藏北商旭造山型金矿床成矿物质来源探讨:C、S、Pb同位素证据

刘洪[1)],李光明[1)],黄瀚霄[1)],肖万峰[2)],闫国强[3)],马东方[1)],张海[1)],张红[1)]

1)中国地质调查局成都地质调查中心,成都,610081;2)河南省地质调查院,郑州,450007;
3)中国地质调查局天津地质调查中心,天津,300170

内容提要:西藏双湖县商旭金矿床位于班公湖—怒江缝合带中段。矿床受近东西向断裂控制,赋存于中—下侏罗统木嘎岗日群浅变质增生混杂岩中。本文研究主成矿阶段石英流体包裹体中CO_2的C同位素及共生硫化物的S—Pb同位素组成特征,并与木嘎岗日群、虾别错—木嘎岗日山花岗岩等主要地质体对比。含金石英脉流体包裹体中CO_2的$\delta^{13}C_{V\text{-}PDB}$值范围为-17.8‰~-23.1‰,均值为-21.3%,接近沉积岩或者变质岩源有机碳,表明商旭金矿床的成矿流体可能来自于木嘎岗日群的变质流体,而含金石英脉中发育着与虾别错—木嘎岗日山花岗岩同时代的少量岩浆锆石,暗示成矿流体还有岩浆热液的加入。共生硫化物$\delta^{34}S_{V\text{-}CDT}$值变化于-4.5‰~4.6‰,均值为-1.6‰,具有深源硫(地幔或下地壳,$\delta^{34}S_{V\text{-}CDT}=-3‰\sim+3‰$)的特征;共生硫化物Pb同位素位素[$n(^{206}Pb)/n(^{204}Pb)=18.350\sim18.690$、$n(^{207}Pb)/n(^{204}Pb)=15.632\sim15.700$、$n(^{208}Pb)/n(^{204}Pb)=38.570\sim38.980$]与早白垩世虾别错—木嘎岗日山花岗岩[$n(^{206}Pb)/n(^{204}Pb)=18.558\sim19.169$、$n(^{207}Pb)/n(^{204}Pb)=15.616\sim15.651$、$n(^{208}Pb)/n(^{204}Pb)=38.838\sim39.154$]基本一致,同时向侏罗统木嘎岗日群[$n(^{206}Pb)/n(^{204}Pb)=18.630\sim18.970$、$n(^{207}Pb)/n(^{204}Pb)=15.619\sim15.673$、$n(^{208}Pb)/n(^{204}Pb)=38.887\sim39.260$]略有漂移,暗示商旭金矿床的Pb可能来源于早白垩世岩浆活动,同时还有部分来自木嘎岗日群中铅的加入。本次研究认为,商旭金矿的成矿物质部分来自深部壳幔岩浆作用,并被成矿热液携带至浅部。木嘎岗日群围岩也贡献了部分成矿物质,被地层中的变质热液携带到成矿流体中。

关键词:西藏;班公湖—怒江;商旭金矿;造山型金矿床;物质来源;稳定同位素

造山型金矿床是指产于变质地体中受构造控制的热液脉状后生金矿床,在时间和空间上与造山作用有关,其矿石工业类型表现出石英脉型、蚀变岩型、糜棱岩型等(Goldfarb et al., 2001, 2004; 陈柏林, 2001; 陈衍景, 2006; Phillips et al., 2015; Groves et al., 2016a; 吴兴源等, 2018)。近年来,以邦布(Pei Yinru et al., 2016a)、马攸木(Jiang Sihong et al., 2009)、念扎(裴英茹, 2016)和折木朗(周峰等, 2011)等金矿床为代表的雅鲁藏布江造山型金矿带(59 ~ 44 Ma)和以镇沅(Deng Jun et al., 2015)、金厂(熊伊曲等, 2015)、长安(张静等, 2010)、大坪(Sun Xiaoming et al., 2009; Liu Junlai et al., 2015)金矿为代表的哀牢山造山型金矿带(35~26 Ma)的发现,表明青藏高原具有发育碰撞造山型金矿床的良好条件(Hou Zengqian et al., 2009; Sun Xiaoming et al., 2009; 侯增谦, 2010)。班公湖—怒江成矿带,为一条呈近东西向展布于青藏高原中部的Cu—Au—Fe多金属成矿带(图1b)(Hou Zengqian et al., 2014; 刘洪等, 2016; 黄瀚霄等, 2016),其成矿作用与冈底斯(拉萨)地块和羌塘地块的碰撞环境有关(宋扬等, 2014; 马国桃等, 2017; 李永灿等, 2017)。通过中国地质调查项目和科技部973项目对班公湖—怒江成矿带商旭、达查等地区金矿床的研究,中国地质调查局成都地质调查中心在班公湖—怒江成矿带中段发现了商旭、达则、作布等多处具有造山型金矿床特征的矿床(点)❶,表明在班公湖—怒江成矿带中段具有发育造山型金矿带的可能。

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作者简介:刘洪,男,1987年生,工程师,2012年获中国地质大学(武汉)硕士学位,主要从事矿床学、矿产勘查研究。Email:cugliu@foxmail.com。通讯作者:黄瀚霄,男,1982年生,高级工程师,2009年获中国地质科学院硕士学位,主要从事青藏高原地质矿产研究。Email:hanxiaohuang@126.com。

商旭金矿床位于班公湖—怒江缝合带中段,受北西西向的脆韧性断裂控制,呈脉状,透镜状产于中—下侏罗统木嘎岗日群浅变质增生混杂岩中。主成矿阶段流体包裹体类型为富液相包裹体和含 CO_2 包裹体,成矿流体为中低温、低盐度、低密度、富含 CO_2 的 $CaCl_2$—NaCl—H_2O 体系流体,具有变质水和大气降水的成分,成矿元素组合为 Au、Ag、As、Sb,各方面的地质特征与典型的碰撞造山型金矿床相似。然而以往的研究工作(肖万峰等, 2013, 2017; 黄瀚霄等, 2014; 刘洪等, 2015;裴英茹等, 2015, 2016, 2017; 刘洪等, 2017;)主要集中在矿床地质特征和成矿流体和初步的物源分析方面,但是对该矿床成矿物质来源的研究较为薄弱,制约了矿床成因机制的探讨。

关于造山型金矿成矿流体及物质来源一直是研究热点,矿床学界众说纷纭(Barnicoat et al., 1991; Kerrich et al., 1998;Nisbitt, 1998; Groves, 2003; 毛景文, 2005; Chang Zhaoshan et al., 2008; Phillips et al., 2010; Large, 2011; Omkins, 2013a, 2013b; Groves et al., 2016b),主要认为有变质地层来源、地幔来源、岩浆来源和大气降水(地下水)等。对于许多矿床类型,同位素分析可以为成矿流体及物质来源提供强有力的证据,由于造山型金矿形成于地壳 3~15 km(Groves et al., 1998),流体通道较长,多种流体加入以及成矿流体在围岩中的水岩反应造成同位素分析具有多解性(Phillips et al., 2009; Goldfarb et al., 2015),因此需要结合矿床实际地质背景,运用多种同位素示踪手段对成矿流体及物质来源进行合理的推断。本文在前人研究基础上,结合矿床地质特征,利用含金石英脉流体包裹体中 CO_2 的 C 同位素,主成矿期共生硫化物的 S、Pb 同位素等多元示踪方法约束商旭造山型金矿床的成矿流体和矿物质来源,这对进一步探讨商旭金矿床的成矿作用过程和成因机制,深入理解班公湖—怒江成矿带中段造山型金矿成矿作用,促进该地区原生金矿床的勘查具有一定的理论和实践意义。

