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滇东北金牛厂铅锌矿床成矿模式：来自流体包裹体、H-O-S-Pb同位素证据

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摘　要：金牛厂铅锌矿床是川滇黔铅锌多金属成矿区滇东北矿集区内产于下寒武统筇竹寺组泥质、钙质粉砂岩中的铅锌矿床，属于非碳酸盐岩容矿的后生热液矿床。区内赋矿地层筇竹寺组Pb、Zn含量异常高，而矿石Pb同位素组成与基底岩石(昆阳群)基本一致，矿源层是基底还是筇竹寺组、该矿床与区内其他赋存于碳酸盐岩中的铅锌矿床成矿机理是否具有一致性，直接关系到铅锌成矿系统研究与矿床深部找矿预测。基于流体包裹体测温及硫化物H-O-S-Pb同位素组成分析，结果表明：1) 流体包裹体均一温度为165~274 ℃，平均216 ℃；盐度为6.5%~14.0%$NaCl_{eqv}$，平均值为7.8%$NaCl_{eqv}$，指示成矿流体属于中低温−中低盐度的富气相流体；显微激光拉曼光谱分析显示流体包裹体的液相成分主要为H_2O，气相成分主要为CH_4；2) 脉石矿物石英的H、O同位素特征表明，成矿流体主要来源于流经深部褶皱基底(昆阳群)的深部流体和含有机质的盆地卤水的混合；3) 硫化物$\delta^{34}S$值与川滇黔成矿区内主要铅锌矿床具有相似性，其还原S主要来源于下伏地层震旦系灯影组和下寒武统渔户村组白云岩中硫酸盐的热化学还原硫作用(TSR)过程；4) 硫化物的Pb同位素组成不仅与基底岩石的铅同位素比值一致，且沿上地壳Pb平均演化线呈直线分布，表明壳源Pb源主要来自基底岩石(昆阳群)，赋矿围岩下寒武统筇竹寺组碎屑岩也贡献了部分Pb。结合矿床对比研究，认为该矿床和川滇黔成矿区内主要铅锌矿床是在同一成矿地质背景下形成，具有相似的成矿模式，但在赋矿围岩、赋矿断裂性质、矿质来源等方面存在自身的特点。该研究可为川滇黔成矿区内铅锌成矿系统研究提供依据，也为该区矿床深部及外围找矿提供新思路。

关键词：流体包裹体测温；H-O-S-Pb同位素；成矿物质来源；成矿模式；金牛厂铅锌矿床

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川滇黔铅锌多金属成矿区(包括川西南、滇东北和黔西北矿集区)位于扬子地块西南缘，是华南低温成矿域的重要组成部分[1−2]，也是我国最大铅锌基地的核心区和最具找矿潜力的成矿区。滇东北

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矿集区展布于南北向小江深断裂带、北西向紫云–垭都深断裂带及北东向弥勒–师宗深断裂带所围成的“三角区”内，因多期次构造活动叠加复合、地质环境多变、成矿动力学机制复杂和成矿地质条件优越，形成了我国独具特色的富锗铅锌多金属矿集区(见图 1)，也成为矿床学研究的热点地区。区内大多数铅锌矿体赋存于震旦系上统灯影组、泥盆系宰格组和石炭系摆佐组、威宁组及二叠系下统茅口组的碳酸盐岩和少量硅质碳酸盐中[3−4]。近年来众多学者针对该区内矿床的成因、物质来源、成矿时代、成矿动力学背景等方面开展了较深入的研究，取得丰硕成果。在矿床成因方面，前人从不同侧重点开展了研究，并提出了不同的观点, 大多数学者的观点为密西西比河谷型(MVT)和沉积为主导的层控型[3, 5−10]；韩润生等提出了会泽型(HZT), 建立了以“构造–流体‘贯入’成矿”模型[4]，在此基础上提出了陆内走滑构造系统控矿–流体贯入成矿论[11]。在成矿物质来源研究方面，存在诸多不同认识：1) 主要来源于区域中元古代基底岩石[8, 11−13]；2) 由碳酸盐岩地层和峨眉山玄武岩共同提供[3, 14−15]；3) 主成矿元素主要来源于中元古代基底地层及震旦系–石炭系沉积岩地层的混合[16−19]。由此可见，区内铅锌矿床成因还需进一步探讨。

金牛厂铅锌矿床位于滇东北矿集区北东向金牛厂–矿山厂构造带上，矿体赋存于下寒武统筇竹寺组泥质、钙质粉砂岩中，赋矿围岩明显不同于川滇黔成矿区内绝大多数铅锌矿床的赋矿围岩(碳酸盐岩)。虽然前人对区内碳酸盐岩容矿的铅锌矿床成矿机理开展了大量研究，但是该矿床成矿物质来源和成矿机理研究不仅基本未涉及，而且与区内其他铅锌矿床成矿机理是否具有一致性，还是重要的科学问题，这直接关系到该区铅锌成矿系统研究和矿床深部及外围找矿预测。故本文基于流体包裹体测温、共生脉石矿物和金属硫化物 H-O-S-Pb 同位素

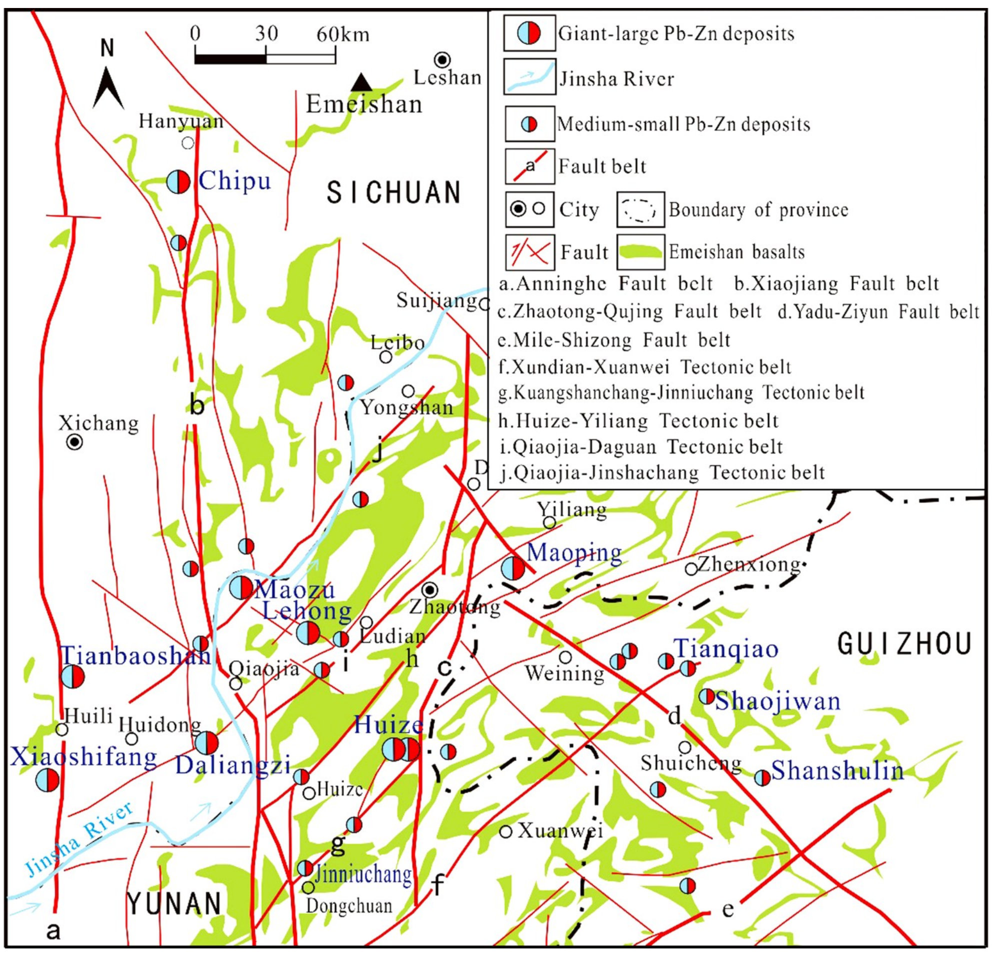

图 1　川滇黔铅锌成矿区主要断裂及矿床分布图[3]

Fig. 1　Distribution map of main faults and deposits in Sichuan－Yunnan－Guizhou Pb-Zn metallogenic triangle area[3]

组成分析，示踪金牛厂铅锌矿床成矿流体和主要矿质来源，为区域成矿机制研究提供新认识，并结合川滇黔成矿区内碳酸盐岩中的铅锌矿床的对比分析，建立矿床成矿模式，揭示与区内其他矿床矿源的异同性，为区内铅锌成矿系统研究和深部及外围找矿提供新思路。

1 区域地质概况

川滇黔铅锌多金属成矿区地处扬子地块西南缘，区域上主要由南北向的安宁河断裂、北西向的康定−彝良−水城断裂、北东向的弥勒−师宗断裂3条边界深大断裂控制。其中构造主要发育多条南北向断裂，配套北东向和北西向次级断裂和褶皱[20]。滇东北矿集区内主要发育八条受北东向构造控制的斜冲走滑−断褶带[11]，它们呈“多”字型展布, 具典型的滇东北“多”字型构造型式[21](见图1)。

川滇黔铅锌多金属成矿区的地层主要由基底与沉积盖层组成。基底地层主要由太古代−早元古代的结晶基底和中元古代的褶皱基底组成[13]。区内昆阳群(会理群)构成褶皱基底，主要由弱变质的海相火山岩和沉积岩组成。新元古代至中生代早期沉积了厚层的海相沉积岩。其中，震旦系主要为厚层白云岩；寒武系以页岩、砂岩为主；奥陶系−志留系主要由碳酸盐岩和泥质粉砂岩、页岩组成；泥盆系主要为砂岩、粉砂岩和碳酸盐岩；石炭系−二叠系以碳酸盐岩和玄武岩为主；三叠系主要为灰岩夹泥灰岩和页岩。晚三叠世时，古特提斯洋闭合和造山事件，在区内前陆盆地诱发强烈的斜冲走滑作用, 形成一系列斜冲走滑−断褶带[21]。区内的侵入岩主要沿安宁河断裂和甘洛−小江断裂呈带状展布，从南到北有晋宁期、澄江期花岗岩，海西期层状基性−超基性岩和印支期碱性、酸性花岗岩出露。火山岩澄江期以中酸性夹基性火山岩、火山碎屑岩为主；印支期以发育大面积的峨眉山玄武岩为特征[22]，其喷发时代为263~251 Ma[23]。

区内成矿构造系统复杂，控制了铅锌矿床广泛分布(见图1)。川西南地区分布的南北向左行走滑断裂(如小江断裂、安宁河断裂等)及其次级构造控制了大梁子、天宝山、茂租、赤普等矿床的分布；滇东北地区北东向斜冲走滑−断褶构造控制了会泽、毛坪等一系列铅锌矿床分布，其中金牛厂铅锌矿位于北东向金牛厂−矿山厂构造带上；黔西北地区北西向斜落走滑断裂(垭都−蟒硐、威宁−水城深断裂)及配套的次级构造控制了猪拱塘、天桥、筲箕湾、杉树林、青山等铅锌矿床分布。滇东北矿集区的铅锌矿床主要赋存于中元古界浅变质板岩[24]、新元古代至二叠纪碳酸盐岩中，矿体呈层状、透镜状和脉状，受斜冲断裂带控制；矿石矿物主要为闪锌矿和方铅矿，含少量黄铁矿毒砂、黄铜矿和斑铜矿，而脉石矿物为方解石、白云石和石英。围岩蚀变包括白云石化、方解石化、硅化和黄铁矿化[24]。

2 矿区地质与矿床地质

2.1 矿区地质

金牛厂矿区位于矿山厂−金牛厂构造带的南端，北东向坪箐倒转背斜和关仓箐断裂、雨碌断裂、待补断裂组成了矿区的基本格架，关仓箐断裂发育于坪箐背斜的轴部偏西，破坏了背斜的完整性，在关仓箐断裂北西盘上，发育了北西西向次级羽状断裂(见图2(a))。其中：1) 坪箐背斜，为北东向轴向、轴面倾向北西的不对称长轴状背斜，南端被金牛厂断裂切失，中部被关仓箐断裂切割破坏。核部由震旦系灯影组组成，两翼向外为下寒武统渔户村组、筇竹寺组、沧浪铺组，至上二叠系玄武岩组，北西翼岩层倾角在28°~35°之间，南东翼渔户村组，筇竹寺组和沧浪铺组地层发生倒转。2) 雨碌断裂(F_1)，为一条与待补断裂同级别的主断裂，北东部与矿山厂断裂相连，南西端交于待补断裂上盘，走向40°，矿区内倾向南东，倾角58°~70°之间，往北东延伸方向倾角逐渐变陡，最终转变为倾向北西，断裂沿线见角砾岩、破碎带及糜棱岩，角砾成分主要为围岩，显示多期活动特征，压扭性力学性质突出。关仓箐断裂(F_2)长20 km，走向25°~65°之间，倾向总体为南东，局部地段为北西，倾角50°~75°之间，断裂带沿线见白云质角砾岩、破碎带、糜棱岩及褐铁矿化，为一压扭性断裂。3) 待补断裂(F_3)，为一条区域性主断裂，北东部与麒麟厂断裂相连，走向40°，矿区内倾向为北西，倾角在65°~75°之间；往

