文章编号：0258-7106（2022）04-0806-17　　**Doi:** 10. 16111/j. 0258-7106. 2022. 04. 009

黔西北乐开铅锌矿床成矿物质来源及矿床成因：来自硫、铅同位素的证据*

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摘　要　赋存于泥盆系望城坡组白云岩中的乐开铅锌矿床位于扬子地块西南缘川滇黔接壤铅锌矿集区，主要发育似层状矿体，具有典型的"逆(逆断裂)导-张(张断裂)运-岩(受断裂影响的碳酸盐岩破碎空间被碳质黏土岩圈闭形成的有利岩性组合)储"构造控矿模式。矿石矿物主要为闪锌矿、方铅矿、黄铁矿，发育(网)脉状、角砾状、浸染状等构造与交代、充填、共边等结构，后生成矿特征明显。硫化物 $\delta^{34}S$ 值为 11.1‰~18.1‰(均值约 14.7‰)，明显高于幔源岩浆硫的 $\delta^{34}S$ 值，与泥盆纪同期海水硫酸盐的 $\delta^{34}S$ 值相近，显示硫化物中的还原硫可能是赋矿地层中的高溶解度硫酸盐热化学反应(TSR)的产物。硫化物铅同位素 $^{206}Pb/^{204}Pb$ 值为 18.400‰~18.767‰(均值为 18.565‰)；$^{207}Pb/^{204}Pb$ 值为 15.660‰~16.058‰(均值为 15.791‰)；$^{208}Pb/^{204}Pb$ 值为 38.580‰~39.432‰(均值为 39.059‰)，变化范围相对较大。铅同位素的 $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ 图解与 $\Delta\gamma$-$\Delta\beta$ 图解显示明显的壳源特征，同时暗示沉积岩石与基底岩石共同提供了成矿物质。综合矿床地质、硫化物硫、铅同位素特征，笔者认为乐开铅锌矿床的成矿过程为盆地流体循环萃取沉积岩石与基底岩石的金属元素后形成含矿流体，含矿流体被深大断裂导入上覆沉积地层的特殊构造部位(被碳质黏土岩圈闭的碳酸盐岩破碎空间)时，富含的热量导致沉积盖层中硫酸盐发生热化学反应(TSR)，生成大量的 S^{2-}，与含矿流体中的 Pb^{2+}、Zn^{2+}、Fe^{2+}等金属阳离子结合成矿。乐开铅锌矿床的地质地球化学特征与 MVT 型矿床类似，因此，乐开铅锌矿床属于 MVT 型铅锌矿床。成矿物质来源与矿床类型的确定有利于川滇黔接壤铅锌矿集区同类型铅锌矿床的勘查与开发。

关键词　地质学；构造控矿模式；硫、铅同位素；矿床成因；乐开铅锌矿床；川滇黔接壤铅锌矿集区

中图分类号：P618.42；P618.43　　**文献标志码：**A

Sources of metallogenic materials and genesis of Lekai lead-zinc deposit in northwestern Guizhou Province: Evidence from S and Pb isotopes

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*　本文得到云南省万人计划青年拔尖人才基金(编号：YNWR-QNBJ-2018-093)、国家自然科学基金(编号：41862007)、昆明理工大学重点学科建设基金(编号：14078384)联合资助

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收稿日期　2021-11-23；改回日期　2022-06-25。张绮玲编辑。

Abstract

The Lekai lead-zinc deposit, which is hosted in the dolomite of the Devonian Wangchengpo Formation, is located in the Sichuan-Yunnan-Guizhou lead-zinc metallogenic province (SYGMP) on the southwest margin of the Yangtze block. It mainly develops layered ore bodies, and has a typical fault-controlled style of ‘reverse fault importing-tension fault transporting-lithologic assemblages stored ore fluids (the fracture space of carbonate rock affected by fault is trapped by carbonaceous clay rock to form favorable ore bearing lithologic association)’. Ore minerals are mainly sphalerite, galena and pyrite, with veined, brecciated, and disseminated structures, and the ore textures consist of metasomatic, co-dissolved and filling morphologies, with obvious epigenetic metallogenic characteristics. The $\delta^{34}S$ values of single grain sulfide range from 11.1‰ to 18.1‰ (mean 14.7‰), which is obviously higher than that of mantle magma-derived sulfur, but close to that of Devonian seawater sulfate, revealed that S^{2-} originated from high-solubility sulfate within the ore-hosting strata through thermochemical sulfide reduction (TSR) processes. The Pb isotope $^{206}Pb/^{204}Pb$ of single grain sulfide ranges from 18.400‰ to 18.767‰ (mean 18.565‰). The $^{207}Pb/^{204}Pb$ values ranged from 15.660‰ to 16.058‰ (mean 15.791‰). The $^{208}Pb/^{204}Pb$ values range from 38.580‰ to 39.432‰ (mean 39.059‰), with a relatively wide range. The $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ and $\triangle\gamma$-$\triangle\beta$ diagrams of Pb isotopes obviously show crust source characteristics, and suggest that the sedimentary rocks and basement rocks both provided ore-forming materials. Based on the characteristics of deposit geology, structural ore-controlling, S and Pb isotopes of sulfide, this paper holds that the metallogenic process of the Lekai lead-zinc deposit is: the basin fluid extracted metal elements from sedimentary rocks and basement rocks and formed ore-bearing fluids; the ore-bearing fluid is diverted by deep faults into special structural parts of the overlying sedimentary strata (carbonate fracture space trapped by carbonaceous clay rocks); under the action of the heat of the ore-bearing fluid, the sulphates in the sedimentary strata underwent TSR, and a large amount of S^{2-} was generated, which combined with the metal cations such as Pb^{2+}, Zn^{2+} and Fe^{2+} in the ore-bearing fluids resulting the formation of sulfide ores. The geological and geochemical characteristics of the Lekai lead-zinc deposit are similar to those of MVT deposits, thus we propose that the Lekai lead-zinc deposit is MVT deposit. The determination of ore-forming material source and deposit type is beneficial to the exploration and development of the same type of lead-zinc deposit in the SYGMP.

Key words: geology, structural ore-control style, S-Pb isotope, genesis of mineral deposit, Lekai lead-zinc deposit, Sichuan-Yunnan-Guizhou lead-zinc metallogenic province (SYGMP)

世界范围内沉积岩型铅锌矿床主要包含密西西比河谷型(MVT)、碎屑岩型(CD,含 SEDEX)与爱尔兰型(Irish)(Leach et al., 2010; Wilkinson et al., 2014),其中MVT型铅锌矿床是一类赋存于台地相碳酸盐岩层序中、成矿流体为盆地卤水、成矿温度较低的铅锌矿床(Leach et al., 1993)。MVT型铅锌矿床的矿床数和矿石储量在超大型铅锌矿床中的比例分别为24%和23% (戴自希, 2005),其铅锌资源量占世界铅锌资源量的20%~27% (张长青等, 2009; Leach et al., 2010),为世界铅锌资源的主要来源之一。该类铅锌矿床分布广泛,在北美洲(美国、加拿大)、南美洲(巴西、秘鲁)、欧洲(爱尔兰、意大利、法国)、亚洲(中国、伊朗)、大洋洲(澳大利亚)、非洲(摩洛哥、纳米比亚)等均有分布(Leach et al., 2001; 毛景文等, 2012),以至于该类型铅锌矿床在动力学背景、控矿构造、物质来源、成矿时代、流体来源、沉淀机制等方面虽取得了丰富成果(Spirakis et al., 1993; Leach et al., 2001; Bradley et al., 2003; 2004; Pannalal et al., 2004; Merce et al., 2004; Leach et al., 2005; Li et al., 2007a; 2007b; 2007c; Stoffell et al., 2008; Shelton et al., 2009; Appold et al., 2011; Pelch et al., 2015),但存在较大差异,未能形成统一的成矿模式。