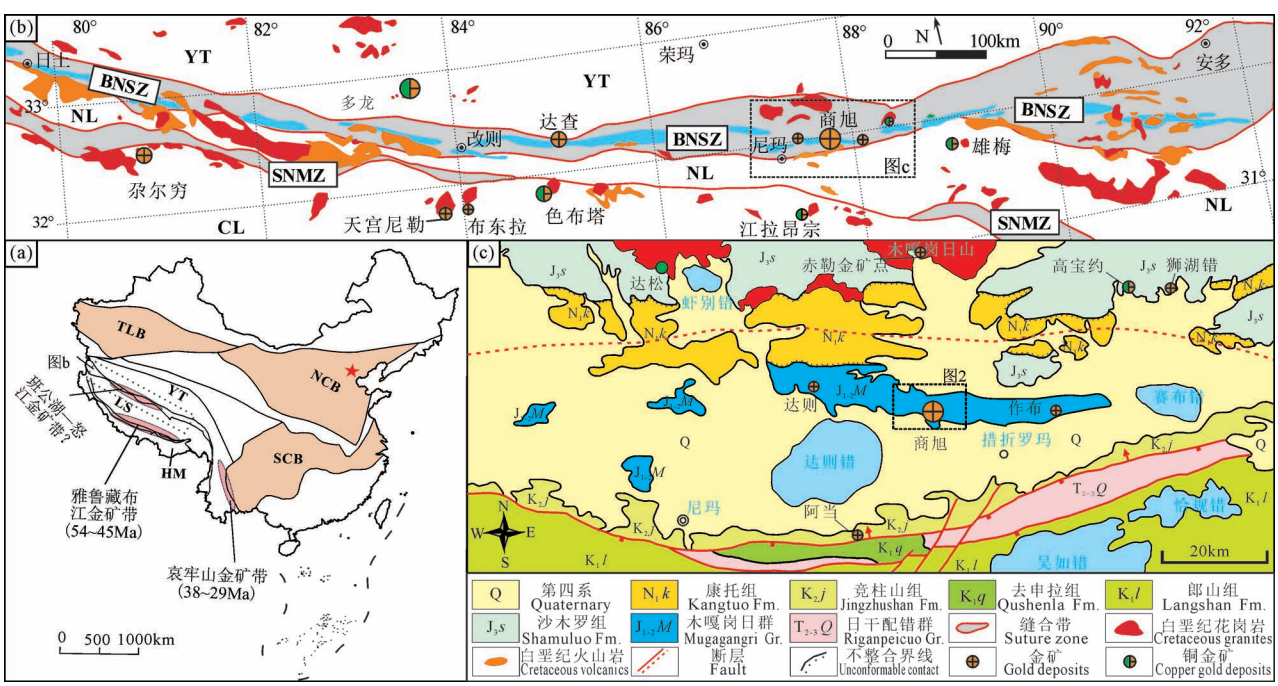


图 1 班公湖—怒江成矿带中段地质简图

[(a) 据 Cao Huawen et al.(2014)、刘洪等(2015)修改; (b)据唐菊兴等(2016)修改; (c) 据黄瀚霄等(2014)修改]

Fig. 1 Geological sketch map of the middle part in Bangong Lake—Nujiang River metallogenic belt [(a) Modified from Cao Huawen et al., 2015; Liu Hong et al., 2015&; (b) modified from Tang Juxing et al., 2014&; (c) Modified from Huang Hanxiao et al., 2014&]

NCB—华北板块; SCB—华南板块; TLB—塔里木板块; YT—羌塘地块; LS—拉萨地块; HM—喜马拉雅地块; BNSZ—班公湖—怒江缝合带; NL—北拉萨地块; SNSZ—狮泉河—纳木措湖蛇绿岩混杂带; CL—中拉萨地块

NCB—North China Block; SCB—South China Block; TLB—Tarim Block; YT—Youtang Block; LS—Lhasa Block; HM—Himalaya Block; BNSZ—Bangong Lake—Nujiang River Suture Zone; NL—North Lhasa Block; SNSZ—Shiquanhe—Nam Lake Suture Zone; CL—Central Lhasa Block

1　地质概况

班公湖—怒江成矿带范围包括班公湖—怒江结合带（王保弟等，2007，2015；Shi Rendeng et al.，2008；潘桂棠等，2009；Wang Baodi et al.，2010，2016；赵元艺等，2010；李光明等，2011；Ding Lin et al.，2013，2017；宋扬等，2013；）及南北两侧地区，包括羌塘地块（YT）、班公湖—怒江缝合带（BNSZ）、狮泉河—纳木错蛇绿岩混杂带（SNMZ）、北拉萨地块（NL）等地质单元（图 1b）（耿全如等，2011）。商旭金矿床位于班公湖—怒江缝合带中段，区域上主要出露中、新生代地层（图 1c）：确哈拉群（$T_{1-3}Q$）砂岩、灰岩、大理岩，木嘎岗日岩群（$J_{1-2}M$）混杂岩，沙木罗组（J_3s）砂岩、钙质板岩，去申拉组（K_1q）的安山岩、玄武岩，郎山组（K_1l）的灰岩，竞柱山组（K_2j）砾岩、砂岩，康托组（N_1k）砂岩、泥岩等。受缝合带主断裂影响，区域构造主线为 NWW 向，为一系列脆性断裂和褶皱构造，具有多期次、变形强烈等特征。岩浆岩分布在北部的虾别错（Kapp et al.，2007）—木嘎岗日山一带（图 1c），形成时代为早白垩世[1]（约 122 Ma）。喷出岩沿缝合带呈断续分布，主要为去申拉组（K_1q）火山岩（107 Ma，吴浩等，2013）。其中木嘎岗日群（$J_{1-2}M$）总体为一套含大量外来岩块和以复理石沉积为基质的浅变质沉积—构造混杂岩，主要岩性以深灰色、暗绿色、灰黑色泥质板岩与变质砂岩、粉砂岩为主，局部夹有灰岩、枕状玄武岩、放射虫硅质岩等岩块，与上覆古近系康托组呈不整合接触，该套地层中集中了较丰富的 Au、Ag、Cu、As、Sb 等元素（李胜荣等，2005），为区域上重要的含金建造。在该群中，已发现商旭（黄瀚霄等，2014）、达则（刘洪等，2017）、作布（欧阳渊等，2016）、达查（肖润等，2002；刘洪等，

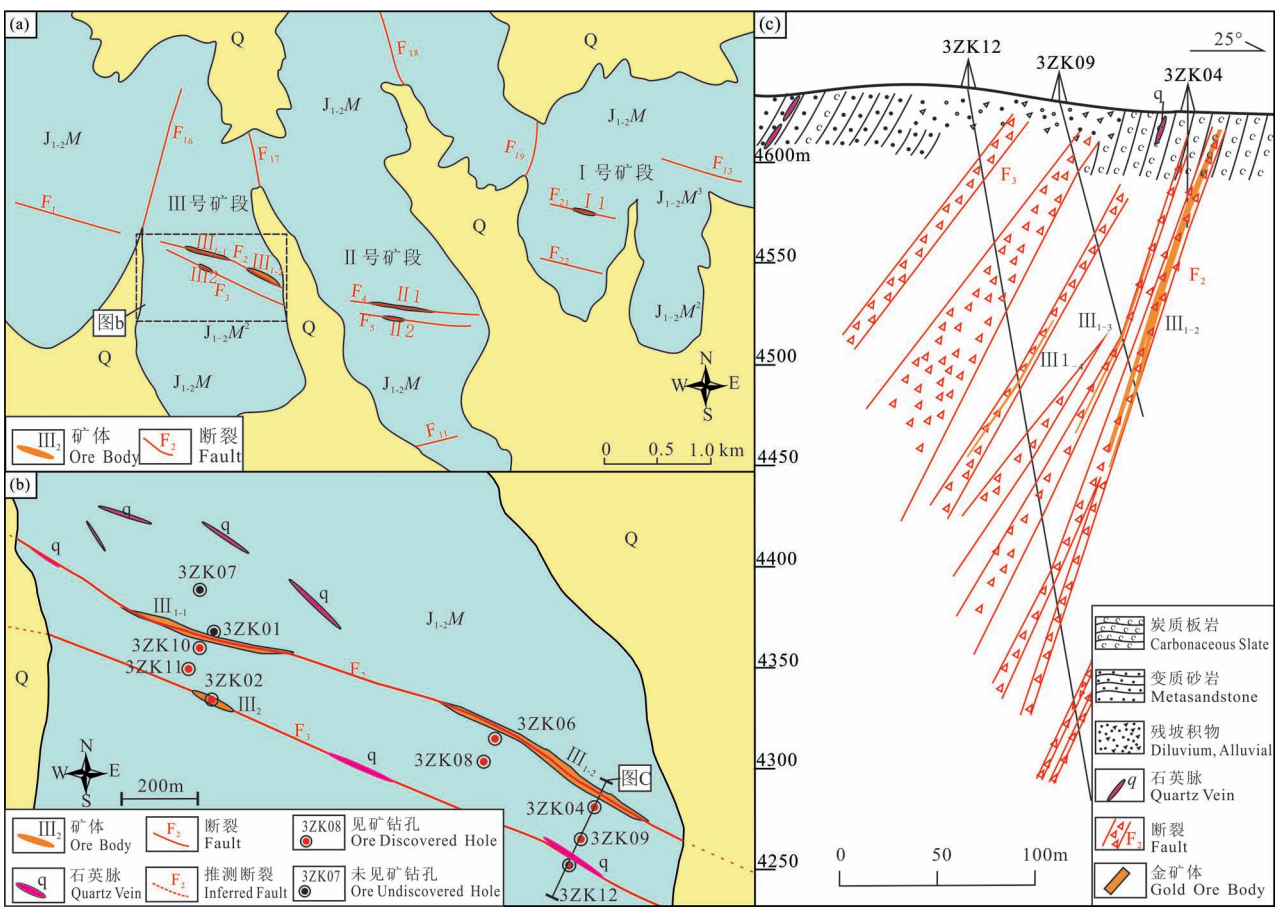


图 2 藏北双湖商旭金矿区地质简图及Ⅲ1 矿体剖面示意图（据刘洪等，2017 修改）

Fig. 2 Geological and Ⅲ$_1$ cross section map of the Shangxu gold deposit, Shuanghu County, northern Xizang (Tibet) (Modified from Liu Hong et al., 2017&)

Q—第四系残坡积物；$J_{1-2}M$—木嘎岗日岩群浅变岩

Q — Quaternary; $J_{1-2}M$— epimetamorphic rock of the Lower—Middle Jurassic Mugagangri Gr.