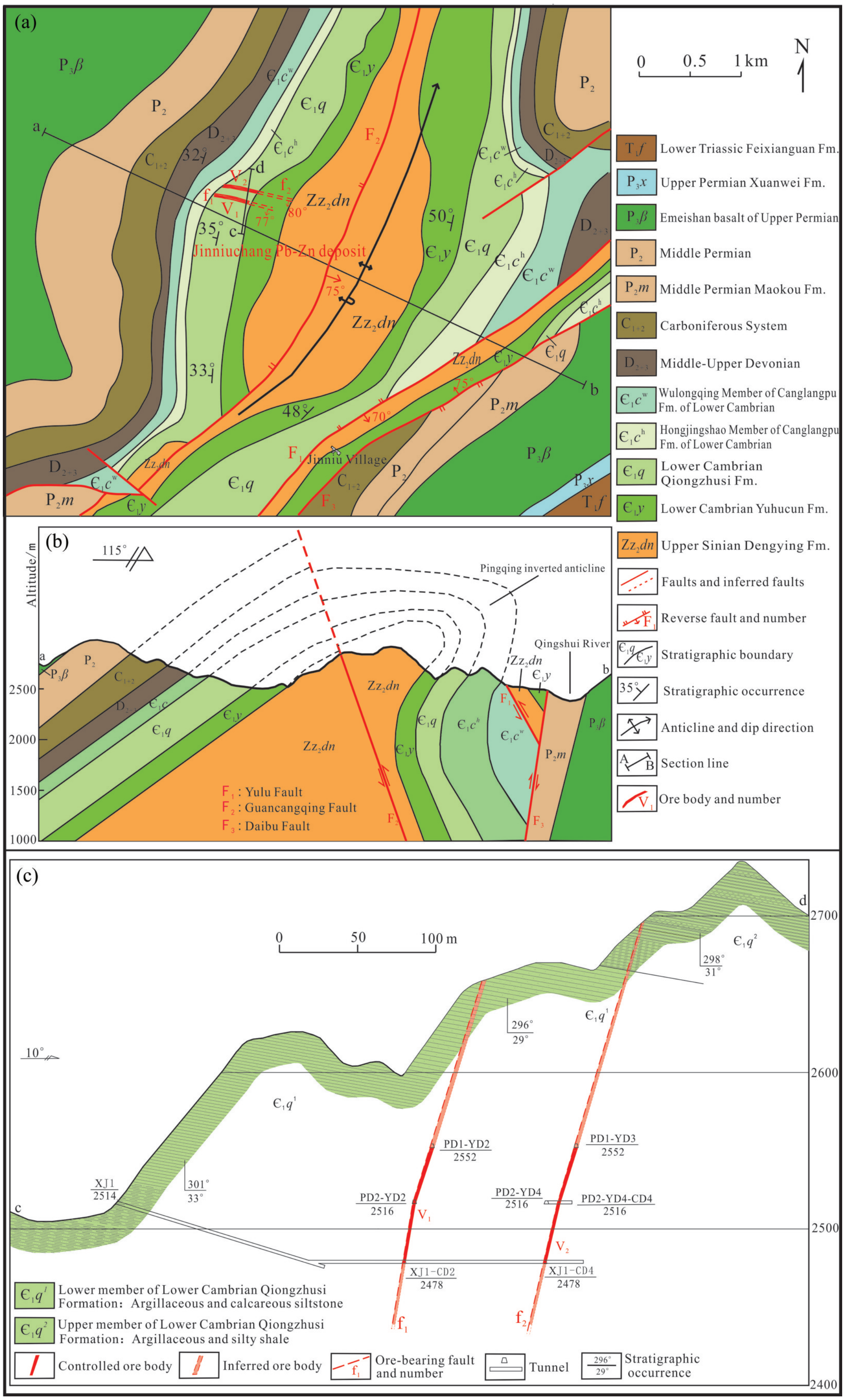

图 2　金牛厂铅锌矿区地质图、矿区构造样式图和矿床勘探线剖面图

Fig. 2　Geological map(a), structure style map(b) and exploration line section(c) of Jinniuchang Pb-Zn deposit

北东延伸方向倾角逐渐变陡，最终转变为倾向南东。断裂沿线见角砾岩、破碎带及糜棱岩，角砾成分主要为围岩，显示出多期活动特征，压扭性力学性质突出(见图2(b))。

矿区出露地层从老至新为：震旦系灯影组(Zz_2dn)、下寒武统渔户村组($Є_1y$)、下寒武统筇竹寺组($Є_1q$)、下寒武统沧浪铺组($Є_1c$)、中泥盆统海口组(D_2h)、上泥盆统宰格组(D_3zg)、下石炭统大塘组(C_1d)、下石炭统摆佐组(C_1b)、上石炭统(C_2)、中二叠统梁山组(P_2l)、中二叠统栖霞组(P_2q)、中二叠统茅口组(P_2m)、上二叠统峨眉山玄武岩组($P_3\beta$)、上二叠统宣威组(P_3x)和下三叠统飞仙关组(T_1f)。其中筇竹寺组下段泥质、钙质粉砂岩为其赋矿层位；上覆地层为下寒武统筇竹寺组上段的泥质、粉砂质页岩，底部含炭质层；下伏地层为下寒武统渔户村组和震旦系灯影组的白云岩。矿区出露的岩浆岩主要为峨眉山玄武岩。其围岩蚀变主要有黄铁矿化、方解石化和硅化(见图2(a))。

2.2 矿床地质特征

在该矿床目前已发现具一定规模的2条铅锌矿体，产于下寒武统筇竹寺组($Є_1q$)的灰色、灰黑色中至厚层状泥质、钙质粉砂岩中，矿体分别充填于北西西向张(扭)性断裂(f_1和f_2)中。V_1号矿体赋存于f_1断裂破碎带之中，走向北西60°~80°，倾向南西，局部地段反转，倾角75°~80°。矿体呈脉状、透镜状，已控制矿体长200 m，延深120 m，厚度0.7~2.5 m，Pb+Zn平均品位8.0%，保有Pb+Zn金属量24779 t；V_2号矿体赋存于f_2断裂破碎带之中，走向北西60°~80°，倾向南西，局部地段反转，倾角70°~80°，矿体呈脉状、透镜状，已控制矿体长217 m，延深120 m，厚度0.5m~3m，Pb+Zn平均品位9.31%，保有Pb+Zn金属量28075 t(见图2(c))。矿石以硫化矿石为主，金属矿物主要为方铅矿，其次为黄铁矿、闪锌矿、黄铜矿，脉石矿物主要为石英，其次为方解石。矿石结构主要有包含结构、交代结构、他形粒状结构和填隙结构等；矿石构造主要有角砾状、条带状、浸染状、脉状、块状构造等(见图3(a)~(c))。

该矿床经历了热液成矿期和表生期。热液成矿期形成了两种主要的矿物组合(见图4)：早成矿阶段的黄铜矿−黄铁矿−方铅矿−闪锌矿−石英组合，黄铁矿交代黄铜矿，方铅矿充填和交代黄铁矿和石英(见图3(f))，且闪锌矿被方铅矿交代呈“孤岛”或“港湾”结构(见图3(d))；成矿晚阶段的方铅矿−黄铁矿−闪锌矿−石英组合，闪锌矿交代早阶段黄铁矿和方铅矿，石英交代和充填闪锌矿(见图3(e))；石英交代早阶段方铅矿和闪锌矿，黄铁矿呈星点状充填于石英空隙中(见图3(d))。

3 样品特征及分析方法

3.1 样品采集

本次在矿区2552 m和2516 m两个中段采集了7件具代表性的原生金属硫化物矿石，并分别挑选方铅矿7件、黄铁矿4件、闪锌矿1件，石英3件。7件矿石样品磨制双面抛光的流体包裹体片(厚度约200 μm)，通过矿相学和流体包裹体岩相学的观察，选取具有代表性的3件包裹体片中25个包裹体进行显微热力学分析。

3.2 分析测试方法

显微测温、单个包裹体成分激光拉曼显微探针测试是在有色金属矿产地质调查中心西南地质调查所（昆明理工大学）流体实验室完成。其中，显微测温仪器为英国Linkam公司THMS 600型冷热台和配有成像分析系统的标准显微镜。实验之前，用国际人工合成流体包裹体标样对冷热台进行了校正。在低温(＜0 ℃)和高温(＞200 ℃)条件下，仪器误差分别为±0.1 ℃和±2 ℃。单个包裹体成分激光拉曼显微探针测试的仪器为英国Renishaw plc公司生产的Renishaw inVia显微共焦激光拉曼光谱仪。

金属硫化物单矿物经手工逐级破碎，过筛至粒径为250~380 μm，在双目镜下手工分离出高纯度的单矿物，纯度大于99%，将挑选出的12件金属硫化物单矿物样品和3件石英单矿物样品分别在玛瑙钵内研磨至75 μm以下和250 μm，然后送实验室分析。H、O、S、Pb同位素测试均在北京科荟测试技术有限公司完成。测试过程和条件如下。

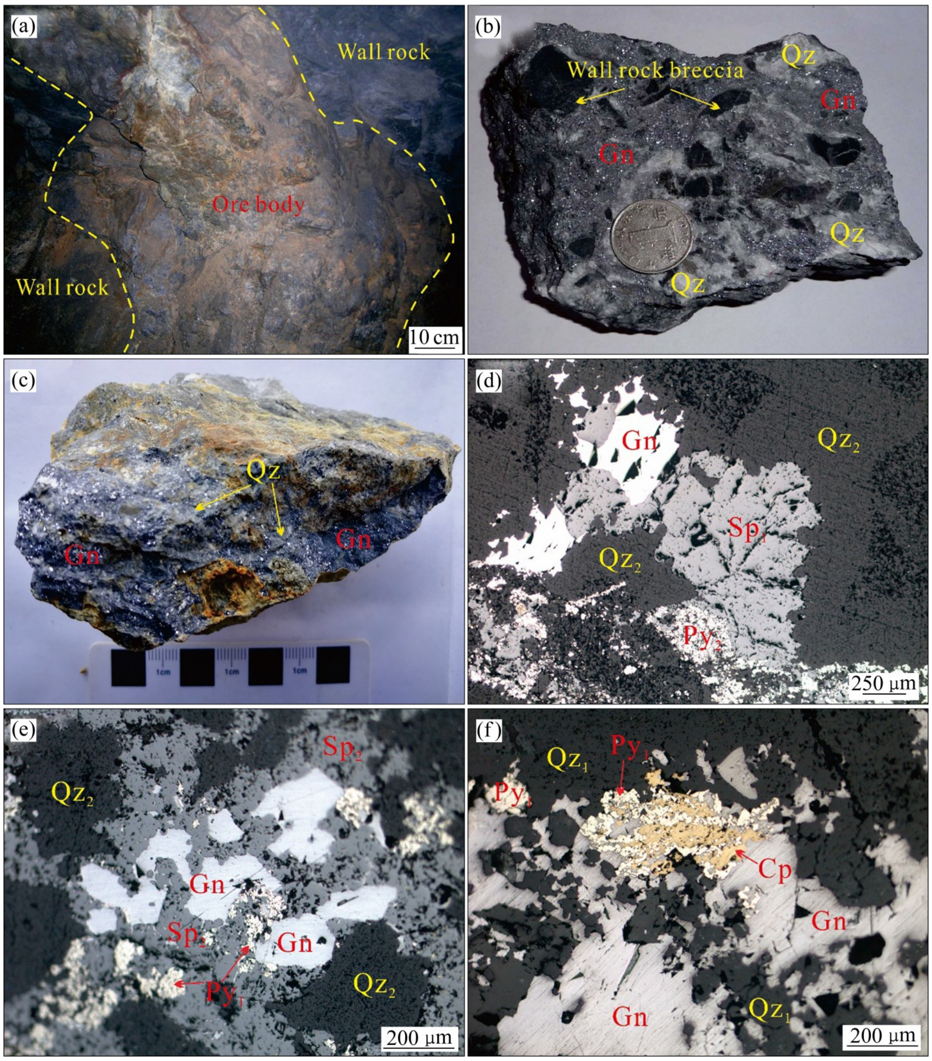

图 3　金牛厂铅锌矿矿体野外照片及矿石显微照片

Fig. 3　Field photos of ore bodies and ore photomicrographs of Jinniuchang Pb-Zn deposit: (a) Boundary between wall rock and ore body in siltstone of Lower Cambrian Qiongzhusi Formation ($\epsilon_1 q$); (b) Breccia ore; (c) Lump ore; (d) Coarse-grained sphalerite+galena+fine-grained pyrite+quartz; (e) Fine-grained pyrite+galena+coarse-grained sphalerite+quartz; (f) Chalcopyrite+fine-grained pyrite+galena+quartz; Gn—Galena; Py_1—Early stage pyrite; Py_2—Late stage pyrite; Sp_1—Early stage sphalerite; Sp_2—Late stage sphalerite; Cp—Chalcopyrite; Qz_1—Early stage quartz; Qz_2—Late stage quartz