扬子地块西南缘的川滇黔接壤铅锌矿集区是中国主要的碳酸盐岩型铅锌矿床产出地(涂光炽, 2001; 黄智龙等, 2004; Huang et al., 2010; 毛景文等, 2012; Zhang et al., 2013; Hu et al., 2017a; 2017b;

Zhou et al., 2018a; 2018b)。川滇黔接壤铅锌矿集区共发现3处超大型铅锌矿床(会泽、乐马厂、猪拱塘),9处大型铅锌矿(天宝山、小石房、大梁子、赤普、乌斯河、毛坪、茂祖、乐红、富乐)以及400余处中-小型铅锌矿床和矿化点(垭都、蟒硐、亮岩、猫猫厂、银厂坡、青山等) (Ye et al., 2011; Hu et al., 2017b; 崔银亮等, 2018; 韩润生等, 2020a),是中国甚至全世界最重要的铅锌多金属资源生产基地之一(黄智龙等, 2004; Hu et al., 2012; Zhang et al., 2015)。该矿集区的铅锌矿床以规模大(中型及以上规模铅锌矿床发育)、含矿层位多(震旦系至二叠系均有工业矿体分布)、构造控矿特征明显(矿体与构造关系密切,"一矿多层"特征明显)、矿石品位高(Pb+Zn普遍约20%)、矿物成分简单(主要矿石矿物为闪锌矿、方铅矿、黄铁矿)为主要特征,是中国最重要的一类铅锌矿床,对其勘查开发可以改变中国铅锌矿床规模小、矿石品位低、选冶难度高的局面。

长期以来,众多学者对川滇黔接壤铅锌矿集区铅锌矿床的地质背景、构造控矿、物质来源、成矿时代及矿床成因等方面进行了大量研究,取得了许多重要成果及认识(黄智龙等, 2001;2004; 李文博等, 2004; 裴荣富等, 2005; 杨永强等, 2006; 张长青等, 2005;2008;2009;金中国等, 2007;2008; 张准等, 2011; 程鹏林等, 2015; 熊伟等, 2015; Zhang et al., 2015; Hu et al., 2017a; 2017b; Zhou et al., 2018a;2018b; 韩润生等, 2014;2019;2020b),提出了地层来源(柳贺昌, 1996; 李文博等, 2002; 涂首业, 2014)、基底来源(Wang et al., 2000; 钱建平, 2001)、混合来源(韩润生等, 2001; 黄智龙等, 2004; Zhou et al., 2013a;2013b;2013c;2013d;2014a;2014b)等多种成矿物质来源观点及燕山期(王奖臻等, 2002; 张长青等, 2005),海西-印支期(管士平等, 1999; 黄智龙等, 2004; 李文博等, 2004),晚印支期—燕山期(蔺志永等, 2010; 毛景文等, 2012; 白俊豪等, 2013; 吴越等, 2013; Zhou et al., 2013a)等不同成矿时代观点。矿床成因及类型经过几十年的系统研究基本趋于统一,为后生热液成因,但矿床类型是否属于MVT型仍存在一定的争议,主要有MVT型(张长青, 2008; 吴越等, 2013; Li W B et al., 2007a;2007b; Li Z L et al., 2018; Xiong et al., 2018)、SYG型(川滇黔型)(Zhou et al., 2018a)、岩浆-热液型(Wang et al., 2000; 王登红, 2001; 李文博等, 2004; 高振敏等, 2004; Liu et al., 2015; 秦建华等, 2016)与HZT型(会泽体)(韩润生等, 2019;2020a;2020b)等4种类型。

川滇黔接壤铅锌矿集区主要由黔西北铅锌成矿带、滇东北铅锌成矿带、川西南铅锌成矿带构成,乐开铅锌矿床位于黔西北成矿带与滇东北成矿带的交界处,与滇东北成矿带铅锌矿床具有类似的成矿条件,对该矿床的研究有利于黔西北成矿带与滇东北成矿带的对比研究。本文主要基于上述研究成果,重点剖析乐开铅锌矿床的矿体赋存特征、控矿构造-岩性组合特征与硫、铅同位素地球化学特征;深入分析成矿物质来源,以期为该类铅锌矿的找矿预测提供依据。

1 区域地质

扬子地块西南缘地处环太平洋构造域和特提斯构造域的结合部位,是中国西南大面积低温成矿域的一个重要单元(涂光炽, 2001; Hu et al., 2017a; 2017b),主要由基底变质岩、海/陆相盖层沉积岩及火成岩构成。基底变质岩主要为古元古代康定群的一套闪长质、花岗质混合片麻岩、混合岩等深变质岩及中-新元古代昆阳/会理群的一套浅海相类复理石碎屑岩夹火山岩-碳酸盐岩建造等浅-中变质岩。盖层序列主要由震旦纪至二叠纪海相及中-新生代陆相沉积岩组成。

火成岩主要为晚二叠世峨眉山玄武岩及同源辉绿岩(Zhou et al., 2018a)。构造变形以断裂发育为主要特征,研究区先后经历了南华纪大陆裂谷(李献华等, 2001)、震旦纪—晚二叠世被动大陆边缘(何斌等, 2005)、晚二叠世—晚三叠世地幔柱活动及陆内裂谷(宋谢炎等, 2002)、晚三叠世晚期—白垩纪前陆盆地造山作用(骆耀南等, 2001)等地质-构造演化阶段。这些构造事件主要控制了该区域内的沉积作用、岩浆作用和成矿作用(柳贺昌等, 1999; 黄智龙等, 2001; Zhou et al., 2013c; 张长青等, 2014)。乐开铅锌矿床主要受晚印支运动活动的一系列断裂和褶皱的控制。

2 矿床地质

乐开铅锌矿床位于会泽-彝良-牛街斜冲走滑-断褶带的南延段,受NE向洛泽河断-褶构造控制。矿区褶皱主要发育NE向的石门背斜和一系列次级褶皱(图1),石门背斜核部出露石炭系汤粑沟组(C_1t)燧

石灰岩与祥摆组(C_1x)碳质黏土岩,NW翼出露石炭系至二叠系碳酸盐岩与碎屑岩,SE翼被洛泽河断裂带(F_1、F_2、F_3)破坏,SE翼次级褶皱的虚脱空间为成矿有利空间。洛泽河断裂在研究区内呈NE向展布,分支为F_1、F_2、F_3三条断层,具“多”字型和“入”字型构造格架,F_2为主要的推覆构造,与F_1、F_3形成叠瓦状逆冲推覆体系,将泥盆系望城坡组(D_3w)白云岩反复推移至地表,形成研究区的地层格架和矿体展布,其与成矿关系密切。研究区内NW向构造规模较小,为NW向垭都-蟒硐断裂的同向次级断裂(图1)。

矿体呈脉状、透镜状及似层状赋存于泥盆系望城坡组(D_3w)中-粗晶蚀变白云岩(含4~5层厚20~50 m的碳质黏土岩)中的褶皱和构造的复合空间,共发育4个铅锌矿(化)体,在平面上、剖面上呈现“缓宽陡窄”和“膨大缩小”的显著特征(图1、图2、图3a)。该矿床的形成经历了2个成矿期:热液成矿期和表生