2014)等多处岩金矿床(点),同时该地层还发育中大量的砂金矿点,显示出良好的金找矿潜力。

商旭金矿床位于西藏双湖县措折罗玛镇达则错北侧(图 1c, 图 2),是由中国地质调查局成都地质调查中心和西藏地质矿产勘查开发局第五地质大队组织勘查评价的,已达到中型规模,并具有大型潜力

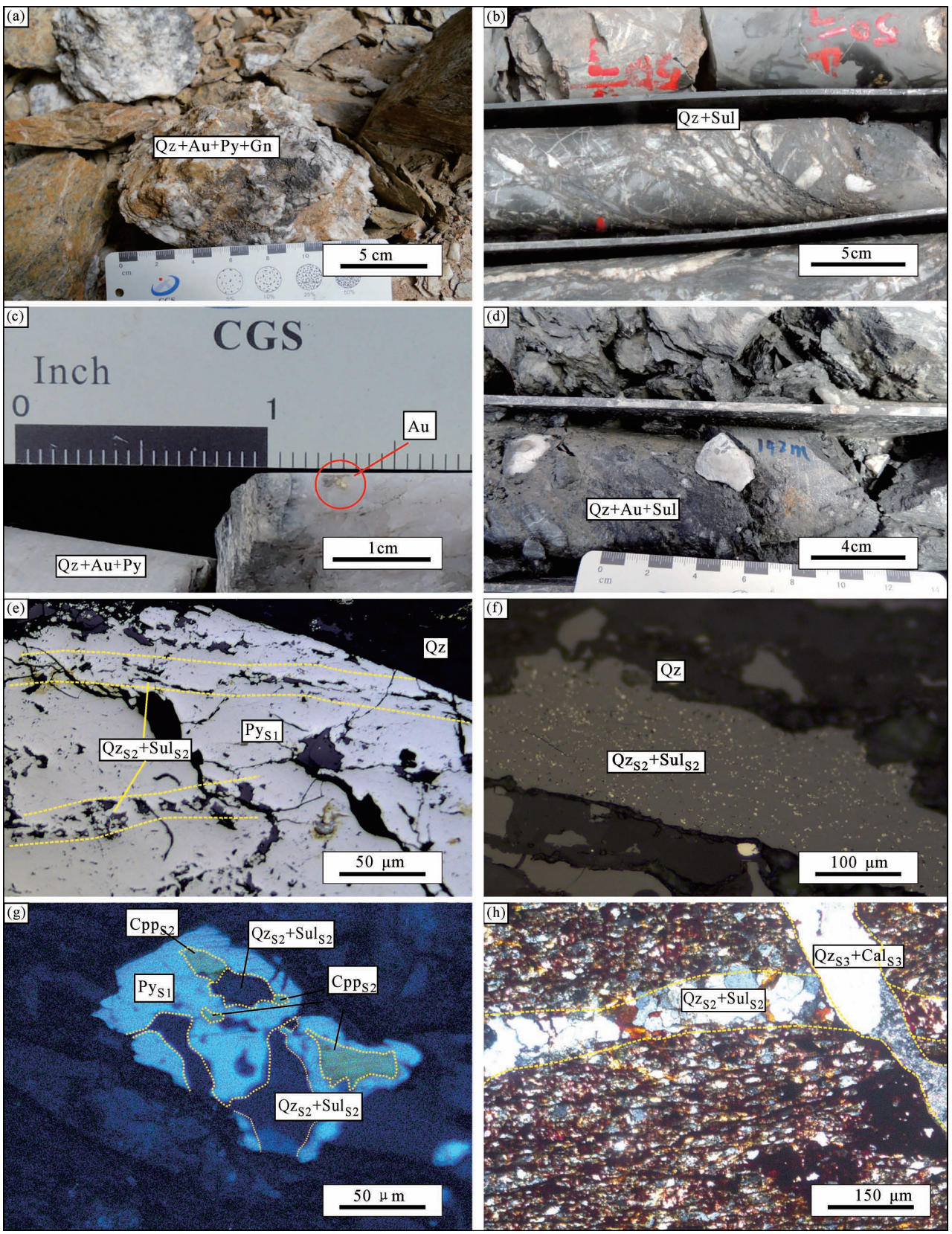


图 3 藏北双湖商旭金矿矿脉野外及镜下特征

Fig. 3 Photos and micro-photos of the Shangxu gold deposit, Shuanghu County, north Xizang (Tibet)

Gn—方铅矿; Qz—石英; Au—自然金; Py—黄铁矿; Cpp—黄铜矿; Sul—硫化物; Cal—碳酸盐矿物; S1—石英—金—黄铁矿—方铅矿阶段; S2—石英网脉—金—多金属硫化物阶段; S3—石英细脉—碳酸盐矿物阶段; (a) S1 阶段含黄铁矿、方解石石英脉; (b) S2 阶段含多金属硫化物石英网脉; (c) S1 阶段石英网脉中的明金; (d) S2 阶段含金破碎带; (e) S2 阶段石英硫化物脉穿插 S2 阶段石英颗粒; (f) S2 阶段石英和共生的细粒金属硫化物; (g) S2 阶段石英、多金属硫化物侵蚀 S1 阶段黄铁矿; (h) S3 阶段石英—碳酸盐矿物脉穿切 S2 阶段石英—硫化物脉

Gn—Galena; Qz—Quartz; Au—Natural gold; Py— Pyrite; Cpp— Chalcopyrite; Sul— Sulfide; Cal— Carbonate minerals; S1— Quartz — Natural gold — Pyrite — Galena Stage; S2— Quartz — Natural gold — Sulfide Stage; S3— Quartz — Carbonate minerals Stage; (a) the quartz vein containing pyrite and calcite in S1 stage; (b) the quartz stockwork containing a variety of sulfides in S2 stage; (c) the quartz vein containing coarse-grained gold S1 stage; (d) the gold-bearing fractured zone in S2 stage; (e) the quartz stockwork containing a variety of sulfides in S2 stage cut across the quartz vein S2 stage; (f) the quartz vein containing a variety of sulfides in S2 stage; (g) the quartz stockwork and a variety of sulfides in S2 stage corrosive the the quartz in S1 stage; (h) the quartz — carbonate minerals vein in S3 stage cut across the quartz vein containing a variety of sulfides in S2 stage

的岩金矿床。该矿床受北西西向脆性断裂控制,呈脉状、透镜体状产出于班公湖—怒江缝合带中段中—下侏罗统木嘎岗日群($J_{1-2}M$)浅变质增生混杂岩中(图 1c, 图 2)。控矿断裂属于北西西向脆韧性逆断裂,断裂面呈舒缓波状,断裂带宽 1~5m,局部被后期近南北向断裂错动,断裂带中岩石碎裂程度较高,破裂面密集,显示出多期次活动的特征,具有早期滑脱伸展、晚期逆冲推覆挤压的复合性质。沿破碎带及其旁侧裂隙中断续有透镜状、带状含硫化物石英脉产出。目前,商旭金矿床共圈出 6 条金矿体(图 2a)金矿体均主要由石英脉、含铅的铁方解石英脉、蚀变岩组成,产于中—下侏罗统木嘎岗日群中,严格受北西西向断裂控制,呈透镜体状或者脉状产出,其局部具有膨缩、分枝等特征(图 2)。矿体产状 5° ~ 30°∠55° ~ 90°,产状主要随断层接触面产状的变化而变化。各矿体规模大小不等,长 54 ~ 723.9 m,厚度变化 1.29 ~ 4.41 m,大部分矿体深部延伸均未得到控制,矿体延深 68~160 m;矿石品位变化较大,一般 1.0 ~ 30 g/t(变异系数 0.4)。矿区内围岩蚀变中为硅化和绢云母化,向外依次为碳酸盐化和绿泥石化。根据蚀变特征,将矿石类型分为石英脉型(图 3a、b、c)和蚀变岩型(图 3d)两类。石

表1 商旭金矿床成矿阶段、矿物生成顺序表

Table 1 Mineralization stages and paragenetic sequence of minerals in Shangxu gold deposit