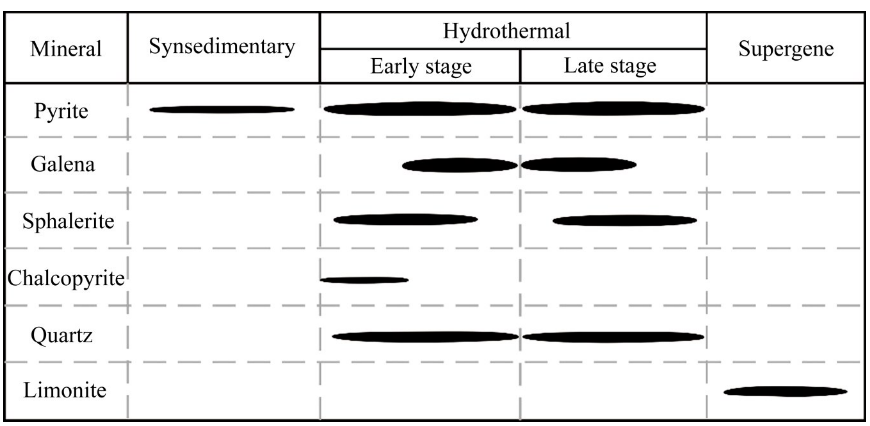

图 4　金牛厂铅锌矿床成矿阶段划分

Fig. 4　Division of metallogenic stages of Jinniuchang Pb-Zn deposit

1) S同位素测定

测试所用仪器设备为美国热电公司的253plus、Flash EA元素分析仪和Conflo IV多用途接口。S同位素分析是将样品通过充分燃烧进行氧化反应，产生的所有气体通过分层充填WO_3和Cu丝的氧化还原反应管，使所有气体充分氧化，同时使生成的少量SO_3通过Cu丝时还原为SO_2，气体通过一根色谱柱将SO_2和其他杂质气体分开后进入质谱仪测试；采用IAEA-S3、GBW04414和GBW04415三种标准物质，标样的分析精度优于0.2‰。

2) Pb同位素测试

样品先用HF+HNO_3混合酸分解，待样品消解完成后，将样品蒸干，加入浓硝酸再次蒸干，去除样品中的F离子，并将样品转化成氯化物，该氯化物样品再用1 mL浓度为2 mol/L的盐酸溶解，然后用树脂交换法分离出Pb，蒸干后用热表面电离质谱法进行Pb同位素测量，全过程实验室流程本底Pb为1×10^{-10} g。仪器型号为GV ISOPROBE−T，Pb同位素采用静态多接收方式测量。

3) 包体H同位素测试

称取10~20 mg粒径为250~380 μm的石英单矿物，和锡杯一同放置在90 ℃的烘箱中干燥12 h，以去除矿物表面的吸附水。烘烤后以锡杯包裹的样品由自动进样器送入填装了玻璃碳粒的高温(1420 ℃)裂解炉中(Flash EA, Thermo)，矿物包体水裂解释放后与玻璃碳瞬间反应生成H_2和CO，被高纯氦气(99.999%)携载经过色谱柱进入质谱仪(253 plus, Thermo)测定H_2的同位素比值δD。国际标准物质(聚乙烯, IAEA-CH-7, $\delta D_{V\text{-}SMOW}$=−100.3‰)的测试精度优于1‰[25]。

4) O同位素测试

将样品研磨并过筛至粒径为75 μm，称取6 mg纯净的石英样品或相当氧含量的硅酸盐矿物，放置在105 ℃的烘箱中烘烤12 h。对硅酸盐样品的O同位素分析则采用传统的BrF_5分析方法[26]，用BrF_5与含氧矿物在真空和高温条件下(580 ℃)反应提取矿物氧，用5 Å分子筛样品管收集O_2气体，标准样品的外分析精度优于±0.2‰，相对标准为V-SMOW。测试仪器为253plus气体同位素比质谱仪。

4 分析结果

4.1 流体包裹体显微测温结果

本次共对25个石英中的原生气−液两相流体包裹体盐度和均一温度进行了测定，其结果见表1。石英中流体包裹体均一温度为165~274 ℃，平均值为216 ℃；盐度为6.5%~14.0%$NaCl_{eqv}$，平均值为7.8%$NaCl_{eqv}$前人对川滇黔成矿区内多个主要矿床的闪锌矿和脉石矿物中的流体包裹体开展了大量研究，获得包裹体均一温度介于115~280 ℃，主要集中于150~250 ℃[24]，而该矿床中流体包裹体均一温度与其基本一致。

4.2 单个流体包裹体激光拉曼光谱分析

通过对典型的流体包裹体中气相和液相进行显微激光拉曼光谱峰值扫描，结果显示石英中的包裹体具有相似的谱线特征，如图5所示。石英中包裹体液体成分为H_2O，含少量CH_4 (2917 cm^{-1})；石英中包裹体气泡成分为CH_4 (2917 cm^{-1})，含少量H_2O。

4.3 S同位素组成

矿石硫化物主要为方铅矿和黄铁矿及极少量闪锌矿，其S同位素测定结果见表2和图6(a)。研究发现，方铅矿(Gn)、闪锌矿(Sp)和黄铁矿(Py)均富含重硫同位素，$\delta^{34}S$值变化范围为9.34‰~25.66‰，平均值为17.16‰。其中7件方铅矿除1件$\delta^{34}S$高达20.70‰之外，其余分布于9.34‰~14.91‰之间，

表1 金牛厂铅锌矿床流体包裹体显微测温结果

Table 1 Microthermometric data of fluid inclusions from Jinniuchang Pb-Zn deposit

Hosted mineral	Generation	Quantity	Microthermometric data					Source
			$T_{m\text{-}ice}$/℃	T_h/℃		Salinity/%$NaCl_{eqv}$		
				Range	Mean	Range	Mean	
Quartzs	Primary	25	−10.1－−4.0	165－274	216	6.5－14.0	7.8	This paper

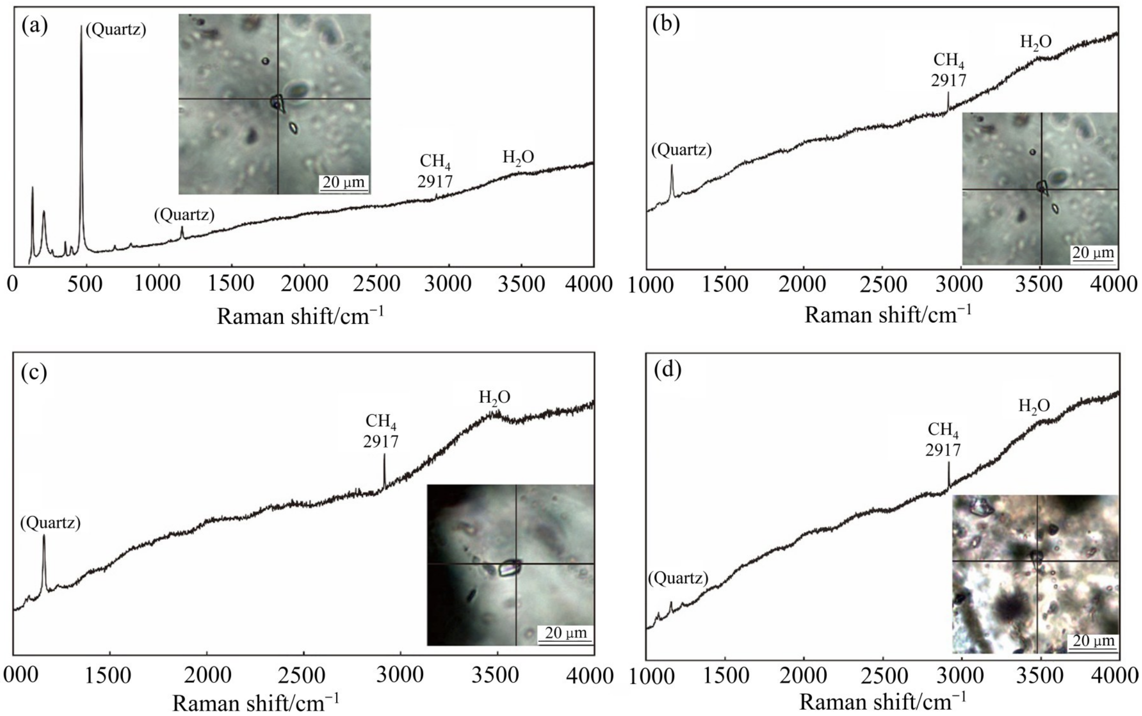

图5　金牛厂铅锌矿床流体包裹体激光拉曼谱图

Fig. 5　Representative Raman spectra of fluid inclusions of Jinniuchang Pb-Zn deposit: (a) Liquid composition of inclusions in quartz including H_2O with small amount of CH_4; (b), (c), (d) Composition of bubbles in inclusions in quartz including CH_4 with small amount of H_2O

表2　金牛厂铅锌矿床矿石硫化物S同位素组成

Table 2　Sulfur isotopic compositions of sulfides from Jinniuchang Pb-Zn deposit

Sample No.	Mineral	$\delta^{34}S$/‰	Source
JNC-1-1	Galena	10.17	This paper
JNC-2-1	Galena	14.16	
JNC-3-1	Galena	20.70	
JNC-4-1	Galena	10.56	
JNC-5-1	Galena	9.34	
JNC-6-1	Galena	14.91	
JNC-7-1	Galena	13.14	
JNC-3-2	Early stage pyrite	25.66	
JNC-4-2	Early stage pyrite	21.86	
JNC-5-2	Late stage pyrite	20.70	
JNC-6-2	Early stage pyrite	23.17	
JNC-5	Early stage sphalerite	21.49	

平均值为12.05‰；4件黄铁矿 $\delta^{34}S$ 分布于20.70‰~25.66‰之间，平均值为22.85‰；1件闪锌矿 $\delta^{34}S$ 值为21.49‰。$\delta^{34}S_{Gn}<\delta^{34}S_{Py}<\delta^{34}S_{Sp}$(见图5(a))，指示该矿床的S同位素达到平衡。

金牛厂铅锌矿床的S同位素特征与川滇黔成矿区内大多数铅锌矿床的S同位素特征基本一致，$\delta^{34}S$ 值在8‰~20‰范围内(见图6(b))。

4.4　H、O同位素组成

该矿床流体包裹体的均一温度范围为165~274 ℃，平均为216 ℃，根据CLAYTON等的计算公式[39]：$1000\ln a=\delta^{18}O_{Qz}-\delta^{18}O_{H_2O}=3.38\times10^6\ T^{-2}-3.4$，式中 T 取216 ℃，$\delta^{18}O_{H_2O}$ 计算结果列入表3。从表3中看出，石英(Qz)的 $\delta^{18}O_{Qz}$ 的变化范围在19.21‰~19.52‰之间(平均值为19.32‰)，δD的变化范围为−75.5‰~−96.4‰(平均值为−87.30‰)；流体的 $\delta^{18}O_{H_2O}$ 分布于8.49‰~8.80‰之间(平均值为8.60‰)。

4.5　Pb同位素组成

金牛厂铅锌矿床矿石硫化物Pb同位素组成见表4。矿石硫化物的 $^{206}Pb/^{204}Pb$ 值变化范围为

17.9513~18.0081，极差值为0.0003；$^{207}Pb/^{204}Pb$变化范围为15.6501~15.6571，极差值为0.0003；$^{208}Pb/^{204}Pb$变化范围为37.9896~38.0918，极差值为0.0007。正常普通Pb的变化率为0.3%~1%，金牛厂铅锌矿矿石硫化物的Pb同位素比值极差均小于1，说明Pb源较稳定。此外，Pb同位素组成变化范围较小，不同矿体、不同矿石类型、不同矿石矿物的Pb同位素组成相近，表明Pb来源较为一致(见表5)。

矿床硫化物的Pb同位素组成与川滇黔成矿区其他主要铅锌矿床明显不同。矿床的Pb同位素组成与赤普矿床相当，在基底岩层(昆阳群)年龄校正的Pb同位素范围内整体呈线形的水平延伸；而会泽、毛坪、茂租、大梁子、天宝山、天桥，筲箕湾和青山矿床的Pb同位素组成均主要在泥盆纪至二叠系碳酸盐岩和基底岩石(昆阳群)的Pb同位素范围内，并垂直延伸(见表5和图8(a))。

表3 川滇黔成矿区内主要铅锌矿床H、O同位素组成

Table 3 H and O isotopic composition of major Pb-Zn deposit in Sichuan－Yunnan－Guizhou Pb-Zn metallogenic triangle area

Deposit	Sample No.	Mineral	δD/‰	$\delta^{18}O_{Qz}$/‰	$\delta^{18}O_{H_2O}$/‰	Source
Jinniuchang	JNC-3-3	Quartz	−75.5	19.52	8.80	This paper
	JNC-6-3	Quartz	−90.0	19.21	8.49	
	JNC-7-3	Quartz	−96.4	19.22	8.50	
Huize		Calcite	−59.8−−43.5		6.9−9.3	Refs. [16, 40]
Maoping		Calcite	−64.0−−35.0		−3.7−−1.1	Ref. [41]
Maozu		Sphalerite, fluorite, quartz, barite	−78.1−−47.9		−6.7−6.9	Refs. [3, 42]
Daliangzi		Calcite, sphalerite, quartz	−74.6−−40.3		−5.3−3.3	Ref. [43]
Tianbaoshan		Sphalerite, quartz	−51.2−−47.6		−1.9−3.7	Refs. [34, 44]
Chipu		Quartz	−151.4−−48.3		5.1−8.2	Ref. [32]