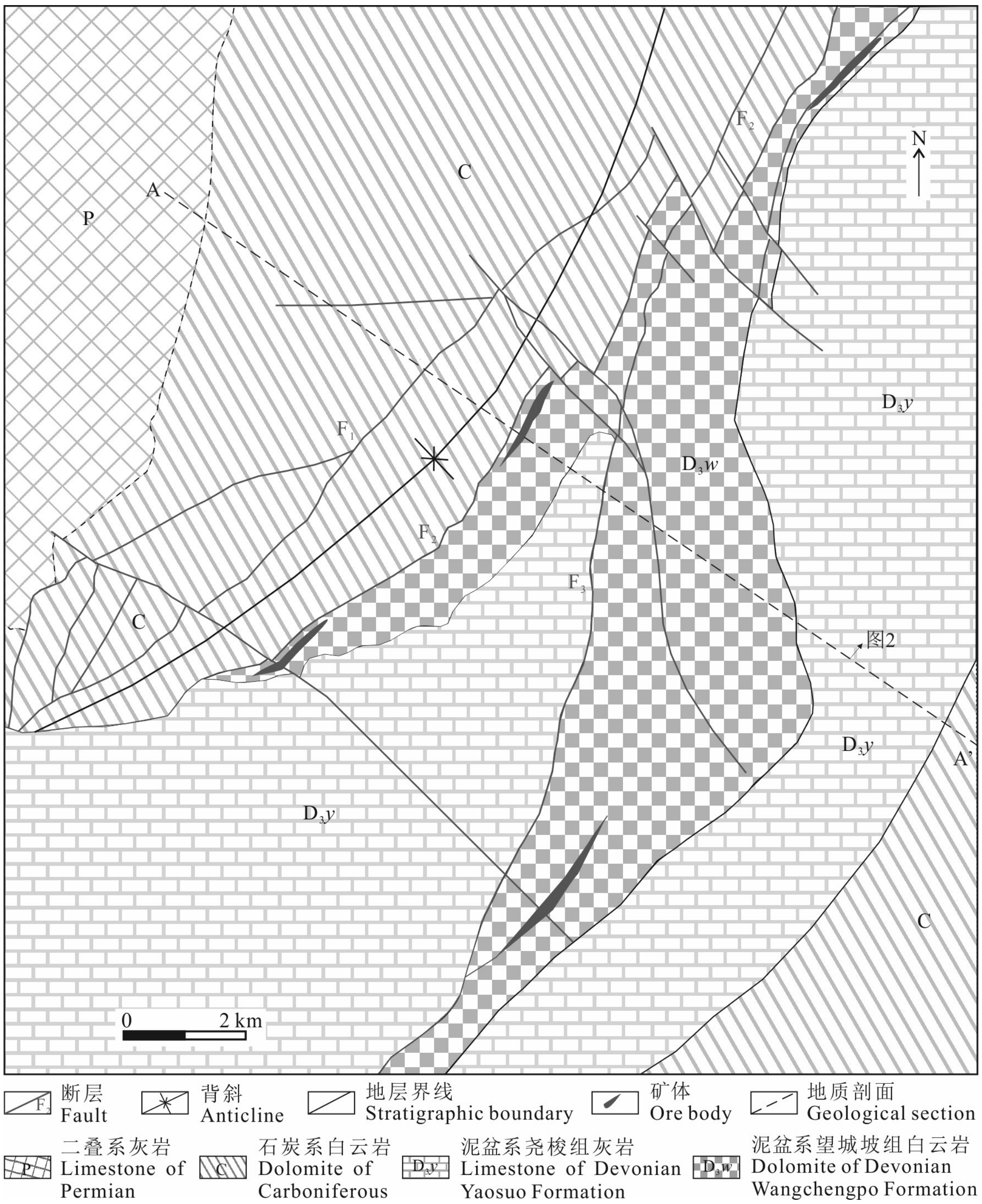

图1　乐开铅锌矿床地质简图

Fig.1　Geologic sketch map of the Lekai lead-zinc deposit

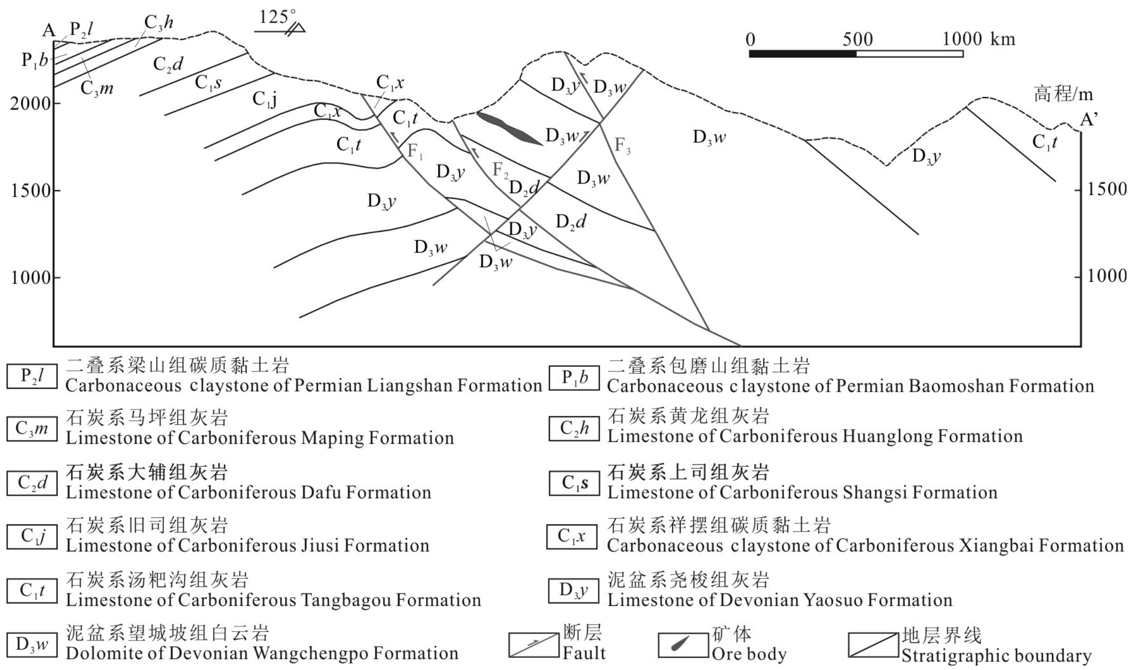

图2 乐开铅锌矿床矿体A-A'剖面图

Fig. 2 Cross section A-A' through the Lekai lead-zinc deposit

氧化期(万新等, 2020)。热液成矿期主要发育闪锌矿、方铅矿、黄铁矿等矿石矿物及白云石、方解石等脉石矿物。

矿石构造以角砾状(图3b)、网脉状(图3c)、浸染状(图3d)为主,矿石结构以半自形-他形晶粒状结构为主(图3e),发育填隙(图3f、g、l)、共边(图3h、i)、交代(图3j、k)、压碎(图3l)等结构。热液成矿期划分为3个阶段:ⅰ 黄铁矿+白云石;ⅱ 方铅矿+黄铁矿+闪锌矿+方解石;ⅲ 方铅矿+黄铁矿。表生氧化期主要矿物为白铅矿、菱锌矿及褐铁矿。矿区围岩蚀变主要为白云石化、方解石化。

3 样品及分析方法

本文研究样品采自乐开铅锌矿床老硐LD3、LD11,在野外详细地质编录与观察描述的基础上,采集有代表性的新鲜矿石样品(鉴于成矿第ⅰ、ⅲ阶段矿石颗粒细小,不易挑选矿物,为避免挑选矿物为混合成分,本次研究主要挑选成矿第ⅱ阶段颗粒相对较粗的硫化物矿石),分析样品以角砾状、脉状、团块状矿石为主,角砾状矿石主要是方铅矿、闪锌矿充填于蚀变白云岩角砾之间;脉状矿石主要为方铅矿、闪锌矿、黄铁矿等呈脉状、条带状穿插于蚀变粗晶白云岩中;团块状矿石主要为方铅矿、闪锌矿呈大小不等的团块分布在蚀变粗晶白云岩中。所选样品整理后粉碎至40~60目,在双目镜下挑选纯度大于99%的黄铁矿、闪锌矿和方铅矿,然后超声清洗样品,再在双目镜下进行反复挑纯。用玛瑙研钵将挑纯的硫化物样品研至200目,以备硫、铅同位素分析。实验均在广州澳实公司(ALS Scandinavia AB)同位素实验室完成。