成矿期 / 主要矿物 \ 成矿阶段	区域变质期	热液期			表生期
		石英－金－黄铁矿－方铅矿阶段（S1）	石英网脉－金－多金属硫化物阶段（S2）	石英细脉-碳酸盐矿物阶段（S3）	
石英	┈┈	———	———	┈┈	
绢云母		———	———	┈┈	
方解石		┈┈	┈┈	———	
黄铁矿		———	———	┈┈	
方铅矿		┈┈	———		
自然金		———	———		
闪锌矿			- - -		
黄铜矿			- - -		
褐铁矿					┈┈
孔雀石					┈┈
黄钾铁矾					┈┈

——— 大量出现 Very extensive　　- - - 少量出现 Lesser　　┈┈ 偶见 A few

英脉型金矿石为含硫化物石英脉,蚀变岩型金矿石是强烈黄铁绢英岩化蚀变的构造岩。矿石构造则以浸染状、及网脉状为主。矿石矿物以自然金为主,而黄铁矿、方铅矿等金属硫化物含量偏少。

根据矿物共生组合特征、脉体穿切关系等综合研究资料,将热液蚀变矿化过程划分为三个成矿阶段(表 1):①石英—金—黄铁矿—方铅矿阶段(S1):主要矿物共生组合为含粗粒硫化物石英大脉(图 3a、c)、粗粒黄铁矿(图 3e、g)、粗粒方铅矿(图 3a)、自然金(裂隙金)(图 3c)等,成矿温度为 200~230℃(肖万峰等, 2017);②石英网脉—金—多金属硫化物阶段(S2):主要矿物共生组合为含硫化物石英网脉(图 3b、e)、细粒黄铁矿(图 3e、f)、细粒方铅矿、细粒闪锌矿和少量细粒黄铜矿(图 3g)等,成矿温度为 183~231℃(肖万峰等, 2017);③石英细脉—碳酸盐矿物阶段(S3):主要矿物共生组合为石英细脉和方解石细脉(图 3h),成矿温度为 140~210℃(肖万峰等, 2017)。各成矿阶段的矿物生成顺序,受成矿流体性质和物理化学条件变化的控制,早阶段形成的产物常被晚阶段的产物切割、叠加、改造,从而使不同阶段形成的矿物叠加产出。与金有关的成矿阶段为石英—金—黄铁矿—方铅矿阶段(S1)和石英网脉—金—多金属硫化物阶段(S2)。

3 实验原理、采样及测试方法

本文主要通过对比研究含金石英脉中流体包裹体 CO_2 的 C 同位素特征以及各成矿阶段硫化物和地层中硫化物的硫 Pb 同位素特征来示踪成矿流体和成矿物质来源,样品主要分布于已发现的 6 个矿体(图 2a)。单矿物分选工作在中国科学院广州地球化学研究所完成,同位素分析测试工作委托核工业北京地质研究院分析测试研究中心完成,分析仪器为 Delta V Plus 型、MAT-253 型和 ISOPROBE-T 型质谱仪。S 同位素分析:硫化物单矿物和氧化亚铜按一定比例研磨至 200 目左右,并在混合均匀,在真空达 20 mPa 状态下加热,进行氧化反应,反应温度为 980℃,生成二氧化硫气体。真空条件下,用冷冻法收集二氧化硫气体,并用 Delta V Plus 气体同位素质谱分析 S 同位素组成,测试结果以 V-CDT 标准报出 S 同位素组成,记为 $\delta^{34}S_{V\text{-}CDT}$,参考标准为 GBW-04414($\delta^{34}S_{V\text{-}CDT}=-0.07\pm0.13‰$)、GBW-04415($\delta^{34}S_{V\text{-}CDT}=22.15\pm0.14‰$)硫化银标准,测试精度优于±0.2‰。Pb 同位素分析:准确称取 0.1~0.2 g 硫化物粉末样品于低压密闭溶样罐(PFA)中,用混合酸($HF+HNO_3+HClO_4$)溶解 24 h。待样品完全溶解后,蒸干,加入 6 mol/L 的盐酸转为氯化物蒸干。用 1 mL 0.5 mol/L HBr 溶解,离心分离,清液加入阴离子交换柱(100-200 目),用 0.5 mol/L HBr 淋洗杂质,用 1 mL 6mol/L 的 HCl 解析铅于聚四氟乙烯的烧杯中,蒸干,用磷酸硅胶将样品点在铼带上,送 ISOPROBE-T 热电离质谱计,用静态接受方式测量 Pb 同位素比值,参考标准为 NBS981[$n(^{208}Pb)/n(^{206}Pb)=2.164940\pm15$, $n(^{207}Pb)/n(^{206}Pb)=0.914338\pm7$, $n(^{204}Pb)/n(^{206}Pb)=0.0591107\pm2$],测试精度优于±0.1 ‰。C 同位素分析:在真空达 20mPa 条件下,通过真过真空热爆法打开流体包裹体,样品与 Cu_2O 反应后,用冷冻法分离除去生成的水,收集纯净的 CO_2 气体存于气钢瓶中,用 0.1mL 气密性进样针吸入约 0.05mL 气体,将样品注入温度为 50℃的 GC/TC 注射器中(稀释比为 1∶30),CO_2 气体样品在流速为 1.0mL/s 的 He 气流带动下,进入温度为 50℃的色谱柱(Poraplot Q 色谱分离柱,规格为 25 m×0.32 mm×10 μm)里,进入 940 ℃氧化炉中反应,最后进入 MAT 253 气体同位素质谱仪测试,以 V-PDB 标准报出 C 同位素组成,记为 $\delta^{13}C_{V\text{-}PDB}$,参考标准为 GBW04417 方解石($\delta^{13}C_{V\text{-}PDB}=-6.06\pm0.03‰$),测试精度优于±0.2‰。

4 测试结果

4.1 石英包裹体 CO_2 的碳同位素组成特征

碳同位素分析结果见表 2,含金石英脉流体包裹体中 CO_2 的 $\delta^{13}C_{V\text{-}PDB}$ 值范围为 -17.8‰~-23.1‰,均值为-21.3‰,略低于典型造山型金矿的 C 同位素(-11‰~+2‰,Mccuaig et al., 1988),而接近于沉积岩或者变质岩源有机碳(-30‰~-15‰,Ohmoto, 1972,表 2)。

4.2 共生硫化物 S—Pb 同位素组成特征

尽管商旭金矿床含金石英脉中相对贫硫化物,但是当区内石英脉中出现硫化物时,金的品位呈现较富的趋势,因而研究含金硫化物的同位素组成特征可以推断出成矿物质硫的组成特征。16 件样品的 $\delta^{34}S_{V\text{-}CDT}$ 值均为 0 值附近(表 3),变化范围不大:其中 4 件围岩中黄铁矿样品 $\delta^{34}S_{V\text{-}CDT}$ 值的变化范围为-3.1‰ ~ 2.2‰,极差为 2.8‰,均值为-2.8‰;4 件蚀变岩型矿石(石英网脉—金—多金属硫化物阶段,S2)中黄铁矿样品的 $\delta^{34}S_{V\text{-}CDT}$ 值的变化范围为-2.9‰ ~ +4.6‰,极差为 7.5‰,均值为-0.29‰;

表 2 藏北双湖县商旭金矿含金石英脉流体包裹体中 CO_2 的碳同位素组成

Table 2 The carbon isotopic composition of the CO_2 in fluid inclusions in auriferous quartz veins of the Shangxu gold deposit, Shuanghu County, north Xizang(Tibet)

样号	采样位置	$\delta^{13}C_{V\text{-}PDB}$(‰)	资料来源
SX111	Ⅲ1 含金石英脉	-23.1	本文
SX118	Ⅱ2 含金石英脉	-23.1	本文
SX119		-17.8	本文
岩浆源或深部源碳		-9~-2	Taylor, 1986
沉积岩或者低级变质岩源		-30~-15	Ohmoto, 1972
碳酸盐岩来源碳		-2~+3	Veize et al., 1980
显生宙海相碳酸盐岩来源碳		0	Veize et al., 1980
大气 CO_2		-12~-7	Taylor, 1986
典型造山型金矿		-11~+2	Mccuaig et al., 1998