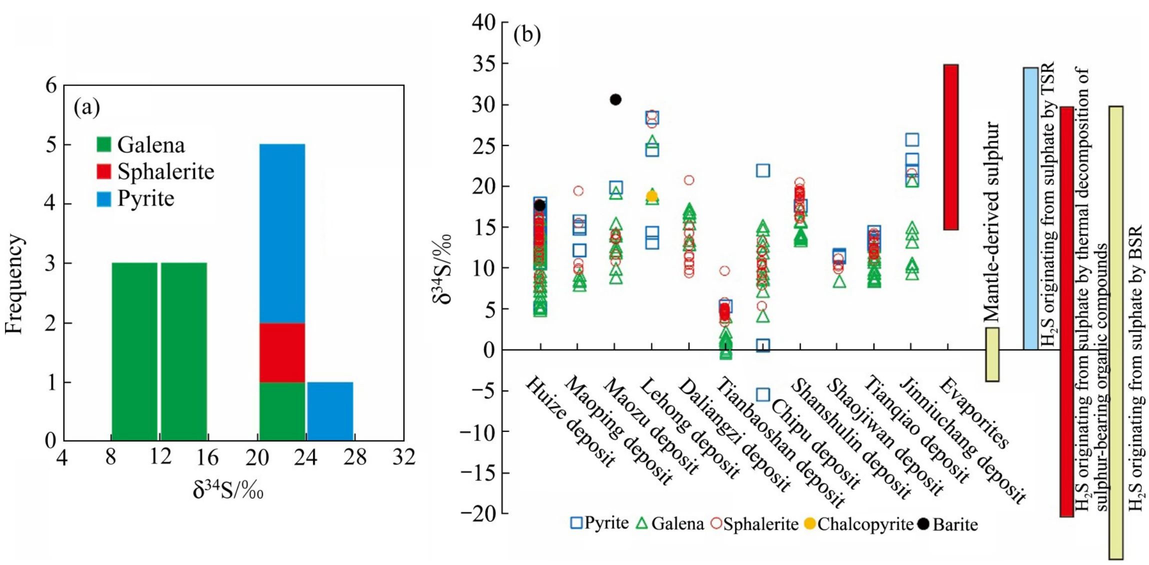

图6 金牛厂铅锌矿床S同位素组成直方图、金牛厂铅锌矿床与川滇黔成矿区内主要铅锌矿床$\delta^{34}S$对比图[27]

Fig. 6 Histograms of sulfur isotopic compositions of sulfides from Jinniuchang deposit(a) and comparison of sulfur isotopic compositions between Jinniuchang Pb-Zn deposit and major deposits in Sichuan－Yunnan－Guizhou Pb-Zn metallogenic triangle area[27](b) (Data source: Huize, Refs. [3, 16, 22, 28]; Maoping, Refs. [3, 29]; Maozu, Refs. [3, 22, 30]; Lehong, Ref. [31]; Daliangzi, Refs. [3, 22, 32−33]; Tianbaoshan, Refs. [3, 22, 34−36]; Chipu, Refs. [22, 32]; Shanshulin, Ref. [37]; Shaojiwan, Ref. [38]; Tianqiao, Ref. [18])

表4　金牛厂铅锌矿床矿石硫化物Pb同位素组成

Table 4　Pb isotopic compositions of sulfides from Jinniuchang Pb-Zn deposit

Sample no	Mineral	$^{206}Pb/^{204}Pb(2\sigma)$	$^{207}Pb/^{204}Pb(2\sigma)$	$^{208}Pb/^{204}Pb(2\sigma)$	Source
JNC-1-1	Galena	17.9996(±0.0004)	15.6547(±0.0003)	38.0687(±0.0008)	This paper
JNC-2-1	Galena	17.9566(±0.0003)	15.6502(±0.0003)	37.9957(±0.0008)	
JNC-3-1	Galena	17.9713(±0.0004)	15.6522(±0.0003)	38.0221(±0.0008)	
JNC-4-1	Galena	17.9869(±0.0003)	15.6538(±0.0002)	38.0504(±0.0006)	
JNC-5-1	Galena	17.9915(±0.0003)	15.6539(±0.0003)	38.0578(±0.0007)	
JNC-6-1	Galena	17.9831(±0.0003)	15.6526(±0.0003)	38.0430(±0.0007)	
JNC-7-1	Galena	17.9513(±0.0003)	15.6499(±0.0003)	37.9893(±0.0007)	
JNC-3-2	Pyrite	18.0057(±0.0004)	15.6571(±0.0004)	38.0865(±0.0010)	
JNC-4-2	Pyrite	18.0081(±0.0004)	15.6568(±0.0003)	38.0918(±0.0007)	
JNC-5-2	Pyrite	17.9883(±0.0002)	15.6540(±0.0002)	38.0587(±0.0006)	
JNC-6-2	Pyrite	17.9992(±0.0003)	15.6554(±0.0002)	38.0670(±0.0006)	
JNC-5	Sphalerite	17.9996(±0.0003)	15.6554(±0.0003)	38.0741(±0.0007)	

表5　金牛厂铅锌矿床、震旦系白云岩、寒武系沉积岩、泥盆系–二叠系碳酸盐岩、前寒武基底岩(昆阳群)和二叠系峨眉山玄武岩的Pb同位素组成统计结果

Table 5　Statistical results of Pb isotope compositions of Jinniuchang Pb-Zn deposit, Sinian dolostone, Cambrian sedimentary rocks, Devonian to Permian carbonate rocks, Precambrian basement rocks (Kunyang group) and Permian Emeishan flood basalts

Mineral/rock	Number of sample	$(^{206}Pb/^{204}Pb)_{200\ Ma}$	$(^{207}Pb/^{204}Pb)_{200\ Ma}$	$(^{208}Pb/^{204}Pb)_{200\ Ma}$	Source
Galena, pyrite, sphalerite of Jinniuchang Pb-Zn deposit	12	17.9513−18.0081	15.6501−15.6571	37.9896−38.0918	This paper
Cambrian sedimentary rocks	4	20.950−22.354	15.837−15.930	40.878−41.928	Ref. [19]
Sinian Dengying Formation (Zz_2dn), Dolostone	20	18.198−18.517	15.699−15.987	38.547−39.271	Refs. [3−4, 8, 12, 28, 45−49]
Devonian－Permian carbonate rocks	80	18.120−18.842	15.500−16.522	38.235−39.685	
Precambrian basement rocks (Kunyang Group)	27	17.781−20.993	15.582−15.985	37.178−40.483	
Permian Emeishan flood basalts	56	18.175−19.019	15.528−15.662	38.380−39.928	

Remarks: $(^{206}Pb/^{204}Pb)_t=(^{206}Pb/^{204}Pb)_p-\mu(e^{\lambda t}-1)$; $(^{207}Pb/^{204}Pb)_t=(^{207}Pb/^{204}Pb)_p-\mu/137.88(e^{\lambda' t}-1)$; $(^{208}Pb/^{204}Pb)_t=(^{208}Pb/^{204}Pb)_p-\omega(e^{\lambda'' t}-1)$; $\lambda=1.55125\times10^{-10}t^{-1}$; $\lambda'=0.8485\times10^{-10}t^{-1}$; $\lambda''=0.49475\times10^{-10}t^{-1}$; t—Sample experience time (200 Ma); p—Initial Pb isotope ratio; μ, ω—Characteristic values

5　讨论

5.1　成矿流体来源

5.1.1　S源

研究矿床的S源必须对硫化物沉淀期间热液中的总S同位素组成加以分析[50]。该矿床矿石中主要含硫矿物为方铅矿和黄铁矿，闪锌矿含量极少，且无重晶石及其他硫酸盐，指示氧逸度低，表明矿石硫化物的δ^{34}S值基本代表热液的总S同位素组成，可用于直接追踪硫源[51]。

矿床位于矿山厂–金牛厂构造带南西段，主要受小江断裂带及其分支构造控制，为成矿流体运移提供通道。矿床硫化物相对富集重S同位素，其硫化物δ^{34}S值变化范围为9.34‰~25.66‰，平均值为17.16‰，明显不同于深源硫；且同位素测年结果

表明，川滇黔铅锌成矿区内矿床主要形成于晚三叠–早侏罗世，集中于200 Ma(见表6)，川滇黔成矿区内主要的岩浆岩为晚二叠世峨眉山玄武岩(256 Ma)[52]及基性辉绿岩脉(156~166 Ma)[53]，玄武岩形成早于铅锌成矿，而辉绿岩脉形成晚于铅锌成矿。

矿体赋存于下寒武统筇竹寺组($\epsilon_1 q$)泥质、钙质粉砂岩的断裂破碎带中，上覆泥质、粉砂质页岩为较理想的隔挡层。矿床矿石矿物组合简单，赋矿围岩和矿石中均不发育硫酸盐矿物，但下伏岩性为寒武系渔户村组和震旦系灯影组的白云岩。前人发现灯影组中有石膏、石盐假晶和鸟眼状白云岩，说明区域灯影组地层中曾有膏盐沉积[54]。扬子地块震旦系灯影期海相硫酸盐的$\delta^{34}S$值介于20.2‰~38.7‰之间[55]，下寒武统梅树村组(渔户村组)磷块岩中的海相硫酸盐$\delta^{34}S$值介于17.4‰~33.6‰[56]。海相硫酸盐可通过细菌还原硫作用(BSR)和热化学还原硫作用(TSR)形成还原S[57]，为沉积岩容矿的金属矿床提供充足的S源。通常，BSR作用主要发生在相对低温条件下(低于120 ℃，一般为50~70 ℃)[58−59]，其形成的S同位素分馏一般为4.0‰~46.0‰，生成H_2S的$\delta^{34}S$值通常为负值[58]；而TSR常在相对较高的温度条件下发生(高于150℃)，在150℃以上条件下，TSR作用可以在海水硫酸盐岩与还原S之间形成10‰~25‰的分馏；随着温度的升高，$\Delta\delta^{34}S$值变小[59−61]。该矿床的流体包裹体的均一温度平均值为216 ℃，与川滇黔成矿区内多个主要矿床的流体包裹体均一温度基本一致，推断TSR可能是将硫酸盐中的SO_4^{2-}转化为热液中H_2S的主要机制。

矿床硫化物$\delta^{34}S$值变化范围为9.34‰~25.66‰，平均值为17.16‰，低于蒸发岩的$\delta^{34}S$值，而与TSR作用造成的硫同位素分馏十分接近；同时，其$\delta^{34}S$值与川滇黔成矿区内大多数铅锌矿床硫化物平均$\delta^{34}S$值(一般为8‰~20‰)非常相近，特别是与会泽、毛坪、大梁子和茂租铅锌矿床的$\delta^{34}S$值基本一致(见图6(b))，其还原S主要来源于围岩中的海水硫酸盐通过TSR生成的还原S[2, 16, 27, 62−64]。

因此，矿床硫化物中的S可能来源于下伏下寒武统渔户村组和震旦系灯影组白云岩中的海水硫酸盐，主要通过TSR生成还原S，随深部流体通过断裂通道为矿床提供了S源。

5.1.2 流体来源

调研发现，金牛厂矿床明显受构造控制。其成矿流体的H、O同位素研究能较好地显示成矿流体来源和演化特征。与北美典型的盆地卤水(Illinois、California盆地)和四川盆地卤水相比，矿床成矿流体具有δD值偏低、$\delta^{18}O_{H_2O}$值偏高的特征。在金牛厂铅锌矿δD−$\delta^{18}O_{H_2O}$关系图(见图7)中，石英的H、O同位素都位于原生岩浆水和有机质流体之间，靠近变质水，且有向有机质流体靠近的趋势。上述特征暗示成矿流体可能具有岩浆水、变质水和有机质流体混合来源特征，并可能有部分大气降水的加入。但是，矿区出露的岩浆岩主要为二叠纪峨眉山玄武岩，它与成矿不在同一时期(见2.1节)，因此成矿流体不可能来自岩浆水。流体包裹体的液相和气相中均含有CH_4成分，且气相成分主要为CH_4，暗示成矿流体中含有有机质；分析认为，可能是流经深部褶皱基底(昆阳群)的深部流体与含有机质的盆地卤水混合，导致δD值偏低；而深部流体在上升过程中与碳酸盐岩发生反应，导致$\delta^{18}O_{H_2O}$值偏高。

矿床$\delta^{18}O_{H_2O}$值的横向漂移不大，而δD值显示出极大的垂向漂移特征，这点与区域上天宝山、大梁子铅锌矿床$\delta^{18}O_{H_2O}$值存在较大横向漂移不同，而与赤普铅锌矿床δD−$\delta^{18}O_{H_2O}$值的特点具有相似性，但δD值变化范围较赤普偏小(见图7)。赤普铅锌矿床可见明显的有机质参与成矿的特征[32]，推测导致矿床成矿流体的H同位素较大的垂向“漂移”的原因可能是成矿过程有有机质氢(δD_{H_2O})的参与。