硫化物的硫同位素在MAT-253气体质谱仪上进行,实验采用Vienna Conyon Diablo Troilite (V-PDB)作为参照标准,硫同位素以STD-1(−0.22‰)、STD-2(22.57‰)、STD-3(−32.53‰)为标样校正,测试误差±0.1‰。硫化物的铅同位素分析在多接受器等离子体质谱仪(MC-ICP-MS)上完成,测试先用混合酸分解,然后用树脂交换法分离出Pb,铅同位素标样NBS 981的分析结果为$^{206}Pb/^{204}Pb=16.936\pm0.003$,$^{207}Pb/^{204}Pb=15.489\pm0.040$,$^{208}Pb/^{204}Pb=36.672\pm0.050$。

4 分析结果

4.1 硫同位素

乐开铅锌矿床13件硫化物的$\delta^{34}S$的值介于

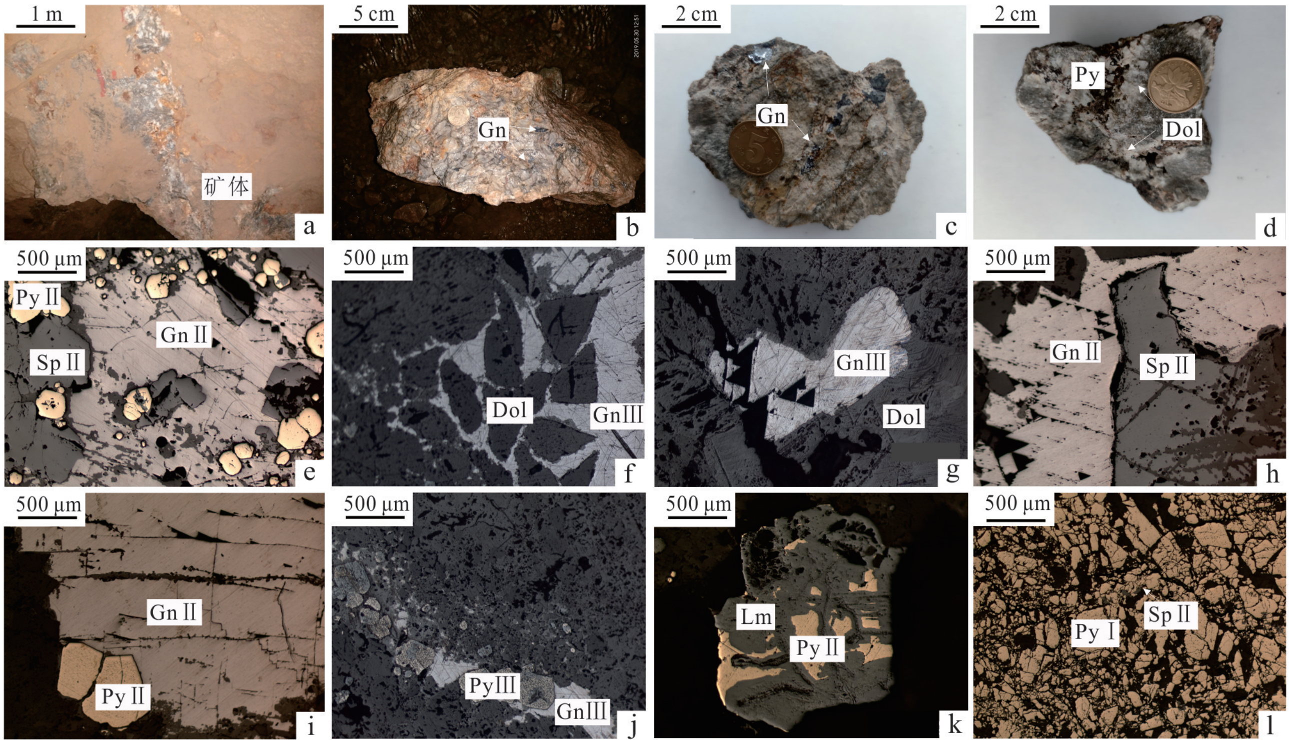

图3 乐开铅锌矿床矿石结构-构造照片

a. 乐开铅锌矿床矿体特征;b. 角砾状铅锌矿石,方铅矿充填于蚀变白云岩角砾之间;c. 方铅矿、闪锌矿呈脉状、团块状;d. 黄铁矿、方铅矿、白云石呈浸染状分布于蚀变粗晶白云岩;e. 方铅矿、闪锌矿、黄铁矿呈半自形-他形晶粒状结构;f. 方铅矿充填于角砾白云石之间;g. 团块状方铅矿充填于破碎白云石中;h. 方铅矿与闪锌矿呈共边结构;i. 方铅矿与黄铁矿呈共边结构;j. 方铅矿与黄铁矿呈脉状交代白云石;k. 褐铁矿交代黄铁矿;l. 黄铁矿在应力作用下发生机械破碎,闪锌矿充填于黄铁矿的破碎空间

Sp—闪锌矿;Py—黄铁矿;Gn—方铅矿;Dol—白云石;Lm—褐铁矿;Ⅰ—ⅰ阶段;Ⅱ—ⅱ阶段;Ⅲ—ⅲ阶段

Fig. 3 Photographs showing the ore texture and structure from the Lekai lead-zinc deposit

a. Orebody characteristics of the Lekai lead-zinc deposit; b. Brecciated lead-zinc ore, galena filled between altered dolomite breccia; c. Galena and sphalerite are veined and lumpy; d. Pyrite, galena, dolomite disseminated in the altered coarse-grained dolomite; e. Galena, sphalerite and pyrite occur in subhedral-anhedral crystalline granular texture; f. Galena is filled between brecciated dolomite; g. Mass galena is filled in broken dolomite; h. Common edge texture formed by galena and sphalerite; i. Common edge texture formed by galena and pyrite; j. Galena and pyrite in veins replacing dolomite; k. Pyrite is metasomatized by limonite; l. Mechanical crushing of pyrite occurs under stress, and sphalerite fills the broken space of pyrite

Sp—Sphalerite; Py—Pyrite; Gn—Galena; Dol—Dolomite; Lm—Limonite; Ⅰ—Stage ⅰ; Ⅱ—Stage ⅱ; Ⅲ—Stage ⅲ

11.1‰~18.1‰,均值14.7‰,显示富集重硫特征(表1)。其中方铅矿(n=6)$\delta^{34}S$的值介于11.1‰~13.3‰,均值12.5‰,闪锌矿(n=6)$\delta^{34}S$的值介于14.7‰~16.9‰,均值16.4‰,黄铁矿(n=1)的$\delta^{34}S$值为18.1‰。

4.2 铅同位素

乐开铅锌矿床的铅同位素组成变化范围较大(表2),方铅矿(n=6)的$^{206}Pb/^{204}Pb$、$^{207}Pb/^{204}Pb$和$^{208}Pb/^{204}Pb$分别为18.400~18.590、15.660~15.850和38.580~39.340,闪锌矿(n=3)的$^{206}Pb/^{204}Pb$、$^{207}Pb/^{204}Pb$和$^{208}Pb/^{204}Pb$分别为18.635~18.767、15.785~16.058和39.052~39.432,黄铁矿(n=1)的$^{206}Pb/^{204}Pb$、$^{207}Pb/^{204}Pb$和$^{208}Pb/^{204}Pb$分别为18.614、15.789和39.158。