石英脉型矿石中 4 件方铅矿样品 $\delta^{34}S_{V\text{-}CDT}$ 值的变化范围为 -4.5 ‰ ~ -2.0‰,极差为 2.5‰,均值为 -3.8‰;石英脉型矿石中 2 件闪锌矿样品 $\delta^{34}S_{V\text{-}CDT}$ 值的变化范围为 -2.6‰ ~ -1.0‰,极差为 1.6‰,均值为 -1.43‰。从表 3 可以看出,石英网脉—金—多金属硫化物阶段(S2)6 件共生硫化物(黄铁矿、闪锌矿、方铅矿)的 $n(^{206}Pb)/n(^{204}Pb)$、$n(^{207}Pb)/n(^{204}Pb)$、$n(^{208}Pb)/n(^{204}Pb)$ 分别为 18.350 ~ 18.690(极差:0.340,均值:18.536)、15.632 ~ 15.700(极差:0.068,均值:15.662)、38.570~38.980(极差:0.410,均值 38.785),早白垩世虾别错—木嘎岗日山花岗岩的 $n(^{206}Pb)/n(^{204}Pb)$、$n(^{207}Pb)/n(^{204}Pb)$、$n(^{208}Pb)/n(^{204}Pb)$ 分别为 18.558 ~ 19.169(极差:0.581,均值 18.867)、15.616 ~ 15.651(极差:0.035,均值 15.642)、38.838 ~ 39.154(极差:0.316,均值 39.034),早—中侏罗统木嘎岗日群变质岩的 $n(^{206}Pb)/n(^{204}Pb)$、$n(^{207}Pb)/n(^{204}Pb)$、$n(^{208}Pb)/n(^{204}Pb)$ 分别为 18.630~18.970(极差:0.340,均值 18.777)、15.619 ~ 15.673(极差:0.054,均值 15.644)、38.887 ~ 39.260(极差:0.373,均值 39.010)。

5 讨论

5.1 成矿流体来源

共生石英脉的氢氧同位素示踪广泛运用于热液型矿床的成矿流体来源研究中(郭东升等, 2007; 胡庆成等, 2012; 刘洪等, 2013a,b)。肖万峰等(2017)通过含金石英脉的氢氧同位素研究发现,与雅江缝合带和哀牢山造山带的造山型金矿相似,商旭金矿成矿流体位于变质热液和或者岩浆热液向雨水线(西藏地热水)偏移的位置(图 4),暗示着商旭金矿的主要成矿流体可能来源于岩浆热液或者变质热液。流体包裹体研究发现,商旭金矿主成矿阶段流体包裹

表 3 藏北双湖商旭金矿硫同位素组成

Table 3 The sulfur isotopic composition of the Shangxu gold deposit, Shuanghu County, north Xizang(Tibet)

样号	矿物	采样位置	载体	$\delta^{34}S_{V\text{-}CDT}$(‰)		资料来源
				测值	均值	
SX114	黄铁矿	班怒带商旭金矿	蚀变围岩	-0.6		本文
SX157	黄铁矿	班怒带商旭金矿	蚀变围岩	-1.3	-0.48	本文
SX160	黄铁矿	班怒带商旭金矿	蚀变围岩	2.2		本文
SX12-1-1	黄铁矿	班怒带商旭金矿	蚀变围岩	-3.1		裴英茹等, 2016
SX112	黄铁矿	班怒带商旭金矿	蚀变岩型矿体	-2.9		本文
SX113	黄铁矿	班怒带商旭金矿	蚀变岩型矿体	-2.9	-0.3	本文
SX147	黄铁矿	班怒带商旭金矿	蚀变岩型矿体	0.1		本文
SX148	黄铁矿	班怒带商旭金矿	蚀变岩型矿体	4.6		本文
SX115	方铅矿	班怒带商旭金矿	石英脉型矿体	-4.5		本文
SX116	方铅矿	班怒带商旭金矿	石英脉型矿体	-2	-3.8	本文
SX14-2-4(1)	方铅矿	班怒带商旭金矿	石英脉型矿体	-4.5		裴英茹等, 2016
SX14-2-4(2)	方铅矿	班怒带商旭金矿	石英脉型矿体	-4.2		裴英茹等, 2016
SX12-1-1	闪锌矿	班怒带商旭金矿	石英脉型矿体	-2.6	-1.8	裴英茹等, 2016
SX14-2-4	闪锌矿	班怒带商旭金矿	石英脉型矿体	-1.0		裴英茹等, 2016
	黄铁矿	班怒带达查金矿	蚀变岩型矿体	1.1~1.6	1.43	肖润等, 2002
	黄铁矿	西大别金城金矿	蚀变岩型矿体	-6.5~5.5	2.3	刘洪, 2012; 刘洪等, 2012, 2013a,b
地幔 $\delta^{34}S$ 值				-3~+3		Chaussidon et al., 1990
变质岩 $\delta^{34}S$ 值				-20~+20		Chaussidon et al., 1990
沉积岩 $\delta^{34}S$ 值				-40~+50		Chaussidon et al., 1990

表 4 藏北双湖县商旭金矿 Pb 同位素组成

Table 4 The Lead isotopic compositions in the Shangxu gold deposit, Shuanghu County, Northern Xizang(Tibet)

编号	测试物质	$\frac{n(^{206}Pb)}{n(^{204}Pb)}$	$\frac{n(^{207}Pb)}{n(^{204}Pb)}$	$\frac{n(^{208}Pb)}{n(^{204}Pb)}$	$\Delta\beta$	$\Delta\gamma$	资料来源
MG06	花岗岩	18.765	15.642	39.003	19.964	34.274	本文
MG08	花岗岩	18.790	15.640	39.053	19.643	32.211	本文
MG11	花岗岩	18.588	15.616	38.838	18.254	28.626	本文
XB05	花岗岩	18.914	15.651	39.050	20.433	25.415	本文
XB06	花岗岩	19.008	15.650	39.154	19.908	33.897	本文
XB07	花岗岩	19.169	15.651	39.115	20.067	32.691	本文
XB09	花岗岩	18.894	15.635	39.006	19.348	32.852	本文
XB10	花岗岩	18.805	15.648	39.054	19.694	30.555	本文
SX112	黄铁矿	18.528	15.639	38.748	20.112	33.357	本文
SX113	黄铁矿	18.447	15.632	38.659	19.667	31.260	本文
SX114	黄铁矿	18.471	15.649	38.711	20.800	32.934	本文
SX12-1-1	闪锌矿	18.350	15.640	38.570	20.222	29.357	裴英茹等, 2016
SX115	方铅矿	18.678	15.697	38.957	23.940	39.685	本文
SX116	方铅矿	18.443	15.645	38.692	20.548	32.613	本文
SX14-2-4(1)	方铅矿	18.690	15.700	38.980	24.136	40.299	裴英茹等, 2016
SX14-2-4(2)	方铅矿	18.680	15.690	38.960	23.483	39.765	裴英茹等, 2016
SX108	木嘎岗日群变质岩	18.970	15.660	39.260	21.526	47.772	本文
19-11b	木嘎岗日群变质岩	18.943	15.622	39.151	19.048	44.863	肖润等, 2002

注：$\Delta\beta=(\beta-\beta_M)/\beta_M\times1000$；$\Delta\gamma=(\gamma-\gamma_M)/\gamma_M\times1000$；$\beta$=样品的 $n(^{207}Pb)/n(^{204}Pb)$；γ=样品的 $n(^{208}Pb)/n(^{204}Pb)$；β_M=地幔的 $n(^{207}Pb)/n(^{204}Pb)=15.33$；$\gamma_M$=地幔的 $n(^{208}Pb)/n(^{204}Pb)=37.47$

体无子晶体(裴英茹等, 2015；肖万峰等, 2017)，成矿流体具有中低温、低盐度、低密度，富集 CO_2 等变质热液的特点(裴英茹等, 2015；肖万峰等, 2017)，而与典型的岩浆热液矿床成矿流体含多种子晶、高盐度的特征(陈衍景, 2006)相差较大。C 同位素分析结果含金石英脉流体包裹体中 CO_2 的 $\delta^{13}C_{PDB}$ 值范围为-17.8‰~-23.1‰，均值为-21.3‰，远离岩浆岩或者深源碳的范围(-9‰~-2‰, Taylor, 1986)，而位于沉积岩或者变质岩源有机碳(-30‰~-15‰, Taylor, 1986)范围内，表明商旭金矿成矿流体运移过程中，有变质围岩流体的加入。本矿区内虽未发现岩浆活动踪迹，然而笔者们在研究含金石英脉时代的过程中，在含金石英脉中发育大量的岩浆锆石，其时代(约 121 Ma❶)与成矿期热液锆石年龄(约 119 Ma❶)以及矿区以北的虾别错—木嘎岗日山一带发育早白垩世的中酸性岩体时代(约 122 Ma❶)一致，暗示着商旭地区深部可能存在早白垩世岩浆活动贡献了部分成矿流体。综上所述，笔者等认为变质热液应该为商旭金城成矿流体的主要贡献者，同时应还有深部岩浆热液的组分。