因此，H、O同位素组成特征指示成矿流体中的水主要来源于流经深部褶皱基底(昆阳群)的深部流体和含有机质的盆地卤水的混合。

5.2 矿质来源

金牛厂铅锌矿床硫化物Pb同位素组成较均一，造成Pb同位素如此均一的原因可能有两个：Pb为混合来源但是混合完全或者Pb为单一来源。虽然硫化物的Pb同位素组成变化范围小，但是在$^{208}Pb/^{204}Pb$−$^{206}Pb/^{204}Pb$图上明显具有线性趋势

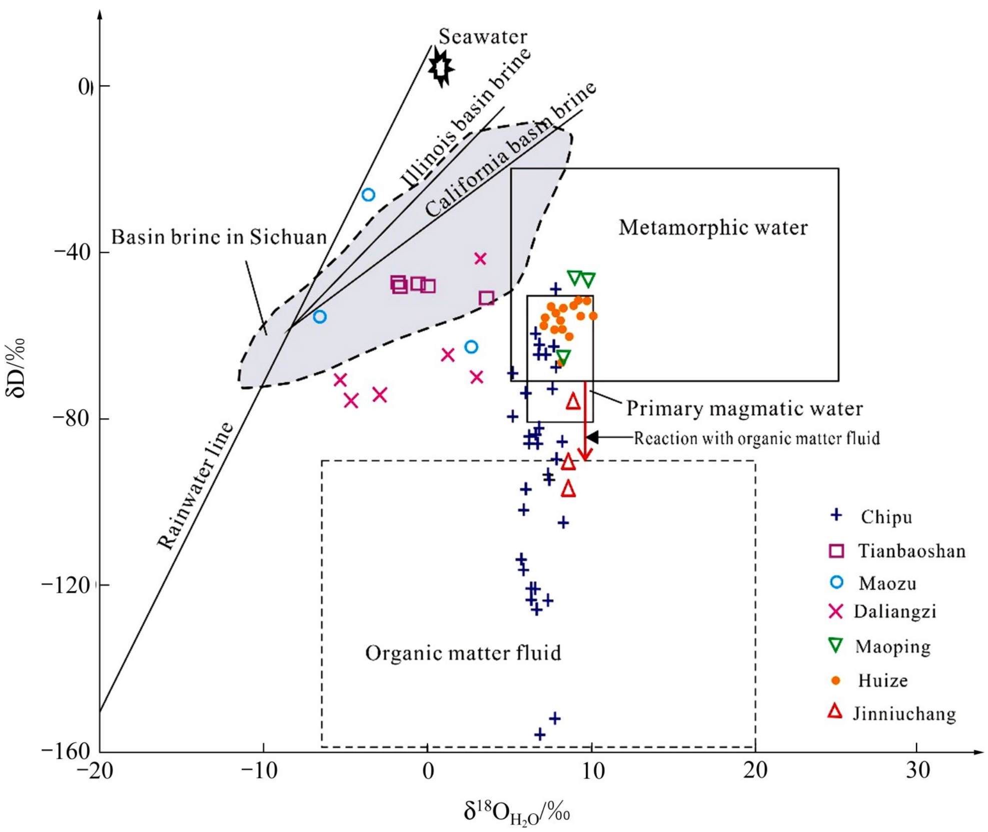

图 7　金牛厂铅锌矿床中石英的 $\delta D-\delta^{18}O_{H_2O}$ 图解[65]

Fig. 7　Diagram of $\delta D-\delta^{18}O_{H_2O}$ for quartz separates from Jinshachang deposit[65]

(见图 8(b))，这种线性趋势通常被解释为 Pb 具有混合来源[66−68]。全部样品 Pb 同位素组成在 $^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb$ 图上(见图 8(a))呈近似水平的直线落在上地壳 Pb 平均演化线上，表明矿石 Pb 主要来源于上地壳，可能有极少量造山带 Pb 的混入。

由于川滇黔铅锌成矿区内绝大部分铅锌矿床赋存于碳酸盐岩中，区域上有大面积峨眉山玄武岩分布和基底岩石(昆阳和会理群)出露。因此，多数学者认为成矿物质由基底岩石、碳酸盐岩和峨眉山玄武岩共同提供，但对它们的贡献程度有不同认识：1) 由沉积岩(碳酸盐岩)主要提供[16]；2) 主要来自前寒纪基底岩石[8]；3) 峨眉山玄武岩不仅提供了部分成矿物质，还是主要的热动力源[14]。

矿床矿石 Pb 同位素组成明显小于该区寒武系沉积岩；与该区域玄武岩、震旦系白云岩、泥盆系−二叠系碳酸盐岩明显不同；而与基底岩石(昆阳群)基本一致(见表 5)。Pb 同位素组成全部落入基底岩石(昆阳群和会理群)范围(见图 8(a))，表明铅锌矿床成矿流体中金属主要由基底岩石(昆阳群)提供。朱林生[69]根据矿区筇竹寺组碎屑岩中 Pb、Zn 含量分别为区域背景值的 16.2 倍和 4.2 倍，且地层和矿石中稀土元素配分模式和特征值的一致性，认为筇竹寺组为矿区的主要矿源层。因此，矿石 Pb 主要来源于基底岩石，可能混入了少量来源于矿体围岩筇竹寺组碎屑岩的 Pb，且二者在成矿过程中经过了均一化的过程。该结论不同于川滇黔成矿区大多数铅锌矿床的矿石 Pb 主要来源于碳酸盐岩的结论。

对于峨眉山玄武岩与成矿的关系，笔者认为峨眉山玄武岩浆活动时限(260~245 Ma)与区域铅锌成矿时代(约 200 Ma)相差超过 40~50 Ma[70−71]，说明峨眉山玄武岩浆活动与铅锌成矿无直接的成因联系，但不能排除成矿流体活化峨眉山玄武岩中的部分成矿物质，即大气降水或层间水下渗过程中活化了峨眉山玄武岩中的部分成矿金属，特别是成矿元素 Zn[18]。

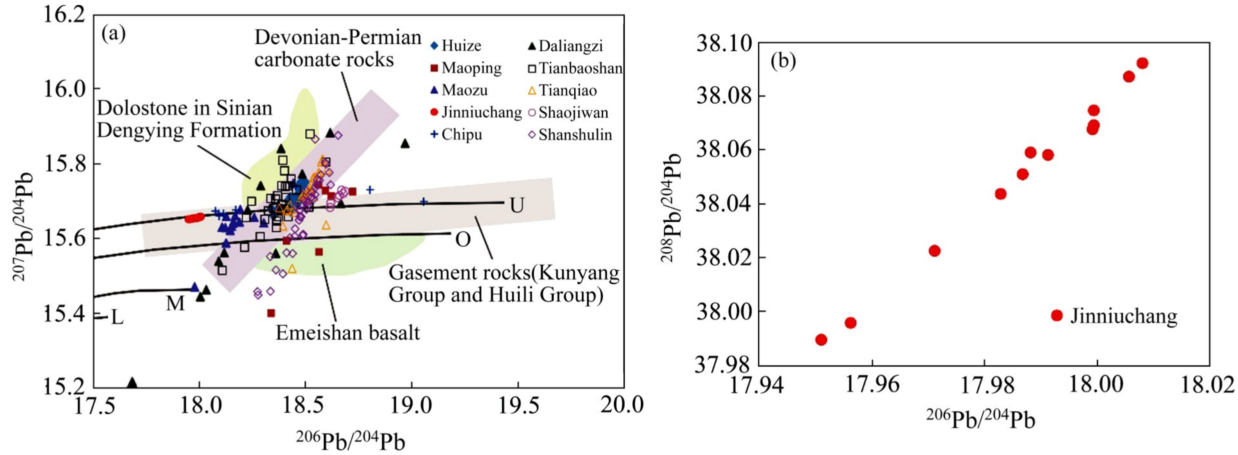

图8 金牛厂铅锌矿床 $^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb$ 构造演化曲线图[72]和金牛厂铅锌矿床 $^{208}Pb/^{204}Pb-^{206}Pb/^{204}Pb$ 关系图

Fig. 8 Plots of $^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb$ for Jinniuchang Pb-Zn deposit[72] (a) and plots of $^{208}Pb/^{204}Pb-^{206}Pb/^{204}Pb$ for Jinniuchang Pb-Zn deposit(b) (Data source: Huize, Refs. [41, 73−74]; Maoping, Refs. [3, 29]; Maozu, Refs. [3, 30]; Chipu, Ref. [32]; Daliangzi, Ref. [75]; Tianbaoshan, Ref. [34]; Tianqiao, Ref. [18]; Shaojiwan, Ref. [38]; Shanshulin, Ref. [37]; U—Upper crust; O—Orogenic belt; M—Mantle; L—Lower crust)

5.3 成矿机理

大量前人研究成果表明，川–滇–黔铅锌多金属成矿区中铅锌矿床在赋矿岩石、构造环境和成矿流体方面有着很多的相似之处[2, 8, 45, 76−77]。通过对比发现(见表6)，金牛厂铅锌矿床具有与川滇黔铅锌成矿区内其他主要矿床相似的特征，如挤压构造背景特征清晰、断褶构造控矿、后生特征明显、矿物组成简单、脉状和透镜状矿体发育、与岩浆(峨眉山地幔柱)活动关系不大等。同时，矿床流体包裹体的均一温度范围为165~274 ℃，盐度值范围为6.5%~14.0%$NaCl_{eqv}$，成矿流体属于中低温–中低盐度的富气相流体，与川滇黔铅锌成矿区主要铅锌矿床基本一致(流体包裹体均一温度范围为115~280 ℃，盐度值范围为0.9%~20.0%$NaCl_{eqv}$(见表6))。因此，金牛厂铅锌矿床可能是在印支晚期(约200 Ma)造山事件触发的一次区域热液事件背景下与其他铅锌矿床同步形成，具有相似的成矿模式，但其也具有自身的特点，如赋矿围岩为下寒武统筇竹寺组碎屑岩、矿体位于逆断层下盘张扭性裂隙中、成矿金属由基底岩石(昆阳群)和矿体围岩筇竹寺组碎屑岩共同提供等。

综合以上研究，金牛厂铅锌矿床的成矿机制为：印支晚期(约200 Ma)碰撞造山事件和特提斯洋闭合在扬子地块西南缘前陆盆地诱发强烈的斜冲走滑作用，形成一系列斜冲走滑断褶构造(如矿区关仓箐断裂与坪箐背斜)[21]。构造动力驱动深部流体沿区域断裂(小江断裂)和分支断裂(待补断裂、关仓箐断裂)向上运移，逐步萃取基底(昆阳群)中的Pb、Zn等主要成矿金属离子，以及上覆地层震旦系灯影组和下寒武统渔户村组海相碳酸盐岩层中的膏盐层硫酸盐。另外，重力驱动部分含有机质盆地卤水沿下寒武统筇竹寺组碎屑岩运移，萃取赋矿地层筇竹寺组中的少量Pb、Zn等成矿金属离子。同时，少量大气降水沿断裂向下运移。当三种流体沿断裂运移至“隔挡层”下寒武统筇竹寺组上段的泥质、砂质页岩时，开始汇集；随着物理、化学等成矿条件的改变，金属硫化物在下寒武统筇竹寺组下段泥质、钙质粉砂岩的有利地质、构造部位沉淀形成矿床(见图9)。

6 结论

1) 金牛厂铅锌矿床流体包裹体的液相和气相中均含有CH_4成分，且气相成分主要为CH_4，成矿流体属于中低温–中低盐度的富气相流体。流体主要来源于流经深部褶皱基底(昆阳群)的深部流体和含有机质的盆地卤水的混合；S主要来源于下伏地层

表 6　川滇黔铅锌多金属成矿区内主要铅锌矿床特征对比

Table 6　Comparison of major Pb-Zn deposits in Sichuan－Yunnan－Guizhou Pb-Zn metallogenic triangle area