5 讨 论

5.1 成矿物质来源

5.1.1 硫同位素约束

乐开铅锌矿床硫化物硫同位素组成具有$\delta^{34}S_{黄铁矿}$(均值约18.1‰) > $\delta^{34}S_{闪锌矿}$(均值约16.4‰) > $\delta^{34}S_{方铅矿}$(均值约12.5‰)的特征,显示S同位素在硫化物间的分馏达到了热力学平衡。乐开铅锌矿床矿石矿物组合简单,主要为闪锌矿、方铅矿、黄铁矿,未发现硫酸盐岩矿物。因此,硫化物(特别是黄铁矿)的$\delta^{34}S$值可近似代表热液流体的$\delta^{34}S_{\Sigma S}$值,(Ohmo-

表 1 乐开铅锌矿床硫化物硫同位素组成表

Table1 Sulfur isotopic composition of sulfides from the Lekai lead-zinc deposit

样品号	矿物类型	$\delta^{34}S$/‰
LD03R0	方铅矿	11.1
LD03R7	方铅矿	12.6
LD03R8	方铅矿	13.1
LD03R10	方铅矿	12.5
LD11R6-1	方铅矿	12.6
LD11R6-6	方铅矿	13.3
LD03R0	闪锌矿	14.7
LD03R5	闪锌矿	16.7
LD03R6	闪锌矿	15.7
LD03R7	闪锌矿	17.4
LD03R8	闪锌矿	16.7
LD03R10	闪锌矿	16.9

to, 1972; Ohmoto et al., 1997)，即 $\delta^{34}S_{\Sigma S} \approx \delta^{34}S_{黄铁矿}$ = 18.1‰。明显高于幔源岩浆硫的 $\delta^{34}S$ 值(0±3‰, Chaussidon et al., 1989)，暗示岩浆作用提供大量硫源的可能性不高。

乐开铅锌矿床硫化物 $\delta^{34}S$ 值为 11.1‰~18.1‰ (均值约 14.7%)，与泥盆纪同期海水硫酸盐的 $\delta^{34}S$ 值(15‰~27‰, Claypool et al., 1980)相近，显示残存的泥盆纪海水硫酸盐可能是乐开铅锌矿床硫的主要来源，此外有研究发现区域各沉积地层中石膏、重晶石等膏岩层的 $\delta^{34}S$ 值为 22‰~28‰(黄智龙等，2004；金中国等, 2008; Zhou et al., 2013a)，而硫酸盐的热化学还原作用可导致 15‰ 的硫同位素分馏(Ohmoto et al., 1997)，即理论上膏岩层热化学还原后生成的硫化物 $\delta^{34}S$ 值约 7‰~13‰，因而不同沉积地层中石膏、重晶石等硫酸盐可能为乐开铅锌矿的形成提供了部分硫来源。

图 4 显示区域上各时代铅锌矿床硫化物的 $\delta^{34}S$ 值及相对应的海水硫酸盐 $\delta^{34}S$ 值的变化。不难发现，垭都、富乐、筲箕湾等赋存于二叠系的铅锌矿床硫化物的 $\delta^{34}S$ 值≤会泽、天桥、青山、杉树林等赋存于石炭系的铅锌矿床的硫化物的 $\delta^{34}S$ 值≤乐开等赋存于泥盆系的铅锌矿床硫化物的 $\delta^{34}S$ 值≤纳雍枝等赋存于寒武系的铅锌矿床的硫化物的 $\delta^{34}S$ 值，此现象与二叠纪海水硫酸盐 $\delta^{34}S$ 值≤石炭纪海水硫酸盐 $\delta^{34}S$ 值≤泥盆纪海水硫酸盐 $\delta^{34}S$ 值≤寒武纪海水硫酸盐 $\delta^{34}S$ 值的现象严格对应，进一步说明各铅锌矿床的硫源主要来自于赋矿地层的海相硫酸盐。乐开铅

表 2 乐开铅锌矿床硫化物铅同位素组成

Table 2 Lead isotopic composition of sulfides from the Lekai lead-zinc deposit

样品号	样品名称	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
LD03R0	方铅矿	18.580	15.850	39.340
LD03R7	方铅矿	18.470	15.730	38.900
LD03R8	方铅矿	18.400	15.670	38.580
LD03R10	方铅矿	18.590	15.810	39.150
LD11R6-1	方铅矿	18.500	15.720	39.120
LD11R6-6	方铅矿	18.430	15.660	38.710
LD03R0	闪锌矿	18.659	15.834	39.152
LD03R6	闪锌矿	18.767	16.058	39.432
LD03R10	闪锌矿	18.635	15.785	39.052
Lkg-1	黄铁矿	18.614	15.789	39.158

锌矿的赋矿围岩为泥盆系望城坡组，岩性为含 4~5 层碳质-有机质的碳酸盐岩，显示其沉积环境较为还原，结合研究区各地层中均未发现残留的石膏及重晶石等硫酸盐，因此，即使不能排除膏岩层(干旱-氧化环境)提供硫源的可能性，但其贡献亦不显著。

海相硫酸盐 SO_4^{2-} 还原为硫化物 S^{2-} 的过程一般是通过热化学还原作用(TSR)或细菌还原作用(BSR)来实现(Ohmoto, 1972; Seal, 2006)。温度和 $\delta^{34}S$ 值的特征分析是区分 TSR 和 BSR 的有效手段。TSR 启动需要的温度条件较高(>100~120℃, Ohmoto, 1972; Seal, 2006)，而 BSR 发生首先需要满足细菌存活的温度，因而通常发生在相对较低温度条件下(<100~120℃, Basuki et al., 2008)。此外，TSR 过程能在短时间内产生大量的 S^{2-}，且 $\delta^{34}S$ 值变化范围小，相对较为集中，$\delta^{34}S$ 值(SO_4^{2-} - S^{2-})可达 15‰~20‰；而 BSR 过程产生大量 S^{2-} 需要时间较长，且产生的 S^{2-} 的 $\delta^{34}S$ 值明显偏负，变化范围亦较宽，$\delta^{34}S$ 值(SO_4^{2-}-S^{2-})可高达 40‰(Ohmoto et al., 1997; Basuki et al., 2008)。乐开铅锌矿床的硫化物 $\delta^{34}S$ 值介于 11.1‰~18.1‰，均值 14.7‰，较为集中；且区域铅锌矿的成矿温度约 160~260℃(朱路艳等, 2016)，显示 TSR 在乐开铅锌成矿流体还原硫的形成过程中起到决定性作用。已有研究发现硫酸盐的溶解度及水溶性硫酸盐的金属阳离子电荷数决定了 TSR 反应速率(罗建军等, 2018)，即 Ca^{2+} 与 Ba^{2+} 等阳离子形成的硫酸盐溶解度低，难以启动大量的 TSR 反应，导致生成的 S^{2-} 有限；与之相反，Al^{3+} 与 Mg^{2+} 等阳离子容易形成溶解度较高的硫酸盐，可以高效快速生成大量的 S^{2-}，进一步说明乐开铅锌矿流体中的还原硫最可能