5.2 成矿物质来源

硫是金中低温搬运重要载体之一，研究硫的来源广泛应用于热液金矿床成矿物质来源和矿质的运移中(江思宏等, 2001；王莉娟等, 2006；胡庆成等, 2012；刘洪等, 2013a,b)，共生硫化物的 S 同位素研究常用于示踪含硫化热液矿床的成矿物质的来源。关于矿床中硫的来源的讨论，必须依据硫化物沉淀期间热液的总 S 同位素组成，含硫热液矿物中的 S 同位素($\delta^{34}S_{硫化物}$)主要受流体中的 S 同位素($\delta^{34}S_{流体}$)和沉淀时的温度、压力、pH 值、氧逸度以及矿物形成时体系开放或封闭程度等因素的制约(Ohmoto, 1997)。在高氧逸度条件下，当主要的硫为硫酸根离子时，可能的矿物组合为重晶石+方解石，此时 $\delta^{34}S_{硫化物}<\delta^{34}S_{热液}$；在低氧逸度条件下，不存在硫酸盐，可能的矿物组合为磁黄铁矿+黄铁矿+方铅矿+闪锌矿+石墨，则有 $\delta^{34}S_{硫化物}\approx\delta^{34}S_{热液}$(Ohmoto et al., 1997；郑永飞等, 2000)　商旭金矿床成矿流体研究(肖万峰等, 2017)表明，本矿床成矿流体为低氧逸度还原状态的富集 CO_2、N_2，并含少量 CH_4、CO 的 $CaCl_2$—NaCl—H_2O 体系流体；同时，商旭矿区矿物组合相对简单，无重晶石等硫酸盐矿物，硫化物主要为黄铁矿，同时还有少量毒砂、闪锌矿、方铅矿、磁黄铁矿及黄铜矿，并广泛发育石墨；此外，商旭矿床的同一成矿阶段的 $\delta^{34}S_{黄铁矿}>\delta^{34}S_{闪锌矿}>$

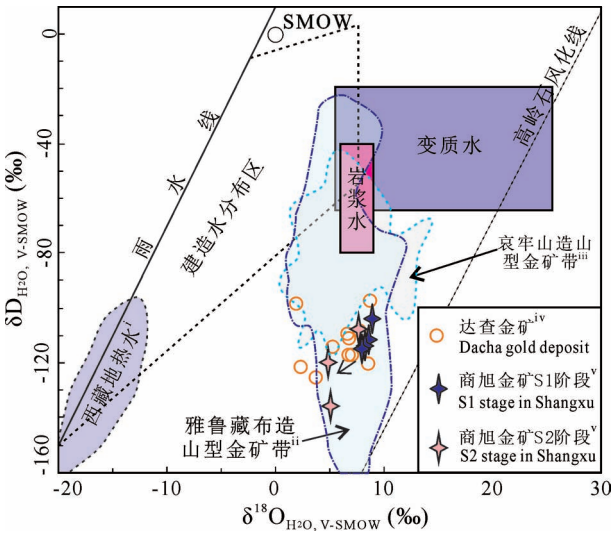


图 4 藏北双湖商旭、达查金矿床成矿流体的 $\delta^{18}O$—δD 图解(i 数据据郑淑蕙等, 1982; ii 数据据 Zhai Wei et al., 2014; Sun Xiaoming et al., 2016; Pei Yinru et al., 2016b; Zhang Xiong et al., 2017; 李华健等, 2017; iii 数据据石贵勇等, 2010; 李士辉等, 2011; Deng Biping et al., 2013; Chen Yaohuang et al., 2014; 李华健等, 2017; iv 数据据肖润等, 2002; v 据肖万峰等, 2017)

Fig. 8 Plot of $\delta^{18}O$ — δD for ore forming fluids from Shangxu and Dacha gold deposit, Shuanghu County, north Xizang (Tibet) (i form Zheng Shuhui et al., 1982&; ii Form Zhai Wei et al., 2014; Sun Xiaoming et al., 2016; Pei Yinru et al., 2016b; Zhang Xiong et al., 2017; Li Huajian et al., 2017&; iii form Shi Guiyong et al., 2010&; Li Shihui et al., 2011; Deng Biping et al., 2013; Chen Yaohuang et al., 2014; Li Huajian et al., 2017&; iv form Xiao Run et al., 2002&; v form Xiao Wanfeng et al., 2017&)

$\delta^{34}S_{方铅矿}$,其基本顺序与同位素平衡的富集顺序一致,表明 S 同位素达到平衡。因此笔者们用商旭金矿成矿热液期硫化物的 S 同位素值($\delta^{34}S_{硫化物}$)来代表成矿热液的 S 同位素值($\delta^{34}S_{热液}$)。成矿热液的 $\delta^{34}S_{V\text{-}CDT}$为-4.5‰ ~ 4.6‰(极差为 9.1‰,均值为-1.6‰)左右,这与西大别地区商南—丹凤缝合带内的金城造山型金矿(刘洪, 2012, 刘洪等, 2012, 2013a,b)矿石中硫化物 $\delta^{34}S$ 值(-6.9‰ ~ 5.5‰)以及班公湖—怒江缝合带中段的达查造山型金矿(肖润等, 2002)矿体中硫化物 $\delta^{34}S_{V\text{-}CDT}$(1.1‰ ~ 1.6‰)相近。自然界中 S 同位素主要为 4 个基本的来源(Ohmoto, 1972; Taylor, 1986; Chaussidon et al., 1990; 郑永飞等, 2000):①深源硫,其 $\delta^{34}S_{V\text{-}CDT}$ 在 0±3‰左右,变化范围小,多认为是上地幔源或地壳深部均一化的结果;②大洋海水,以富 ^{34}S 为特征,其 $\delta^{34}S_{V\text{-}CDT}$为较大正值;③沉积物中还原硫,与生物成因有关,以富 ^{32}S 为特征,其 $\delta^{34}S_{V\text{-}CDT}$为较大负值,可达-20‰;④混合成因的硫,这类 S 同位素数据特点为变化范围很宽,变质岩 $\delta^{34}S_{V\text{-}CDT}$值为-20 ~ +20‰,沉积岩 $\delta^{34}S$ 值为-50 ~ +50‰。对比以上 3 个端元,不难发现商旭金矿床成矿流体的 S 同位素变化($\delta^{34}S_{V\text{-}CDT}$=-4.5‰~+4.6‰,表 3,图 6),具有深源硫(地幔或下地壳,$\delta^{34}S_{V\text{-}CDT}$=-3‰~+3‰)的特征,这可能与深部的壳幔岩浆作用有关,而变化范围略大于深源硫,平均值($\delta^{34}S_{V\text{-}CDT}$=-1.6‰)偏向负值则可能反应了少量木嘎岗日群成矿物质的加入。

硫同位素等稳定同位素很易因水岩反应、相分离、氧化作用、多种流体混合等过程而发生同位素分馏,因此单个同位素很难有效判断成矿物质来源,综合多种同位素方法并结合矿区地质实际情况才能更

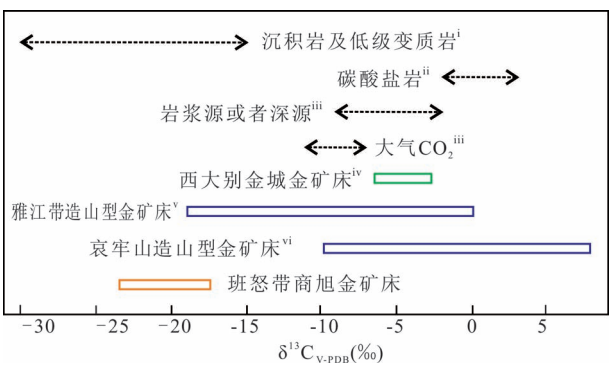


图 5 藏北双湖商旭金矿含金石英脉流体包裹体中 CO_2 的碳同位素组成(i 数据据 Ohmoto, 1972; ii 数据据 Veize et al., 1980; iii 数据据 Taylor, 1986; iv 数据据刘洪, 2012; 刘洪等, 2012, 2013a,b; v 数据据 Zhai Wei et al., 2014; Sun Xiaoming et al., 2016; Pei Yinru et al., 2016b; Zhang Xiong et al, 2017; 李华健等, 2017; vi 数据据石贵勇等, 2010; 李士辉等, 2011; Deng Biping et al., 2013; Chen yaohuang et al., 2014; 李华健等, 2017)

Fig. 5 The carbon isotopic composition of CO_2 in the fluid inclusions in auriferous quartz veins of the Shangxu deposit, Shuanghu County, north Xizang (Tibet) (i form Ohmoto, 1972; ii form Veize et al., 1980; iii from Taylor, 1986; iv from Liu Hong, 2012&; Liu Hong et al. 2012&, 2013a&, 2013b&; v from Zhai Wei et al., 2014; Sun Xiaoming et al., 2016; Pei Yinru et al., 2016b; Zhang Xiong et al., 2017; Li Huajian et al., 2017&; vi form Shi Guiyong et al., 2010&; Li Shihui et al., 2011; Deng Biping et al., 2013; Chen Yaohuang et al., 2014; Li Huajian et al., 2017&)