Deposits	Province	Host rocks	Reserves and grade	Ore-controlling structures	Orebody	Ore-forming fluids	Symbiotic minerals	Ore－forming age (Ma) and test method	Source
Huize	NE Yunnan	Early Carboniferous dolostone	＞5 Mt Pb+Zn; 800 t Ge; 25%–30% Pb+Zn	NE-trending thrust faults	Stratiform, lenticular	Salinity: 6%–12% NaCl; Th: 164–220 ℃	Galena, sphalerite, pyrite, arsenopyrite, chalcopyrite, limonite, calcite, dolomite, quartz	223.5±3.9, 226±6.4, 196.3±1.8 (sphalerite Rb-Sr)	Refs. [11, 28, 78]
Maoping		Late Devonian and Carboniferous dolostone and limestone	3 Mt Pb+Zn; ＞25% Pb+Zn	NE-trending faults and anticline	Stratiform, lenticular, vein	Salinity: 6.7% −13.8%NaCl; Th: 123–206 ℃	Sphalerite, galena, pyrite, calcite, quartz	321.7±5.8 (sphalerite Rb-Sr)	Refs. [11, 79–80]
Maozu		Late Sinian dolostone	2 Mt Pb+Zn; 12%–14% Pb+Zn	NE-trending thrust -fold	Stratiform	Salinity: 2.8%–5.3% NaCl; Th: 153–248 ℃	Sphalerite, galena, calcite, dolomite, quartz, fluorite	196±13 (calcite Sm-Nd)	Refs. [11, 30]
Lehong		Late Sinian dolostone	2.4 Mt Pb+Zn; ＞15% Pb+Zn	NW-trending fault	Stratiform, lenticular, vein	Salinity: 11.3%–14.5% NaCl; Th: 165–229 ℃	Sphalerite, galena, pyrite, arsenopyrite, dolomite, quartz	200.9±8.3 (sphalerite Rb-Sr)	Refs. [11, 32, 81]
Jinniuchang		Argillaceous siltstone of Lower CambrianQiongzhusi formation	＜0.1 Mt Pb+Zn; ＜10% Pb+Zn	NE-trending fault fold structure	Vein	Salinity: 6.5%–14.0% NaCl; Th: 165–274 ℃	Galena, sphalerite, pyrite, calcite, quartz	No data	This paper
Daliangzi	SW Sichuan	Late Sinian dolostone	4.5Mt Pb+Zn; 10%–12% Pb+Zn	NW-trending thrust faults	Lenticular, vein, cystic	Salinity: 18% NaCl; Th: 170–225 ℃	Sphalerite, galena, pyrite, arsenopyrite, chalcopyrite, tetrahedrite, quartz, calcite, dolomite	204.4±1.2 (calcite Sm-Nd)	Refs. [32, 45]
Tianbaoshan		Late Sinian dolostone	2.6Mt Pb+Zn; 6%–12% Pb+Zn	NW-trending thrust faults	Stratiform, lenticular, vein	Salinity: 12.4%–20% NaCl; Th: 157–267 ℃	Sphalerite, galena, chalcopyrite, dolomite, calcite, quartz	＞166 (zircon U-Pb age of diabase)	Refs. [34, 53]
Chipu		Late Sinian dolostone	0.65 Mt Pb+Zn; 10.4% Pb+Zn	NW-trending thrust faults	Stratiform, lenticular	Salinity: 8.5%–17% NaCl; Th: 130–250 ℃	Sphalerite, galena, pyrite, dolomite, calcite, quartz, asphalt	292.0±9.7, 165.7±9.9 (bitumen Re-Os)	Refs. [32, 82]
Shanshulin	NW Guizhou	Late Carboniferous dolomitic limestone	＞0.5 Mt Pb+Zn; ＞20% Pb+Zn	NW-trending thrust faults	Stratiform, vein	Salinity: ＜15% NaCl; Th: 150–280 ℃	Sphalerite, galena, pyrite, dolomite, calcite	No data	Refs. [37, 83]
Shaojiwan		Early Permian and Middle Devonian dolomitic limestone and dolostone	0.5 Mt Pb+Zn; 15%–20% Pb+Zn	NW-trending thrust-fold	Stratiform	Salinity: 0.9%–17.5% NaCl; Th: 115–170 ℃	Sphalerite, galena, pyrite, dolomite, calcite	No data	Refs. [38, 83]
Tianqiao		Carboniferous dolostone	0.4Mt Pb + Zn； 15-18% Pb + Zn	NW-trending thrust-fold	Stratiform	Salinity: 9.6%–14.2% NaCl; Th: 150–270 ℃	Sphalerite, galena, pyrite, dolomite, calcite	191.9±6.9 (sphalerite Rb-Sr)	Refs. [18, 70]

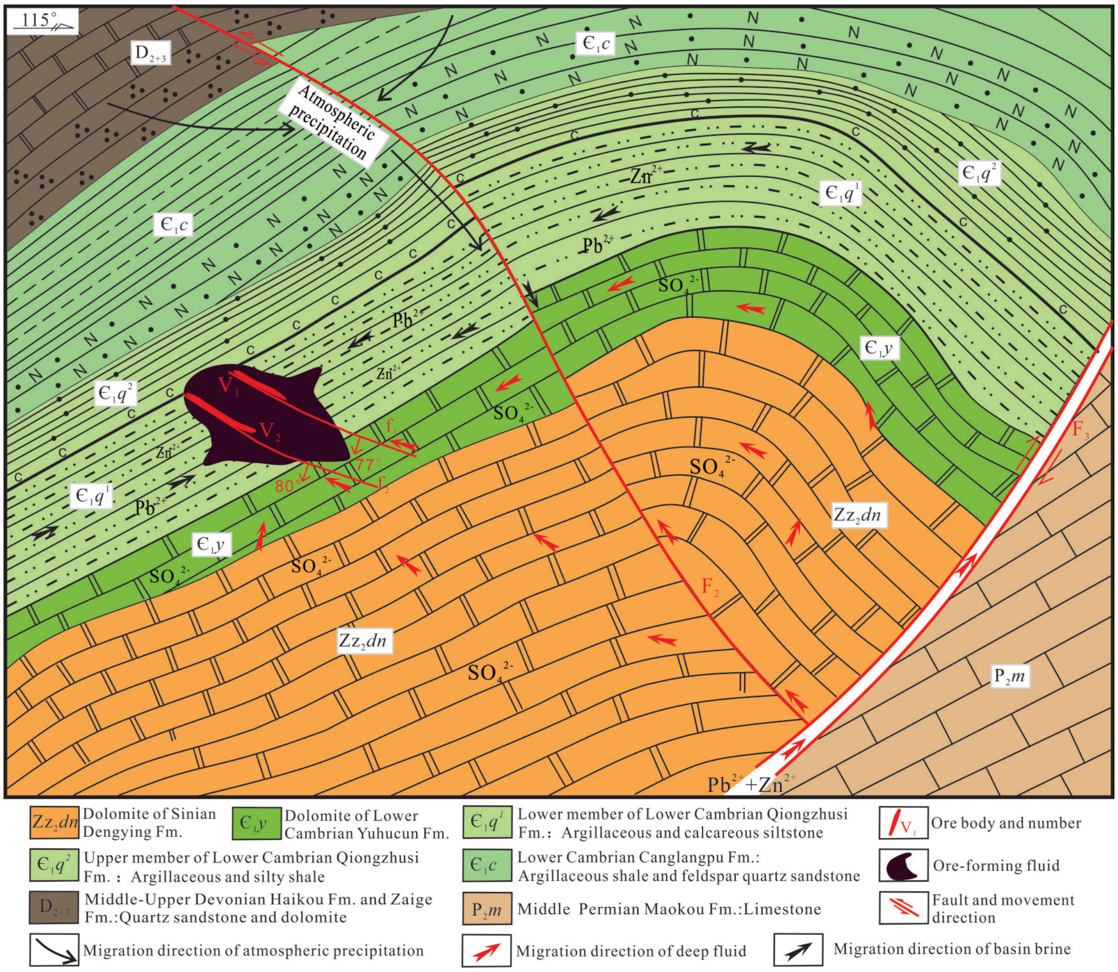

图9　金牛厂铅锌矿床成矿模式图

Fig. 9　Metallogenic model of Jinniuchang Pb-Zn deposit

震旦系灯影组和下寒武统渔户村组白云岩中海相硫酸盐通过TSR生成。

2) 矿石硫化物的Pb同位素组成与灯影组白云岩、泥盆系−二叠系碳酸盐岩和峨眉山玄武岩明显不同，且沿上地壳Pb平均演化线呈直线分布，与基底岩石(昆阳群)的Pb同位素比值完全一致，表明Pb源主要来自基底岩石(昆阳群)，少部分来自赋矿围岩下寒武统筇竹寺组碎屑岩，且二者在成矿过程中经过了均一化的过程。

3) 该矿床和川滇黔成矿区内其他铅锌矿床在印支晚期碰撞造山触发的一次区域热液事件背景下同步形成，具有相似的成矿模式；但在赋矿围岩、赋矿断裂性质、矿质来源等方面存在自身的特点。

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REFERENCES

[1] HU R Z, CHEN W T, XU D R, et al. Reviews and new metallogenic models of mineral deposits in South China: An introduction[J]. Journal of Asian Earth Sciences, 2017, 137: 1−8.

[2] HU R Z, FU S L, HUANG Y, et al. The giant South China Mesozoic low-temperature metallogenic domain: Reviews and a new geodynamic model[J]. Journal of Asian Earth Sciences, 2017,137: 9−34.

[3] 柳贺昌, 林文达. 滇东北铅锌银矿床规律研究[M]. 昆明: 云南大学出版社, 1999.
LIU He-chang, LIN Wen-da. Regularity research of Ag, Zn, Pb ore deposits north-east Yunnan Province, China[M]. Kunming: Yunnan University Press, 1999.

[4] 韩润生, 胡煜昭, 王学琨, 等. 滇东北富锗银铅锌多金属矿集区矿床模型[J]. 地质学报, 2012, 86(2): 280−294.
HAN Run-sheng, HU Yu-zhao, WANG Xue-kun, et al. Mineralization model of rich Ge-Ag-bearing Zn-Pb polymetallic deposit concentrated district in northeastern Yunnan, China[J]. Acta Geologica Sinica, 2012, 86(2): 280−294.

[5] 张位及. 试论滇东北铅锌矿床的沉积成因和成矿规律[J]. 地质与勘探, 1984, 20(7): 11−16.
ZHANG Wei-ji. A preliminary discussion on the sedimentary origin and metallogenic rule of Pb-Zn deposits in northeastern Yunnan [J]. Geology and Exploration, 1984, 20(7): 11−16.

[6] 陈士杰. 黔西滇东北铅锌矿成因探讨[J]. 贵州地质, 1986(3): 211−222.
CHEN Shi-jie. Research on the genesis of lead-zinc ore-deposits in western Guizhou and northeastern Yunnan[J]. Guizhou Geology, 1986 (3): 211−222.

[7] 廖 文. 滇东、黔西铅锌金属区硫、铅同位素组成特征与成矿模式探讨[J]. 地质与勘探, 1984, 20(1): 0−6.
LIAO Wen. A discussion on the S and Pb isotopic composition characteristics and metallogenic model of the Pb-Zn ore zones in eastern Yunnan and western Guizhou[J]. Geology and Exploration, 1984, 20(1): 0−6..

[8] ZHOU C X, WEI S S, GUO J Y, et al. The source of metals in the Qilinchang Zn-Pb deposit, northeastern Yunnan,China: Pb-Sr isotope constraints[J]. Economic Geology, 2001, 96(3): 583–598.

[9] 王奖臻, 李朝阳, 李泽琴, 等. 川、滇、黔交界地区密西西比河谷型铅锌矿床与美国同类矿床的对比[J]. 矿物岩石地球化学通报, 2002, 21: 127−132.
WANG Jiang-zhen, LI Chao-yang, LI Ze-qin, et al. The comparison of Mississippi valley-type lead-zinc deposits in southwest of China and in mid-continent of United States[J]. Bulletin of Mineralogy, Petrology and Geochemistry, 2002, 21: 127−132.

[10] 张长青, 毛景文, 吴锁平, 等. 川滇黔地区MVT铅锌矿床分布、特征及成因[J]. 矿床地质, 2005, 24(3): 336−348.
ZHANG Chang-qing, MAO Jing-wen, WU Suo-ping, et al. Distribution, characteristics and genesis of Mississippi Valley-Type lead-zinc deposits in Sichuan-Yunnan-Guizhou area[J]. Mineral Deposits, 2005, 24(3): 336−348.

[11] 韩润生, 张 艳, 王 峰, 等. 滇东北矿集区富锗铅锌矿床成矿机制与隐伏矿定位预测[M]. 北京: 科学出版社, 2019.
HAN Run-sheng, ZHANG Yan, WANG Feng, et al. Metallogenic mechanism of germanium-rich lead-zinc deposits and location prediction of concealed minerals in northeast Yunnan ore concentration area[M]. Beijing: Science Press, 2019.

[12] 胡耀国. 贵州银厂坡银多金属矿床银的赋存状态、成矿物质来源与成矿机制[D]. 贵阳: 中国科学院地球化学研究所, 2000: 10−55.
HU Yao-guo. Occurrence state, ore-forming material source and metallogenic mechanism of silver in Yinchangpo silver polymetallic deposit, Guizhou Province[D]. Guiyang: Institute of Geochemistry, Chinese Academy of Sciences, 2000: 10−55.

[13] 邓海琳, 李朝阳, 涂光炽, 等. 滇东北乐马厂独立银矿床S同位素地球化学[J]. 中国科学(D辑), 1999, 29(6): 496−503.
DENG Hai-lin, LI Chao-yang, TU Guang-chi, et al. Strontium isotope geochemistry of the Lemachang independent silver ore deposit, northeastern Yunnan[J]. Scientia Sinica (Terrae), 1999, 29(6): 496−503.

[14] 黄智龙, 陈 进, 韩润生. 云南会泽超大型铅锌矿床地球化学及成因兼论峨眉山玄武岩与铅锌成矿的关系[M]. 北京: 地质出版社, 2004.
HUANG Zhi-long, CHEN Jin, HAN Run-sheng. Geochemistry and genesis of Huize super-large Pb-Zn deposit in Yunnan Province, and discussion on the relationship between Emeishan basalt and Pb-Zn mineralization[M]. Beijing: Geological Publishing House, 2004.

[15] 涂首业. 四川会理天宝山铅锌矿矿相学特征及意义[D]. 成都: 成都理工大学, 2014.
TU Shou-ye. The mineralography characteristics and its genetic significance of the Tianbaoshan Pb-Zn deposit in Huili Sichuan[D]. Chengdu: Chengdu University of Technology, 2014.

