿体(7、9、10 中段)中白钨矿 Sm-Nd 等时线法年龄为  $402 \pm 6\text{Ma}$ (彭建堂等, 2003),指示该矿可能存在加里东期陆内造山成矿作用,但由于燕山期成矿作用的叠加改造,导致仅有局部浅部矿脉尚未遭受到改造(或改造程度较小)而保留加里东期成矿信息。区内板溪(石英 Ar-Ar 法: $397.4 \pm$

0.4Ma 和  $422.2 \pm 0.2$ Ma, 彭建堂等, 2003) 和黄金洞(石英流体包裹体 Rb-Sr 等时线法:  $462 \pm 18$ Ma, 韩凤彬等, 2010) 的成矿年龄亦反映二者存在加里东期和燕山期(年龄值上文已述)两期成矿作用。这与前人推测该区大多数矿床无论其成矿作用起始于何时都容易受到燕山期成矿作用的影响(王甫仁等, 1993)相一致,进一步揭示了中-晚侏罗世到早白垩世期间热液活动事件对区域金锑钨矿化具有重大贡献。

## 6 结论

(1) 年代学研究表明,沃溪矿床白钨矿(149.0 ~ 139.8Ma)与黑钨矿(137.8 ~ 134.8Ma)形成较早,自然金和辉钨矿形成较晚,且自然金直到晚碳酸盐阶段(125.8 ~ 123.8Ma)仍有少量产出,表现出明显的多阶段成矿特征。

(2) 沃溪矿床含矿石英脉在晚侏罗世-早白垩世(149.0 ~ 123.8Ma)期内经历了液压致裂作用引发的多次裂开-愈合过程,这种过程促进了成矿元素(尤其是金)的活化,并为含矿热液的运移和沉淀提供了动力和空间。

(3) 沃溪矿床及雪峰隆起区内部分矿床可能经历了加里东期陆内造山成矿作用,并叠加了不同程度的燕山期伸展构造背景下深部流体改造作用。

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