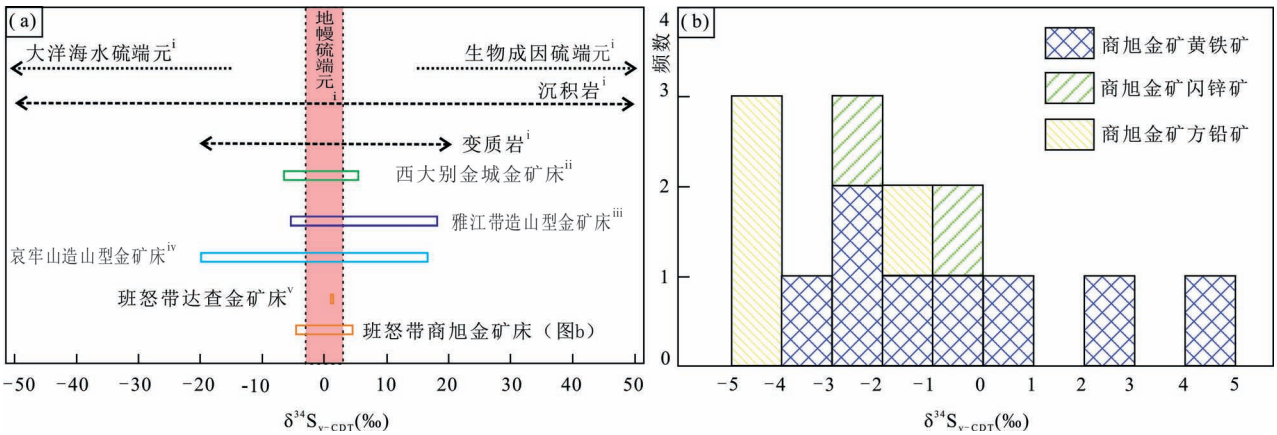


图 6 藏北双湖商旭金矿硫化物硫同位素组成图（i 数据据 Ohmoto, 1972; Taylor, 1986; Chaussidon et al., 1990; ii 数据据刘洪, 2012; 刘洪等, 2012, 2013a,b; iii 数据据 Zhai Wei et al., 2014; Sun Xiaoming et al., 2016; Pei Yinru et al., 2016b; Zhang Xiong et al., 2017; 李华健等, 2017; iv 数据据石贵勇等, 2010; 李士辉等, 2011; Deng Biping et al., 2013; Chen Yaohuang et al., 2014; 李华健等, 2017; v 数据据肖润等, 2002）

Fig. 6 The sulfur isotopic composition of the sulfides in the Shangxu deposit, Shuanghu County, north Xizang (Tibet) (i form Ohmoto, 1972; Taylor, 1986; Chaussidon et al., 1990; ii Liu Hong, 2012&; Liu Hong et al. 2012&, 2013a&,2013b&; iii from Zhai Wei et al., 2014; Sun Xiaoming et al., 2016; Pei et al., 2016b; Zhang Xiong et al., 2017; Li Huajian et al., 2017&; iv form Shi Guiyong et al., 2010&; Li Shihui et al., 2011; Deng Biping et al., 2013; Chen Yaohuang et al., 2014; Li Huajian et al., 2017&; v form Xaio run et al., 2002)

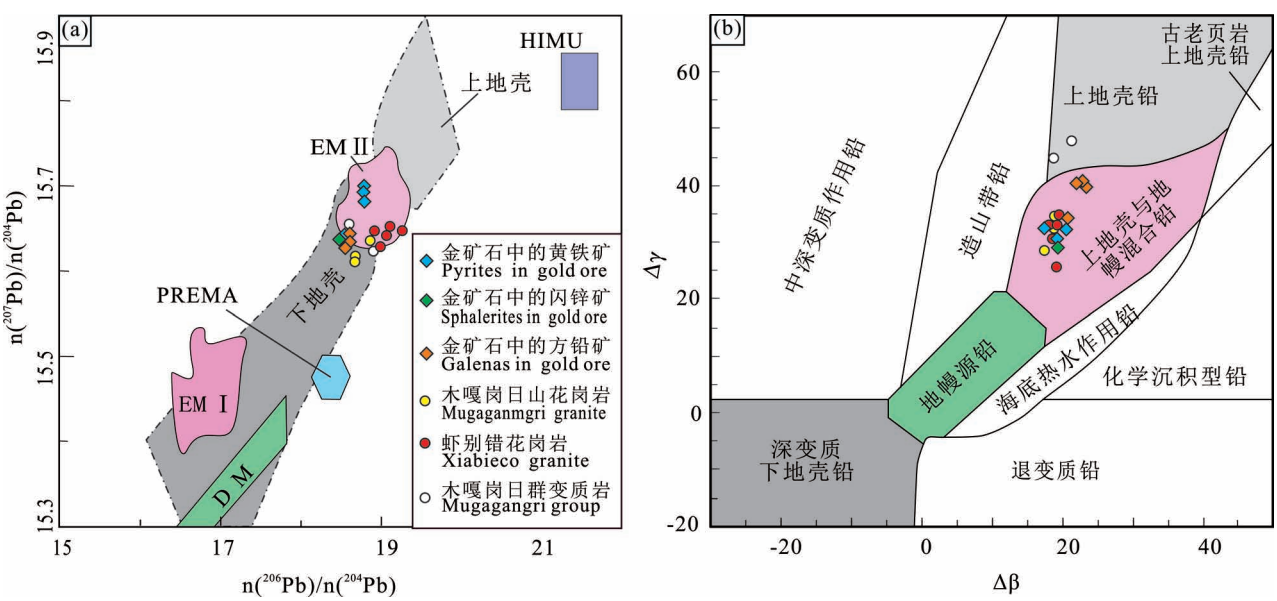


图 7 藏北双湖商旭金矿 Pb 同位素构造模式图

［(a) 底图据 Zartman et al., 1981; Wilson et al., 1989; Miller et al., 1999 修改; (b) 底图据朱炳泉, 1998 修改］

Fig. 7 Structural model for lead isotope in the Shangxu deposit, Shuanghu County, north Xizang (Tibet) [(a) Base-map modified from Zartman et al., 1981; Wilson et al., 1989; Miller et al., 1999; (b) Base-map modified from Zhu Bingquan, 1998#]

DM—亏损地幔; EM Ⅰ— Ⅰ型富集地幔; EM Ⅱ—Ⅱ型富集地幔; MORB—洋中脊玄武岩; PREMA—普通地幔; BSE—整个硅酸盐地球; HIMU—高 μ 地幔; $\Delta\beta=(\beta-\beta_M)/\beta_M\times1000$; $\Delta\gamma=(\gamma-\gamma_M)/\gamma_M\times1000$; β=样品的 $n(^{207}Pb)/n(^{204}Pb)$; γ=样品的 $n(^{208}Pb)/n(^{204}Pb)$; β_M=地幔的 $n(^{207}Pb)/n(^{204}Pb)=15.33$; γ_M=地幔的 $n(^{208}Pb)/n(^{204}Pb)=37.47$

DM—Depleted Mantle; EM Ⅰ—Type Ⅰ Enriched Mantle; EM Ⅱ—Type Ⅱ Enriched Mantle; MORB—Mid-Ocean Ridge Basalt; PREMA—Ordinary Mantle; BSE—Silicate Earth; HIMU—Highμ Mantle; $\Delta\beta=(\beta-\beta_M)/\beta_M\times1000$; $\Delta\gamma=(\gamma-\gamma_M)/\gamma_M\times1000$; $\beta=n(^{207}Pb)/n(^{204}Pb)_{sample}$; $\gamma=n(^{208}Pb)/n(^{204}Pb)_{sample}$; $\beta_M=n(^{207}Pb)/n(^{204}Pb)_{Mantle}=15.33$; $\gamma_M=n(^{208}Pb)/n(^{204}Pb)_{Mantle}=37.47$

好地约束热液型矿床的成矿物质来源。不同放射成因 Pb 同位素反映不同地质环境和物质组成(Zartman et al., 1981; Wilson et al., 1989;朱炳泉, 1998; Miller et al., 1999),可作为物质来源的示踪计。在 Pb 同位素构造模式图(图 7a)上,商旭金矿主成矿阶段共生硫化物与下—中侏罗统木嘎岗日群以及早白垩世虾别错—木嘎岗日山花岗岩的 Pb 同位素组成非常靠近,数据点都落在Ⅱ型富集地幔(EMⅡ)中及附近;在 Δβ—Δγ 成因判别图解上(图 7b),商旭金矿床主成矿阶段共生硫化物 Pb 同位素大部分投点主要落在上地壳与地幔混合的俯冲带铅范围内,和早白垩世虾别错—木嘎岗日山花岗岩较为一致,反映出商旭金矿床与同时代的早白垩世虾别错—木嘎岗日山花岗岩具有一致的 Pb 源,同时,商旭金矿床的 Pb 同位素投点不完全与虾别错—木嘎岗日山花岗岩一致,而向下—中侏罗统木嘎岗日群有一定的漂移(图 7b),暗示着商旭金矿的 Pb 源还有木嘎岗日群物质的加入。

基于前面建立的成矿流体和物质来源分析笔者们认为,该矿床的初始成矿流体为来自壳幔作用分异的深部岩浆流体;岩浆流体携带着深部的成矿物质沿区域大型剪切带上涌到浅部的下—中侏罗统木嘎岗日群时,又有大量来自地层的变质流体的加入,同时携带来了部分成矿物质;最后,成矿流体在 NWW 向的脆韧性构造中沉淀富集成矿。

6　结论

(1)商旭金矿的初始成矿流体为深部的岩浆热液,并向上运移到浅部的木嘎岗日群后有大量的变质流体的加入,使得商旭金矿成矿流体主要表现为变质流体的特征。

(2)商旭金矿的成矿物质部分来自深部壳幔岩浆作用,并被成矿热液携带至浅部,同时木嘎岗日群围岩也贡献了部分成矿物质,随着地层中的变质热液加入到成矿流体中。

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注　释 / Note

❶ 中国地质调查局成都地质调查中心. 2017. 西藏双湖商旭金矿调查评价成果报告.