[16] 李文博, 黄智龙, 张 冠. 云南会泽铅锌矿田成矿物质来源: Pb、S、C、H、O、Srr同位素制约[J]. 岩石学报, 2006, 22 (10): 2567−2580.
LI Wen-bo, HUANG Zhi-long, ZHANG Guan. Sources of the ore metals of the Huize ore field in Yunnan Province: Constraints from Pb, S, C, H, O and Sr isotope geochemistry [J]. Acta Petrologica Sinica, 2006, 22(10): 2567−2580.

[17] 张长青, 毛景文, 余金杰, 等. 四川甘洛赤普铅锌矿床流体包裹体特征及成矿机制初步探讨[J]. 岩石学报, 2007, 23 (10): 2541−2552.
ZHANG Chang-qing, MAO Jing-wen, YU Jin-jie, et al. Study on fluid inclusion and the metallogenetic mechanism of Chipu Pb-Zn deposit in Sichuan, China[J]. Acta Petrologica Sinica, 2007, 23(10): 2541−2552.

[18] ZHOU J X, HUANG Z L, ZHOU M F, et al. Constraints of C-O-S-Pb isotope compositions and Rb-Sr isotopic age on

the origin of the Tianqiao carbonate-hosted Pb-Zn deposit, SW China[J]. Ore Geology Reviews, 2013, 53(8): 77−92.

[19] ZHOU J X, BAI J H, HUANG Z L, et al. Geology, isotope geochemistry and geochronology of the Jinshachang carbonate-hosted Pb-Zn deposit, southwest China[J]. Journal of Asian Earth Sciences, 2015, 98: 272−284.

[20] 张志斌, 李朝阳, 涂光炽, 等. 川、滇、黔接壤地区铅锌矿床产出的大地构造演化背景及成矿作用[J]. 大地构造与成矿学, 2006, 30(3): 343−354.

ZHANG Zhi-bin, LI Chao-yang, TU Guang-chi, et al. Geotectonic evolution background and ore-forming process of Pb-Zn deposits in Chuan–Dian–Qian area of southwest China[J]. Geotectonica et Metallogenia, 2006, 30(3): 343−354.

[21] 韩润生, 王 峰, 胡煜昭, 等. 会泽型(HZT)富锗银铅锌矿床成矿构造动力学研究及年代学约束[J]. 大地构造与成矿学, 2014, 38(4): 758−771.

HAN Run-sheng, WANG Feng, HU Yu-zhao, et al. Metallogenic tectonic dynamics and chronology constrains on the Huize-type (HZT) germanium-rich silver-zinc-lead deposits[J]. Geotectonica et Metallogenia, 2014, 38(4): 758−771.

[22] 张长青. 中国川滇黔交界地区密西西比型(MVT)铅锌矿床成矿模型[D]. 北京: 中国地质科学院, 2008.

ZHANG Chang-qing. The genetic model of Mississippi valley-type deposits in the boundary area of Sichuan, Yunnan and Guizhou provinces, China[D]. Beijing: Chinese Academy of Geological Sciences, 2008.

[23] GONG H S, HAN R S, WU P, et al. Constraints of S-Pb-Sr isotope compositions and Rb-Sr isotopic age on the origin of the Laoyingqing noncarbonate-hosted Pb-Zn deposit in the Kunyang group, SW China[J]. Geofluids, 2021, 2021: 8844312.

[24] GONG B, ZHENG Y F, CHEN R X. An online method combining a thermal conversion elemental analyzer with isotope ratio mass spectrometry for the determination of hydrogen isotope composition and water concentration in geological samples[J]. Rapid Communications in Mass Spectrometry, 2007, 21(8): 1386−1392.

[25] CLAYTON R N, MAYEDA T K. The use of bromine pentafluoride in the extraction of oxygen from oxides and silicates for isotopic analysis[J]. Geochimica et Cosmochimica Acta, 1963, 27(1): 43−52.

[26] 孔志岗, 吴 越, 张 锋, 等. 川滇黔地区典型铅锌矿床成矿物质来源分析: 来自S-Pb同位素证据[J]. 地学前缘, 2018, 25(1): 125−137.

KONG Zhi-gang, WU Yue, ZHANG Feng, et al. Sources of ore-forming material of typical Pb-Zn deposits in the Sichuan-Yunnan-Guizhou metallogenic province: Constraints from the S-Pb isotopic compositions[J]. Earth Science Frontiers, 2018, 25(1): 125−137.

[27] HAN R S, LIU C Q, HUANG Z L, et al. Geological features and origin of the Huize carbonate-hosted Zn-Pb- (Ag) District, Yunnan, South China[J]. Ore Geology Reviews, 2007, 31: 360−383.

[28] 王超伟, 李 元, 罗海燕, 等. 云南毛坪铅锌矿床的成因探讨[J]. 昆明理工大学学报(理工版), 2009, 34(1): 7−11.

WANG Chao-wei, LI Yuan, LUO Hai-yan, et al. Genesis of Maoping Pb-Zn deposit in Yunnan Province[J]. Journal of Kunming University of Science and Technology (Science and Technology), 2009, 34(1): 7−11.

[29] ZHOU J X, HUANG Z L, YAN Z F. The origin of the Maozu carbonate-hosted Pb-Zn deposit, southwest China: Constrained by C-O-S-Pb isotopic compositions and Sm-Nd isotopic age[J]. Journal of Asian Earth Sciences, 2013, 73: 39−47.

[30] 张云新, 吴 越, 田 广, 等. 云南乐红铅锌矿床成矿时代与成矿物质来源: Rb-Sr和S同位素制约[J]. 矿物学报, 2014, 34(3): 305−311.

ZHANG Yun-xin, WU Yue, TIAN Guang, et al. Mineralization age and the source of ore-forming material at Lehong Pb-Zn deposit, Yunnan province: Constraints from Rb-Sr and S isotopes system[J]. Acta Mineralogica Sinica, 2014, 34(3): 305−311.

[31] 吴 越. 川滇黔地区MVT铅锌矿床大规模成矿作用的时代与机制[D]. 北京: 中国地质大学(北京), 2013.

WU Yue. The age and ore-forming process of MVT deposits in the boundary area of Sichuan − Yunnan − Guizhou provinces, southwest China[D]. Beijing: China University of Geosciences(Beijing), 2013.

[32] 袁 波, 毛景文, 闫兴虎, 等. 四川大梁子铅锌矿成矿物质来源与成矿机制: 硫、碳、氢、氧、锶同位素及闪锌矿微量元素制约[J]. 岩石学报, 2014, 30(1): 209−220.

YUAN Bo, MAO Jing-wen, YAN Xing-hu, et al. Sources of metallogenic materials and metallogenic mechanism of Daliangzi Ore Field in Sichuan Province: Constraints from geochemistry of S, C, H, O, Sr isotope and trace element in sphalerite[J]. Acta Petrologica Sinica, 2014, 30(1): 209−220.

[33] ZHOU J X, GAO J G, CHEN D, et al. Ore genesis of the Tianbaoshan carbonate-hosted Pb-Zn deposit, Southwest China: geologic and isotopic (C-H-O-S-Pb) evidence[J]. International Geology Review, 2013, 55(10): 1300−1310.

[34] ZHU C W, WEN H J, ZHANG Y X, et al. Cadmium and sulfur isotopic compositions of the Tianbaoshan Zn-Pb-Cd deposit, Sichuan Province, China[J]. Ore Geology Reviews,

2016, 76: 152−162.

[35] 何承真, 肖朝益, 温汉捷, 等. 四川天宝山铅锌矿床的锌−硫同位素组成及成矿物质来源[J]. 岩石学报, 2016, 32(11): 3394−3406.
HE Cheng-zhen, XIAO Chao-yi, WEN Han-jie, et al. Zn-S isotopic compositions of the Tianbaoshan carbonate-hosted Pb-Zn deposit in Sichuan, China: Implications for source of ore components[J]. Acta Petrologica Sinica, 2016, 32(11): 3394−3406.

[36] ZHOU J X, HUANG Z L, LV Z C, et al. Geology, isotope geochemistry and ore genesis of the Shanshulin carbonate-hosted Pb-Zn deposit, southwest China[J]. Ore Geology Reviews, 2014, 63: 209−225.

[37] ZHOU J X, HUANG Z L, BAO G P. Geological and sulfur-lead-strontium isotopic studies of the Shaojiwan Pb-Zn deposit, southwest China: Implications for the origin of hydrothermal fluids[J]. Journal of Geochemical Exploration, 2013, 128: 51−61.

[38] CLAYTON R N, O'NEIL J R, MAYEDA T K. Oxygen isotope exchange between quartz and water[J]. Journal of Geophysical Research, 1972, 77(17): 3057−3067.

[39] 郭 欣. 滇东北地区铅锌矿床成矿作用与成矿规律[D]. 北京: 中国地质大学(北京), 2012.
GUO Xin. Mineralization and metallogenic pattern of lead-zinc deposits in Northeast Yunnan[D]. Beijing: China University of Geosciences(Beijing), 2012.

[40] 韩润生, 陈 进, 黄智龙, 等. 构造成矿动力学及隐伏矿定位预测——以云南会泽铅锌(银、锗)矿床为例[M]. 北京: 科学出版社, 2006.
HAN Run-sheng, CHEN Jin, HUANG Zhi-long, et al. Dynamics of tectonic ore-forming processes and Localization-prognosis of concealed orebodies—As exemplified by the Huize Super-large Zn-Pb- (Ag-Ge) district, Yunnan[M]. Beijing: Science Press, 2006.

[41] 阙梅英, 罗安屏, 张立生, 等. 滇东北上震旦一下寒武统层控铅锌矿[M]. 成都: 成都科技大学出版社, 1993.
QUE Mei-ying, LUO An-ping, ZHANG Li-sheng, et al. Upper Sinian and Lower Cambrian stratified lead-zinc deposits in northeastern Yunnan[M]. Chengdu: Chengdu University of Science and Technology Press, 1993.

[42] 杨应选, 柯成熙, 林方成, 等. 康滇地轴东缘铅锌矿床成因及成矿规律[M]. 成都: 四川科技出版社, 1994.
YANG Ying-xuan, KE Cheng-xi, LIN Fang-cheng, et al. Metallogeny of lead-zinc deposit the eastern margin of Kangdian axis[M]. Chengdu: Sichuan Science and Technology Publishing House, 1994.

[43] 王小春. 天宝山铅锌矿床成因分析[J]. 成都地质学院学报, 1992, 19(3): 10−20.
WANG Xiao-chun. Genesis analysis of the Tianbaoshan[J]. Journal of Chengdu College of Technology, 1992, 19(3): 10−20.

[44] ZHENG M H, WANGX C. Ore genesis s of the Daliangzi Pb-Zn deposit in Sichuan, China[J]. Economic Geology, 1991, 86: 831−846.

[45] YAN Z F, HUANG Z L, XU C, et al. Signatures of the source for the Emeishan flood basalts in the Ertan area: Pb isotope evidence[J]. Chinese Journal of Geochemistry, 2007, 26(2): 207−213.

[46] WANG X C, ZHANG Z R, ZHENG M H, et al. Metallogenic mechanism of the Tianbaoshan Pb-Zn deposit, Sichuan[J]. Chinese Journal of Geochemistry, 2000, 19: 121.

[47] WANG J Z, LI Z Q, NI S J. Origin of ore-forming fluids of Mississippi Valley-type (MVT) Pb-Zn deposits in Kangdian area, China[J]. Chinese Journal of Geochemistry, 2003, 22: 369−376.

[48] WANG C M, DENG J, ZHANG S T, et al. Sediment-hosted Pb-Zn deposits in southwest Sanjiang Tethys and Kangdian area on the western margin of Yangtze craton[J]. Acta Geologica Sinica (English Edition), 2010, 84: 1428−1438.

[49] OHMOTO H, RYE R O. Isotopes of sulfur and carbon[M]. BARNES H L, ed. Geochemistry of Hydrothermal Ore Deposits, 2nd ed. New York: John Wiley and Sons, Inc, 1979: 798.

[50] OHMOTO H. Systematics of sulfur and carbon isotopes in hydrothermal ore deposits[J]. Economic Geology, 1972, 67(5): 551−578.

[51] 胡瑞忠, 陶 琰, 钟 宏, 等. 地幔柱成矿系统: 以峨眉山地幔柱为例[J]. 地学前缘, 2005, 12(1): 42−54.
HU Rui-zhong, TAO Yan, ZHONG Hong, et al. Mineralization systems of a mantle plume: A case study from the Emeishan igneous province, southwest China[J]. Earth Science Frontiers, 2005, 12(1): 42−54.

[52] 王 瑞, 张长青, 吴 越, 等. 四川天宝山铅锌矿辉绿岩脉形成时代与成矿关系探讨[J]. 矿床地质, 2012, 31(S1): 449−450.
WANG Rui, ZHANG Chang-qing, WU Yue, et al. Discussion on the relationship between diabase vein formation age and mineralization in Tianbaoshan lead-zinc mine, Sichuan Province[J]. Mineral Deposits, 2012, 31(S1): 449−450.

[53] 王小春. 论四川天宝山铅锌矿床的成矿物理化学条件[J]. 四川地质学报, 1990, 10(1): 34−42.
WANG Xiao-chun. Discussion on the ore forming physicochemical conditions of Tianbaoshan lead-zinc

deposit in Sichuan[J]. Acta Geologica Sichuan, 1990, 10(1): 34−42.