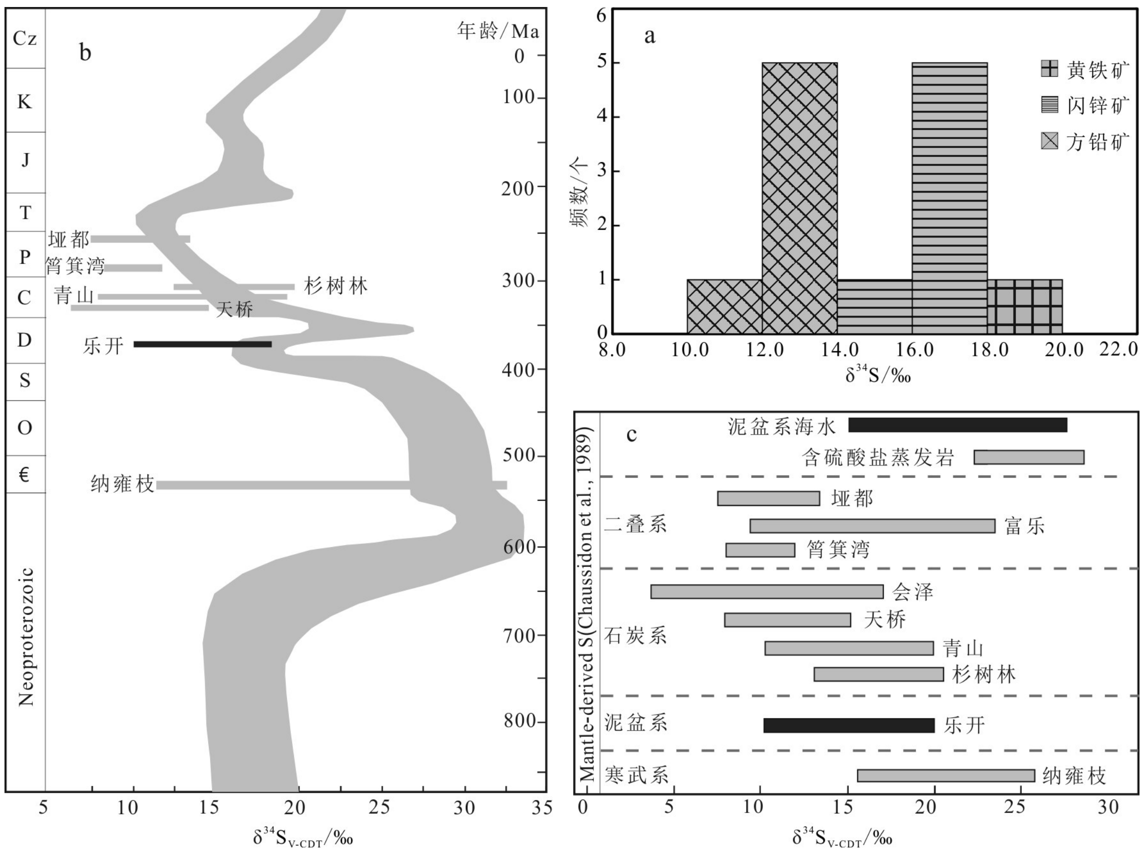

图4　乐开铅锌矿床硫化物组成直方图(a)、各时期海水硫同位素组成变化图(b)及赋存于各时代地层中的铅锌矿床的硫同位素组成特征(c, Claypool et al., 1980; 黄智龙等, 2004; Zhou et al., 2013a; 2013b; 2013c; 2013d, 2014a; 2014b; 2018b; 金中国等, 2016; 崔银亮等, 2018)

Fig. 4　Sulfur isotopic composition histogram of sulfides from the Lekai lead-zinc deposit(a), variation characteristics of sulfur isotope composition in seawater during different periods(b) and sulfur isotopic composition of lead-zinc deposits hosted in strata of different ages (c, after Claypool et al., 1980; Huang et al., 2004; Zhou et al., 2013a, 2013b; 2013c; 2013d, 2014a; 2014b; 2018b; Jin et al., 2016; Cui et al., 2018)

是泥盆纪海相硫酸盐TSR的产物，而膏岩层的贡献可能性较低。泥盆系望城坡组中粗晶白云岩中夹的4~5层的碳质-有机质层发挥了还原障的作用。

5.1.2　铅同位素约束

研究显示川滇黔接壤铅锌矿集区潜在的金属源区主要有元古代基底浅变质岩石、震旦系—中二叠统赋矿沉积岩与晚二叠世峨眉山玄武岩3种(Zheng et al., 1991; Zhou et al., 2001；1998; 黄智龙等, 2004; 金中国等, 2016; Tan et al., 2017; Wang et al., 2018)，且3种源区的贡献方式及比例决定着不同铅锌矿床差异的铅同位素组成。

在$^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$图解(图5a)中，乐开铅锌矿床硫化物铅同位素数据投影于上地壳Pb平均演化线附近，与△γ-△β图解(图5b)中绝大多数测点数据位于上地壳铅，2个测点的数据位于俯冲带范围的结果高度一致，显示了明显的壳源特征。图5c显示，乐开铅锌矿床硫化物Pb同位素的投影区与二叠系峨眉山玄武岩、前寒武系沉积岩范围明显不同，而多数测点位于泥盆系—二叠系碳酸盐岩范围，少量测点位于古元古代基底岩石范围，显示出泥盆系—二叠系碳酸盐岩提供了主要的Pb来源，古元古代基底岩石也是Pb的源区之一。同时，乐开铅锌矿床硫化物的铅同位素组成与川滇黔接壤矿集区垭都(He et al., 2021)、纳雍枝(金中国等, 2016)等铅锌矿床硫化物的铅同位素组成存在差异，而与天桥(Zhou et al., 2013a)、富乐(崔银亮等, 2018)等铅锌矿床硫化物的铅同位素组成类似。垭都、纳雍枝等矿床的成矿金属物质被证实来源于基底，富乐、天桥铅锌矿床的成