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Sources of Ore-forming Materials in the Shangxu Orogenic Gold Deposit, Northern Xizang(Tibet): Constraints form C, S, and Pb Isotopes

LIU Hong[1)], LI Guangming[1)], HUANG Hanxiao[1)], XIAO Wanfeng[2)], YAN Guoqiang[3)], MA Dongfang[1)], ZHANG Hai[1)], ZHANG Hong[1)]

1) *Chengdu Center, China Geological Survey, Chengdu*, 610081;

2) *Henan Institute of Geological Survey, Zhengzhou*, 450001;

3) *Tianjin Center, China Geological Survey, Tianjin*, 300170

Objectives: The Shangxu gold deposit in the Shuanghu County, Xizang(Tibet), is located in the central segment of the Bangong Lake — Nujiang River suture. The deposit is controlled by EW-trending faults, and is hosted in melange of the Middle—Lower Jurassic Mugagangri Group. In this study we focus on the sources of ore-forming materials in the Shangxu orogenic gold deposit, was beneficial for the study of genesis for the ore deposit, and provide new constraints for understanding the dynamic background of orogenic gold metallization in the Bangong Lake — Nujiang River suture.

Methods: In this study, the Carbon isotopes of the CO_2 inclusions in ore-stage quartz, and the sulfur and lead isotopes of sulfides are analyzed for discuss the sources of ore-forming materials in the Shangxu orogenic gold deposit.

Results: The $\delta^{13}C_{CO_2(V\text{-}PDB)}$ values of fluid inclusions range from -17.8‰ to -23.1‰, with a mean of -21.3%, which is similar to that of the sedimentary or metamorphic rocks. This indicate that the ore-forming fluids of the Shangxu gold deposit may originated from the Mugagangri Group. Meanwhile, a few magmatic zircons, which yield the same U-Pb age with the Xiabie Co - Mogagangri San granite, are detected in auriferous quartz veins, suggesting that the magmatic hydrothermal fluids may have been involved during the ore-forming process. The $\delta^{34}S_{V\text{-}CDT}$ values of sulfides vary from -4.5‰ to 4.6‰, with a mean of -1.6‰, which is characteristic of a deep sulfur source, The Pb isotopic compositions of the sulfides($n(^{206}Pb)/n(^{204}Pb)=18.350\sim18.690$, $n(^{207}Pb)/n(^{204}Pb)=15.632\sim15.700$, $n(^{208}Pb)/n(^{204}Pb)=38.570\sim38.980$) are similar to those of the Xiabie Co - Mogagangri San granite($n(^{206}Pb)/n(^{204}Pb)=18.558\sim19.169$, $n(^{207}Pb)/n(^{204}Pb)=15.616\sim15.651$, $n(^{208}Pb)/n(^{204}Pb)=38.838\sim39.154$) and slightly drifting to the Jurassic Mugagangri Group ($n(^{206}Pb)/n(^{204}Pb)=18.630\sim18.970$, $n(^{207}Pb)/n(^{204}Pb)=15.619\sim15.673$, $n(^{208}Pb)/n(^{204}Pb)=38.887\sim39.260$), implying that Pb in the Shangxu gold deposit may have been sourced from the magmatic activity in Early Cretaceous, with minor contribution from the Mugagangri Group.

Conclusions: According to the above discussions, we suggest that the ore-forming materials of the Shangxu gold deposit were mainly derived from deep crustal — mantle magmatism, and were carried by deep-seated fluids to the shallow crust. The Mugagangri Group also contributed part of the ore-forming materials, which were brought by the metamorphic hydrothermal fluids.

Keywords: Xizang(Tibet); Bangong Lake — Nujiang River suture zone; Shangxu gold deposit; orogenic gold deposits; source of ore-forming materials; stable Isotope

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First author: LIU Hong, male; born in 1987 in Chongqing City; master; graduated from China University of

Geosciences (wuhan); engineer of Chengdu Center, China Geological Survey. He is now interested in the study on metallogeny and exploration. Email: cugliu@foxmail.com

Corresponding author: HUANG Hanxiao, male; born in 1982 in Mianyang City; master; graduated from Chinese Academy of Geological Sciences; senior engineer of Chengdu Center, China Geological Survey. He is now interested in the study on metallogeny and exploration. Email: hanxiaohuang@126.com

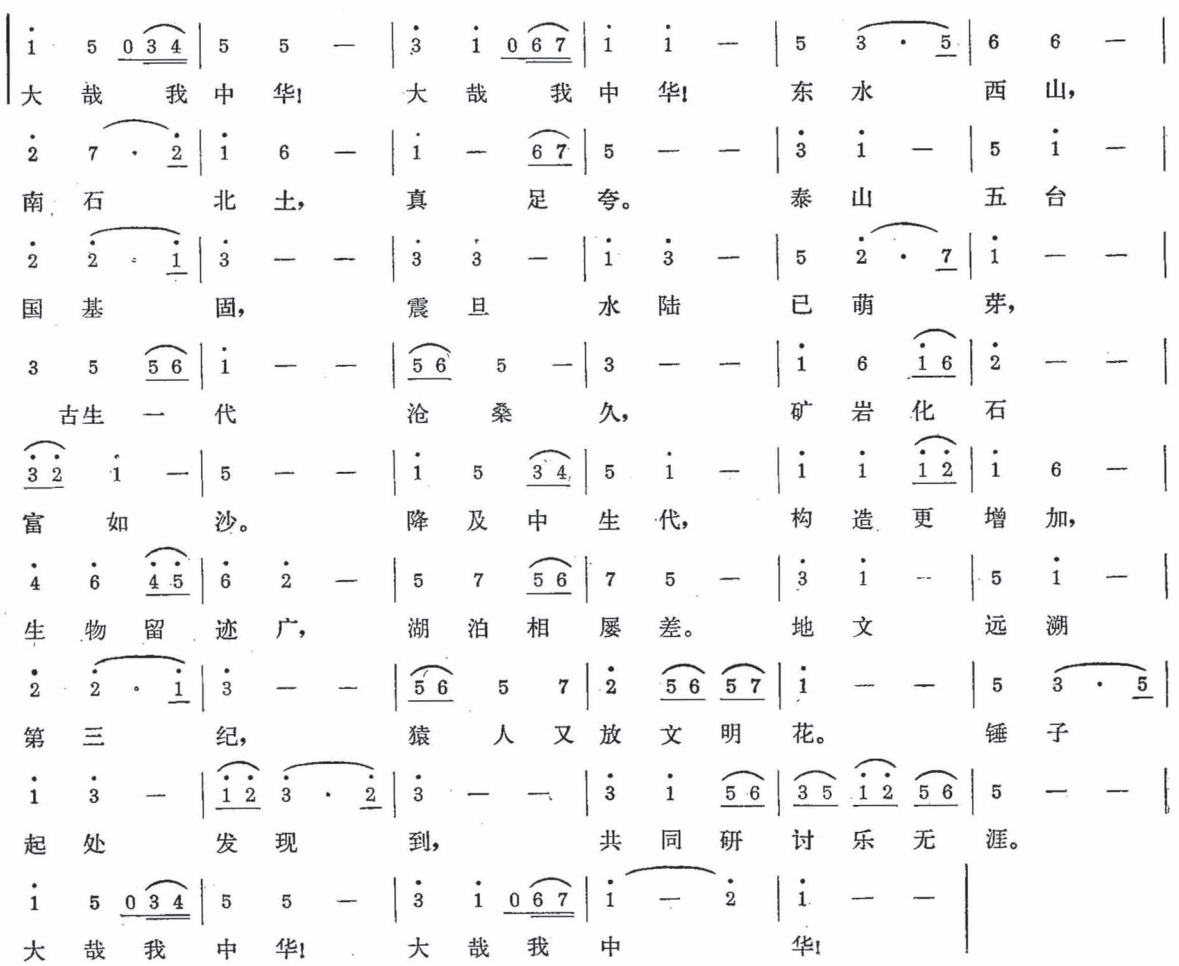
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