[54] 张同钢, 储雪蕾, 张启锐, 等. 扬子地台灯影组碳酸盐岩中的硫和碳同位素记录[J]. 岩石学报, 2004, 20(3): 717−724.
ZHANG Tong-gang, CHU Xue-lei, ZHANG Qi-rui, et al. The sulfur and carbon isotopic records in carbonates of the Dengying Formation in the Yangtze Platform, China[J]. Acta Petrologica Sinica, 2004, 20(3): 717−724.

[55] SHIELDS G A, STRAUSS H, HOWE S S, et al. Sulphur isotope compositions of sedimentary phosphorites from the basal Cambrian of China: Implications for Neoproterozoic-Cambrian biogeochemical cycling[J]. Journal of the Geological Society, 1999, 156(5): 943−955.

[56] OHMOTO H. Stable isotope geochemistry of ore deposits[J]. Reviews in Mineralogy and Geochemistry, 1986, 16(1): 491−560.

[57] 陈 兴, 薛春纪. 西天山乌拉根大规模铅锌成矿中 H_2S 成因: 菌生结构和硫同位素组成约束[J]. 岩石学报, 2016, 32(5): 1301−1314.
CHEN Xing, XUE Chun-ji. Origin of H_2S in Uragen large-scale Zn-Pb mineralization, western Tien Shan: Bacteriogenic structure and S-isotopic constraints[J]. Acta Petrologica Sinica, 2016, 32(5): 1301−1314.

[58] MACHEL H G, KROUSE H R, SASSEN R. Products and distinguishing criteria of bacterial and thermochemical sulfate reduction[J]. Applied Geochemistry, 1995, 10(4): 373−389.

[59] MACHEL H G. Bacterial and thermochemical sulfate reduction in diagenetic settings—old and new insights[J]. Sedimentary Geology, 2001, 140(1/2): 143−175.

[60] YUAN S D, CHOU I M, BURRUSS R C. Disproportionation and thermochemica1 sulfate reduction reactions in S-H_2O-CH_4 and S-D_2O-CH_4 systems from 200 to 340 ℃ at elevated pressures[J]. Geochimica et Cosmochimica Acta, 2013, 118: 263−275.

[61] LIU W H, ZHANG J, WANG J. Sulfur isotope analysis of carbonate-hosted Zn-Pb deposits in northwestern Guizhou Province, Southwest China: Implications for the source of reduced sulfur[J]. Journal of Geochemical Exploration, 2017, 181: 31−44.

[62] ZHOU J X, LUO K, WANG X C, et al. Ore genesis of the Fule Pb-Zn deposit and its relationship with the Emeishan Large Igneous Province: Evidence from mineralogy, bulk C-O-S and in situ S-Pb isotopes[J]. Gondwana Research, 2018, 54: 161−179.

[63] ZHOU J X, XIANG Z Z, ZHOU M F, et al. The giant Upper Yangtze Pb-Zn province in SW China: reviews, new advances and a new genetic model[J]. Journal of Asian Earth Sciences, 2018, 154: 280−315.

[64] KESLER S E, VENNEMANN T W, FREDERICKSON C, et al. Hydrogen and oxygen isotope evidence for origin of MVT-forming brines, southern Appalachians[J]. Geochimica et Cosmochimica Acta, 1997, 61(7): 1513−1523.

[65] CANALS A, CARDELLACH E. Ore lead and sulphur isotope pattern from the low-temperature veins of the Catalonian Coastal Ranges (NE Spain) [J]. Mineralium Deposita, 1997, 32: 243−249.

[66] 侯明兰, 丁 昕, 蒋少涌. 胶东蓬莱河西金矿床铅、硫同位素地球化学特征[J]. 地球学报, 2004, 25(2): 145−150.
HOU Ming-lan, DING Xi, JIANG Shao-yong. Lead and sulfur isotope geochemistry of the Hexi gold deposit in Penglai, eastern Shandong[J]. Acta Geoscientica Sinica, 2004, 25(2): 145−150.

[67] 蒋少涌, 杨 涛, 李 亮, 等. 大西洋洋中脊TAG热液区硫化物铅和硫同位素研究[J]. 岩石学报, 2006, 22(10): 2597−2602.
JIANG Shao-yong, YANG Tao, LI Liang, et al. Lead and sulfur isotopic compositions of sulfides from the TAG hydrothermal field, Mid-Atlantic Ridge[J]. Acta Petrologica Sinica, 2006, 22(10): 2597−2602.

[68] 朱林生. 会泽金牛厂铅锌矿床成矿地质条件及成矿预测[D]. 昆明: 昆明理工大学, 2009.
ZHU Lin-sheng. Metallogenic geological conditions and metallogenic prediction of the Jinniuchang Pb-Zn deposit in Huize[D]. Kunming: Kunming University of Science and Technology, 2009.

[69] ZHOU J X, HUANG Z L, ZHOU G F, et al. Trace elements and rare earth elements of sulfide minerals in the Tianqiao Pb-Zn ore deposit, Guizhou Province, China[J]. Acta Geologica Sinica (English Edition), 2011, 85(1): 189−199.

[70] 鲍 淼, 周家喜, 黄智龙, 等. 铅锌矿床定年方法及川−滇−黔铅锌成矿域年代学研究进展[J]. 矿物学报, 2011, 31(3): 391−396.
BAO Miao, ZHOU Jia-xi, HUANG Zhi-long, et al. Dating methods for Pb-Zn deposits and chronology research progress of Sichuan−Yunnan−Guizhou Pb-Zn metallogenic Province: A review[J]. Acta Mineralogica Sinica, 2011, 31(3): 391−396.

[71] ZARTMAN R E, DOE B R. Plumbotectonics—the model[J]. Tectonophysics, 1981, 75(1/2): 135−162.

[72] 周朝宪. 滇东北麒麟厂锌铅矿床成矿金属来源、成矿流体特征和成矿机理研究[J]. 矿物岩石地球化学通报, 1998, 17(1): 36−38.
ZHOU Chao-xian. The source of mineralizing metals,

geochemical characterization of ore-forming solution, and metallogenetic mechanism of Qilinchang Zn-Pb deposit, northeastern Yunnan Province, China[J]. Bulletin of Mineralogy, Petrology and Geochemistry, 1998, 17(1): 36−38.

[73] 李 波. 滇东北地区会泽、松梁铅锌矿床流体地球化学与构造地球化学研究[D]. 昆明: 昆明理工大学, 2010.
LI Bo. The study of fluid inclusions geochemistry and tectonic geochemistry of lead-zinc deposits: taking Huize and Songliang lead-zinc deposits for examples, in the northeast of Yunnan province, China[D]. Kunming: Kunming University of Science and Technology, 2010.

[74] 朱赖民, 袁海华, 栾世伟. 四川底苏、大梁子铅锌矿床同位素地球化学特征及成矿物质来源探讨[J]. 矿物岩石, 1995, 15(1): 72−79.
ZHU Lai-min, YUAN Hai-hua, LUAN Shi-wei. A study of isotopic geochemical features and minerogenetic material source of the disu and Daliangzi Pb-Zn deposits, Sichuan[J]. Journal of Mineralogy and Petrology, 1995, 15(1): 72−79.

[75] ZAW K, PETERS S G, CROMIE P, et al. Nature, diversity of deposit types and metallogenic relations of South China[J]. Ore Geology Reviews, 2007, 31(1/2/3/4): 3−47.

[76] ZHANG C Q, WU Y, HOU L, et al. Geodynamic setting of mineralization of Mississippi Valley-type deposits in world-class Sichuan-Yunnan-Guizhou Zn-Pb triangle, southwest China: Implications from age-dating studies in the past decade and the Sm-Nd age of Jinshachang deposit[J]. Journal of Asian Earth Sciences, 2015, 103: 103−114.

[77] YIN M D, LI W B, SUN X W. Rb-Sr isotopic dating of sphalerite from the giant Huize Zn-Pb ore field, Yunnan Province, Southwestern China[J]. Chinese Journal of Geochemistry, 2009, 28(1): 70−75.

[78] HAN R S, ZOU H J, HU B, et al. Features of fluid inclusions and sources of ore-forming fluid in the Maoping carbonate-hosted Zn-Pb- (Ag-Ge) deposit, Yunnan, China[J]. Acta Petrologica Sinica, 2007, 23(9): 2109−2118.

[79] 沈战武, 金灿海, 代堰锫, 等. 滇东北毛坪铅锌矿床的成矿时代: 闪锌矿 Rb-Sr 定年[J]. 高校地质学报, 2016, 22(2): 213−218.
SHEN Zhan-wu, JIN Can-hai, DAI Yan-pei, et al. Mineralization age of the Maoping Pb-Zn deposit in the northeastern Yunnan Province: Evidence from Rb-Sr isotopic dating of sphalerites[J]. Geological Journal of China Universities, 2016, 22(2): 213−218.

[80] 毛景文, 周振华, 丰成友, 等. 初论中国三叠纪大规模成矿作用及其动力学背景[J]. 中国地质, 2012, 39(6): 1437−1471.
MAO Jing-wen, ZHOU Zhen-hua, FENG Cheng-you, et al. A preliminary study of the Triassic large-scale mineralization in China and its geodynamic setting[J]. Geology in China, 2012, 39(6): 1437−1471.

[81] WU Y, ZHANG C Q, MAO J W, et al. The genetic relationship between hydrocarbon systems and Mississippi Valley-type Zn-Pb deposits along the SW margin of Sichuan Basin, China[J]. International Geology Review, 2013, 55(8): 941−957.

[82] 韩润生, 王明志, 金中国, 等. 黔西北铅锌多金属矿集区成矿构造体系及其控矿机制[J]. 地质学报, 2020, 94(3): 850−868.
HAN Run-sheng, WANG Ming-zhi, JIN Zhong-guo, et al. Ore-controlling mechanism of NE-trending ore-forming structural system at Zn-Pb polymetallic ore concentration area in northwestern Guizhou[J]. Acta Geologica Sinica, 2020, 94(3): 850−868.

Constraints of fluid inclusion and H-O-S-Pb isotope compositions on metallogenic model of Jinniuchang Pb-Zn deposit, SW China

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Abstract: The Jinniuchang Pb-Zn deposit hosted in the argillaceous and calcareous siltstone of the Lower

Cambrian Qiongzhusi Formation is a non-carbonate-hosted epigenetic hydrothermal deposit in the deposit-concentrated district in northeastern Yunnan of the Sichuan–Yunnan–Guizhou Pb-Zn polymetallic metallogenic triangle area(SYGT). The content of Pb and Zn in the ore-bearing strata of the mining area is abnormally high, and the Pb isotopic composition of the ore is basically consistent with that of the basement rocks (Kunyang group). Whether the ore source layer is the basement or the Qiongzhusi Formation, and whether the Jinniuchang deposit has the same metallogenic mechanism as other carbonate-hosted Pb-Zn deposits in the district, which are related to the Pb-Zn metallogenic system and the prospecting potential of deep deposits. Based on the microthermometry of fluid inclusions and the sulfide H-O-S-Pb isotopic composition analysis, the following results are achieved: 1) The homogenisation temperatures of fluid inclusions in quartz range from 165 ℃ to 274 ℃, with an average value of 216 ℃; the salinity range from 6.5% to 14.0% $NaCl_{eqv}$, with an average value of 7.8% $NaCl_{eqv}$, indicating the ore-forming fluid belongs to the gas-rich fluid with medium-low temperature and medium-low salinity. Microscopic laser Raman spectroscopy analysis shows that the liquid phase composition of fluid inclusions is mainly H_2O, and the gas phase composition is mainly CH_4. 2) The H and O isotopic composition characteristics of the gangue mineral quartz indicate that the ore-forming fluid is mainly derived from the mixing of deep source metamorphic water flowing through deep fold basement (Kunyang group) and organic-containing basin brine. 3) The sulfides' $\delta^{34}S$ values are similar to the main Pb-Zn deposits in the SYGT, which is interpreted as that the reduced S is mainly derived from sulfates in marine sedimentary rocks in dolomites of the Sinian Dengying Formation and the Lower Cambrian Yuhucun Formation through thermochemical reduction of sulfur (TSR). 4) Sulfides have Pb isotopic compositions that form a linear trend on the average crustal Pb growth curve in $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plot. Moreover, Pb isotopic ratios are consistent with the basement rocks, consequently suggesting crustal Pb sources with the majority of Pb are derived from the basement rocks (Kunyang group). The clastic rocks of the Lower Cambrian Qiongzhusi Formation also provide part of the Pb sources. Combined with the comparative study of the deposit, we conclude that the Jinniuchang deposit and major Pb-Zn deposits in the SYGT formed under the same metallogenic geological background and had a similar metallogenic model, but the Jinniuchang deposit has its own characteristics in terms of ore-bearing wall rock, ore-bearing fracture properties, and mineral sources. This achievement provides a basis for the study of the Pb-Zn metallogenic system and a new idea for the deep and peripheral prospecting of the Pb-Zn deposits in the SYGT.

Key words: microthermometry of fluid inclusions; H-O-S-Pb isotopes; source of ore-forming materials; metallogenic model; Jinniuchang Pb-Zn deposit

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