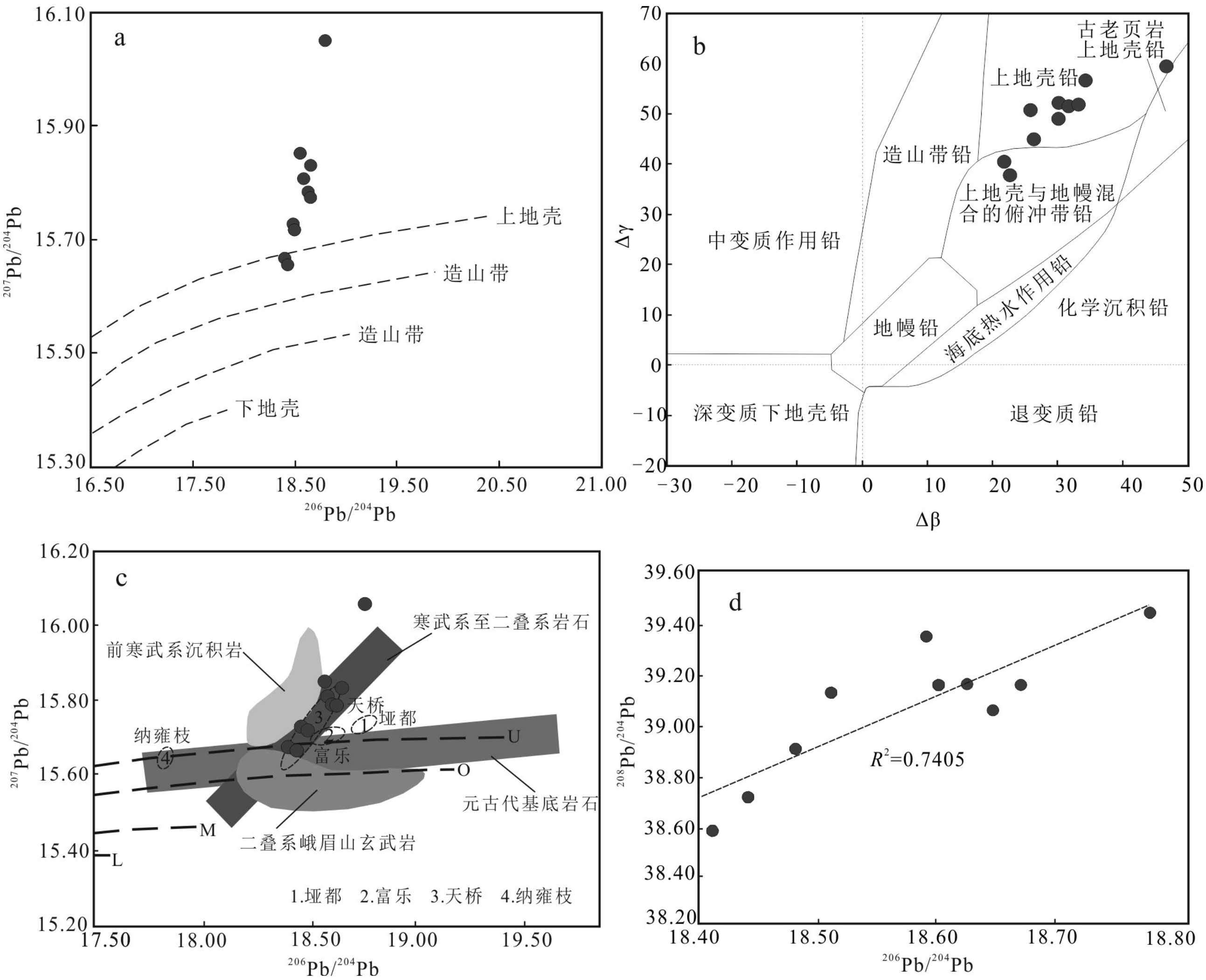

图5 乐开铅锌矿床硫化物 $^{207}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ 图解(a, Zartman et al., 1981)、△γ-△β图 (b, Zartman et al., 1981)和显示二叠系峨眉山玄武岩、寒武系至二叠系沉积岩、前寒武系沉积岩、元古代基底岩石的 $^{207}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ 范围图(c, 数据来源黄智龙等, 2004; Zhou et al., 2013a, 2014a; 金中国等, 2016; 崔银亮等, 2018)及乐开铅锌矿床硫化物 $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ 图解(d)

Fig. 5 Plots of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ of sulfides from the Lekai lead-zinc deposit(a, Zartman et al., 1981), plots of △γ vs. △β (b, Zartman et al., 1981), plot of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ showing the field of the late Permian Emeishan basalts, Cambrian to Permian sedimentary rocks, Precambrian sedimentary rocks and Proterozoic basement rocks (c, Whole-rock Pb isotopic data are taken from Huang et al., 2004; Zhou et al., 2013a, 2014a; Jin et al., 2016; Cui et al., 2018) and Plots of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ of sulfides from the Lekai lead-zinc deposit(d)

矿金属物质为基底与沉积地层的混合来源，暗示峨眉山玄武岩及前寒武纪沉积岩作为乐开铅锌矿床主要金属源区的可能性较小，主要的源区应为沉积地层碳酸盐岩与基底岩石。此外，众多研究发现基底岩石富含丰富的Zn、Pb等成矿元素(周朝宪, 1998; 黄智龙等, 2004; Zhou et al., 2018a)，且川滇黔接壤铅锌矿集区的锶同位素组成变化范围约为0.7107~0.7155(顾尚义等, 1997; 周朝宪, 1998)，属酸性岩石的初始范围(0.700~0.737)，明显高于正常海相沉积碳酸盐岩的 $^{87}Sr/^{86}Sr$ 比值(0.7080)、海水的 $^{87}Sr/^{86}Sr$ 比值(0.7090)以及碳酸盐岩的 $^{87}Sr/^{86}Sr$ 比值(0.7079)，峨眉山玄武岩的 $^{87}Sr/^{86}Sr$ 比值0.7066~0.7082(邓海琳等, 1999)，显示存在有放射成因的锶，暗示成矿流体流经富放射成因锶的基底岩石(周朝宪, 1998)。因此，笔者认为沉积地层与基底岩石共同为乐开铅锌矿床提供金属来源的可能性

很高。

乐开铅锌矿床硫化物铅同位素组成相对较为集中,表明乐开铅锌矿床成矿物质来源单一或均一化程度很高(黄智龙等, 2004)。司荣军(2005)研究富乐铅锌矿时,认为其金属可能来源于扬子地块西南缘沉积岩石,成矿前的成矿流体存在均一化过程。那么乐开都铅锌矿床的成矿流体是否存在多来源混合且成矿前存在均一化过程? 在 $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$(图 5d)图解上不难发现,乐开铅锌矿床硫化物铅同位素大致呈线性分布的特征,但也具有局部集中分布的特征,暗示成矿流体演化过程中铅同位素可能存在均一化过程。

5.2　控矿构造模式

控矿构造模式的研究对确定矿体空间位置具有重要意义,其有利于成矿模型的建立与深部矿体的预测,可为矿体的精准定位研究提供科学依据(何志威等, 2020)。川滇黔接壤铅锌矿集区的控矿构造模式多种多样,而且分级控矿特征较为明显(韩润生等, 2020a; 何志威等, 2020)。何志威等(2020)深入剖析了黔西北铅锌成矿带 7 个典型铅锌矿床的控矿岩性组合与构造样式,厘定了 2 种控矿岩性组合(碳质页岩+碳酸盐岩+碳质页岩组合和碳质页岩+含碳质泥质碳酸盐岩组合)和 4 种构造控矿样式(张断裂-背斜、断裂复合空间、逆断裂纵向羽状节理和平行次级断裂),总结了"流体-构造组合导入-岩性组合圈闭"的成矿过程。为本文解析乐开铅锌矿的控矿特征提供了参考。

洛泽河断裂为 NE 向展布的区域性深大断裂,其多次活动形成的一系列断层与褶皱构成典型的断层-褶皱体系,该断层-褶皱体系对热水(流体)成矿具有引导、激发动力、演化等控制作用,为成矿物质的运输与汇聚提供通道,是矿体形成、保存及矿体规模、形态、品位、厚度变化的重要因素(罗卫等, 2010)。区域上,富强、云炉河坝、昊星、乐开、银厂坡等矿床均受到该类断层-褶皱体系控制。研究区内 F_2 断层为洛泽河断裂的南延段,是深部含矿流体进入沉积地层的通道。同时 F_2 断层与其次级断裂 F_1、F_3 断层多次将泥盆系上统的望城坡组白云岩推移至地表,造成该组白云岩受热蚀变重结晶的同时形成较好的层间破碎空间,而该粗晶白云岩含多层碳质黏土岩,易与破碎白云岩形成具有一定储存空间的封闭体系,同时在铅锌矿的成矿作用中主要起到还原剂的作用,类似石油成矿体系的"储-盖"结构,为典型的"碳质页岩+碳酸盐岩+碳质页岩"的含矿岩性组合(何志威等, 2020),是铅锌流体卸载成矿的有利场所(图 6)。而受 F_1、F_2、F_3 断层影响形成的一系列张断裂是将含矿流体分流运移到成矿地点(有利的含矿岩性组合空间)的运矿构造。

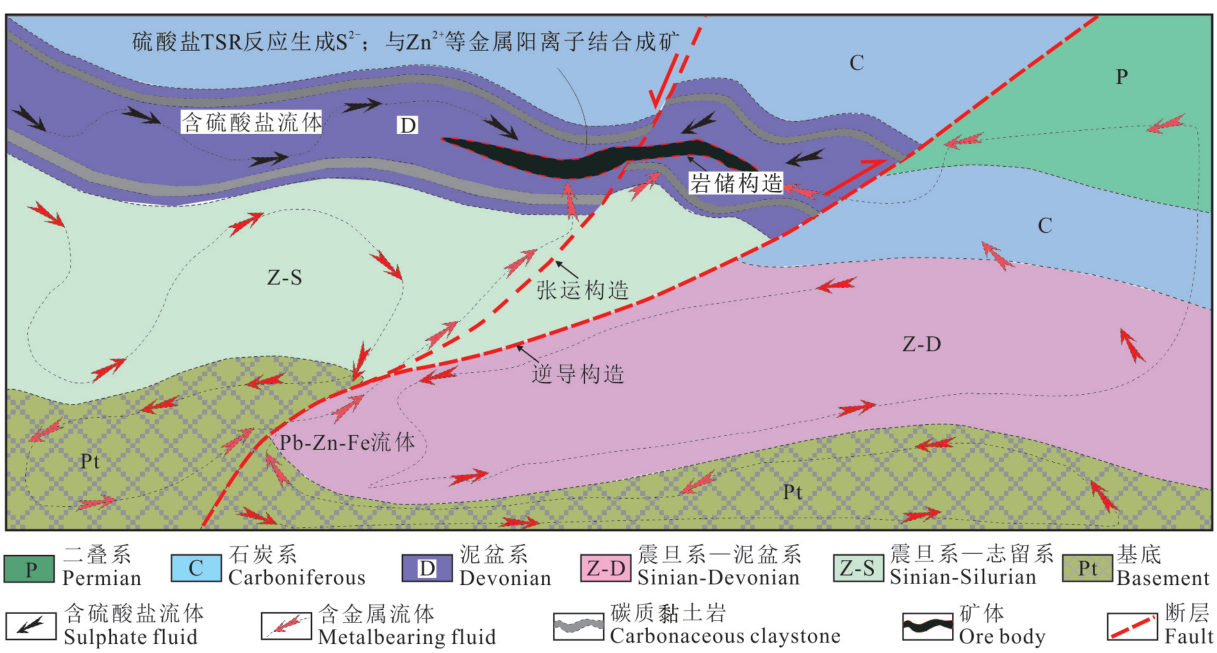

图 6　乐开铅锌矿成矿模式图

Fig. 6　Schematized metallogenic model of the Lekai lead-zinc deposit

综上所述,乐开铅锌矿床的控矿构造模式具有典型的“逆(逆断裂)导-张(张断裂)运-岩(碳质黏土岩封闭碳酸盐岩的断裂破碎空间形成有利的含矿岩性组合)储”的特征,是断裂复合空间控矿的典型模式(图6)。

5.3 矿床成因及过程

目前川滇黔接壤矿集区铅锌矿床成因类型有MVT型(张长青, 2008; 吴越, 2013; Li et al., 2018; Xiong et al., 2018)、SYG型(川滇黔型)(Zhou et al., 2018a)、岩浆-热液型(Wang et al., 2000; 王登红, 2001; 李文博等, 2004; 高振敏等, 2004; Liu et al., 2015; 秦建华等, 2016)、HZT型(会泽体)(韩润生等, 2019;2020a;2020b)、热水喷流沉积(陈国勇等, 2015)与沉积-改造成因(柳贺昌等, 1999)等,未能形成统一认识。乐开铅锌矿床主要发育似层状矿体,矿石呈(网)脉状、角砾状、浸染状等构造与交代、充填、共边等结构,具有典型的“逆(逆断裂)导-张(张断裂)运-岩(碳质黏土岩封闭碳酸盐岩的断裂破碎空间形成有利的含矿岩性组合)储”的构造控矿模式,后生成矿特征明显,因而基本可以排除其为热水喷流沉积及沉积-改造成因。研究区除了基底发育变质火成岩以外,周围还出露二叠系峨眉山玄武岩,因峨眉山玄武岩与铅锌矿的分布较吻合,可以为铅锌矿的成矿提供金属来源及热源,因而川滇黔接壤铅锌矿被认为是以峨眉山玄武岩为主的岩浆-热液型。但随着成矿年代学的研究深入,川滇黔接壤地区铅锌矿与峨眉山玄武岩的年龄基本被准确测定,前者为200 Ma(Zhou et al., 2014b),与后者(251~262 Ma)的年龄相差较大(宋谢炎等, 2002; 刘成英等, 2009),显示以峨眉山玄武岩为主的岩浆作用作为川滇黔接壤地区铅锌矿的主要成矿作用的可能性较小。乐开铅锌矿床的大地构造背景、成矿作用、矿物组合及矿化(蚀变)等特征与典型的MVT型铅锌矿床相似,但乐开铅锌矿的构造控矿特征明显、异常高的矿石品位(Pb+Zn一般大于10%,富矿可高达30%~40%)、较高的温度(160~260℃)和盐度($w(NaCl_{eq})$ 10%~22%)及低密度的CO_2-CH_4-N_2的卤水(朱路艳等, 2016)及显著富集的稀散元素(司荣军, 2005)等特征,又与典型的MVT矿床有一定的区别。因此,本文暂时把乐开铅锌矿床划归为类MVT矿床,它应归属于MVT型铅锌矿床大类。

乐开铅锌矿床硫化物的硫、铅同位素研究,发现成矿物质中S来源于地壳沉积岩,海相硫酸盐的热化学反应(TSR)是硫化物中S^{2-}的主要来源方式;而成矿金属元素主要来源于沉积地层,但在成矿流体流经基底地层过程中萃取了部分基底岩石的金属元素。基于此,笔者认为乐开铅锌矿的成矿过程如下:峨眉山地幔柱活动导致扬子地块西南缘具有较高温度的区域背景,目前虽然有证据显示峨眉山地幔柱活动与铅锌矿床的成矿无直接关系,但其加热板块,为活化成矿物质提供热量是不争的事实。随后的早印支运动,强烈挤压作用驱动了沉积地层(盆地)大规模的循环流体,该流体在高温度的加持下,不断地活化、淋滤、萃取岩石中的金属元素,进而形成富含金属的流体。随着印支运动进行到晚期,扬子地块西南缘构造背景从挤压转向伸展,形成的深大断裂沟通到基底岩石时,含矿流体进入基底循环萃取基底成矿金属元素;然后,沿着深大断裂返回沉积地层向着压力释放的部位不断排泄,当高温的含金属流体随断层进入沉积地层中特殊的构造部分(碳质黏土岩封闭的碳酸盐岩的断裂破碎空间)时,导致沉积盖层中硫酸盐发生热化学反应(TSR),生成大量的S^{2-},与含矿流体中的Pb^{2+}、Zn^{2+}、Fe^{2+}等金属元素结合而形成硫化物矿石(图6)。中心矿体为条带状、网脉状、角砾状矿石,是金属硫化物与碳酸盐岩发生选择性交代或以胶结物的形式充填角砾岩裂隙的结果;边缘矿体为浸染状矿石,是金属硫化物以颗粒或晶簇的形式充填碳酸盐岩颗粒之间或孔洞的结果。

6 结 论

本文基于对黔西北铅锌成矿带乐开铅锌矿床地质特征、构造控矿特征和硫化物硫、铅同位素地球化学研究,得出以下认识:

(1)乐开铅锌矿床主要发育似层状矿体,矿石呈(网)脉状、角砾状、浸染状等构造与交代、充填、共边等结构。矿体与构造关系密切,具有典型的“逆(逆断裂)导-张(张断裂)运-岩(碳质黏土岩封闭碳酸盐岩的断裂破碎空间形成有利的含矿岩性组合)储”的构造控矿模式,后生成矿特征明显。

(2)乐开铅锌矿床硫化物的硫同位素结果显示S来源于地壳沉积岩,海相硫酸盐的热化学反应(TSR)是硫化物中S^{2-}的主要来源方式;铅同位素暗示成矿金属元素主要来源于沉积地层,但成矿流体流经基底地层并萃取了基底岩石的金属元素。

（3）乐开铅锌矿的成矿过程:盆地流体循环萃取沉积岩石与基底岩石的金属元素后形成含矿流体,含矿流体被深大断裂导入上覆沉积地层的特殊的构造部位(碳质黏土岩封闭的碳酸盐岩的断裂破碎空间)时,热流体导致沉积地层中硫酸盐发生热化学反应(TSR),生成大量的S^{2-},与含矿流体中的Pb^{2+}、Zn^{2+}、Fe^{2+}等金属阳离子结合成矿。该矿床成因类型可划归为MVT型。

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