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胶东辽上金矿床 C、O、S、Pb 同位素组成及矿床成因

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摘 要: 辽上金矿床是胶莱盆地东北缘地区近年来新发现的一处特大型金矿床,以黄铁矿、白云石为载金矿物而区别于“焦家式”、“玲珑式”金矿床。为探讨新类型金矿床成矿流体特征和成矿物质来源,对该矿床载金白云石 C、O 和黄铁矿 S、Pb 进行了同位素分析。结果显示,载金矿物白云石中 $\delta^{13}C_{V\text{-}PDB}$ 值为-4.60‰~-3.60‰,$\delta^{18}O_{V\text{-}SMOW}$ 值集中在 9.6‰~10.6‰;黄铁矿 $\delta^{34}S$ 值为+7.2‰~+9.4‰,均值为+8.2‰;黄铁矿 $^{206}Pb/^{204}Pb$、$^{207}Pb/^{204}Pb$ 与 $^{208}Pb/^{204}Pb$ 值分别为 17.027~17.576、15.435~15.503、37.706~38.205。结合胶莱盆地构造-岩浆演化背景,认为辽上金矿床 C-H-O 含矿流体主要源于地幔,上升过程中有大气降水参与及壳源成矿物质混入,具有壳幔混合特征,成因类型为含金黄铁矿碳酸盐脉充填型低温热液金矿床。

关键词: 同位素组成; 成矿流体; 成矿物质; 辽上金矿床; 胶东
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C, O, S and Pb isotopic compositions and genesis of the Liaoshang gold deposit in Jiaodong Peninsula

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Abstract: The Liaoshang gold deposit is a newly discovered superlarge gold deposit on the northeast margin of Jiaolai Basin, which is different from “Jiaojia-type” and “Linglong-type” gold deposits by unique gold bearing minerals of pyrite and dolomite. The isotopic analysis of C, O for Au-bearing dolomite and S, Pb for Au-bearing pyrite from this deposit was carried out in order to identify the source of ore-forming materials and fluids for this new type gold deposit. The results show that the $\delta^{13}C_{V\text{-}PDB}$ and the $\delta^{18}O_{V\text{-}SMOW}$ values of dolomite range from -4.60‰ to -3.60‰ and 9.6‰ to 10.6‰, respectively. The $\delta^{34}S$ values of Au-bearing pyrite vary from +7.2‰ to +9.4‰ with an average of +8.2‰. The results of Pb isotope from Au-bearing pyrite vary from 17.027 to 17.576, 15.435 to 15.503, and 37.706 to 38.205 for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios, respectively. Combined with the tectono-magmatic evolution in the Jiaolai Basin, the authors hold that the ore-bearing C-H-O fluids of the Liaoshang gold deposit mainly originated from the mantle. Furthermore, the meteoric water and crustal ore-forming

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materials were involved during the ascending process of ore-forming fluids, resulting in the characteristics of crust-mantle mixing. In conclusion, the genetic type of Liaoshang gold deposit should be the pyrite-carbonate vein type low temperature hydrothermal gold deposit.

Key words: isotope composition; ore-forming fluids; ore-forming material; Liaoshang gold deposit; Jiaodong Peninsula

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胶东地区是中国最大的黄金勘查与生产基地,同时也是世界第三大金矿集中区,资源/储量超过5 000 t(于学峰等, 2016; Deng and Wang, 2016; 宋明春, 2017; 王金辉, 2020)。该区金矿找矿勘查、成矿理论、成矿预测研究等工作一直备受国内外地质学家关注(邓军等, 2010; 姜晓辉等, 2011; Hu *et al.*, 2013; 吕古贤等, 2013; Yang *et al.*, 2013; 杨立强等, 2014; 宋明春等, 2014, 2015; Fan *et al.*, 2016; Wen *et al.*, 2016; Xu *et al.*, 2016; Guo *et al.*, 2017; 杨奎锋等, 2017; Zhang *et al.*, 2017; Deng *et al.*, 2018; 张龙等, 2020)。其金矿床类型主要包括破碎带蚀变岩型(俗称"焦家式")和石英脉型(俗称"玲珑式"),区域上产出的大多数金矿床均有这两种矿化样式发育。破碎带蚀变岩型金矿以三山岛、焦家、新城等矿床为代表,主要受控于NE向区域主断裂;石英脉型金矿以玲珑和九曲等矿床为代表,主要受控于次级断裂。Lu等(2007)和Guo等(2017)通过对这两种类型矿床H-O-S稳定同位素、流体包裹体均一温度和成分组成等研究,认为胶东地区破碎带蚀变岩型和石英脉型金矿床其实是同一次成矿作用的结果,只是在不同的赋矿围岩和成矿热液温压条件影响下的不同表现形式。近年来,随着胶东东部深部找矿的不断推进,在胶莱盆地东北缘金矿集中区首次发现了黄铁矿碳酸盐脉型特大型金矿床(Au金属量达69 t)——辽上金矿。该矿床是一种以金赋存于黄铁矿-碳酸盐(细)脉中为显著特征的新类型金矿床,其矿石类型明显不同于胶东地区"焦家式"和"玲珑式"金矿床中以硅化、绢英岩化为主的矿石类型,是胶东又一具备寻找特大型金矿床潜力的新矿床类型,被称之为"辽上式"金矿(李国华等, 2016, 2017)。

前人对胶东地区"焦家式"和"玲珑式"金矿床开展了系统深入地研究,并取得了诸多创新性的成果和认识,极大地促进了胶东地区金成矿理论的提升和找矿实践的突破,但对于近年来新发现的具有较大找矿潜力的黄铁矿碳酸盐脉型新类型金矿床("辽上式"金矿)的研究涉及较少。前人仅从该类型矿床地质特征、矿物学特征、成矿规律等方面进行了初步分析探讨(纪攀等, 2016; 李国华等, 2016, 2017; 王志新等, 2017),关于其成矿流体和成矿物质来源、矿床成因等缺乏较为详细的研究。本文在详细的野外调研和室内研究基础上,对辽上金矿床中黄铁矿碳酸盐脉型矿石中白云石、黄铁矿分别开展了C、O和S、Pb同位素组成分析,结合其矿床地质和矿石组构特征,探讨了辽上黄铁矿碳酸盐脉型金矿成矿流体、成矿物质来源及矿床成因,为建立该新类型金矿床成因模式提供了证据。

1 区域地质背景

胶莱盆地东北缘金矿集中区位于华北板块与苏鲁造山带交汇部位(图1a)。区内壳幔作用强烈,构造岩浆活动频繁,区域成矿条件优越。区内地层主要由前寒武系变质岩、白垩系陆源碎屑沉积岩和火山岩组成。前寒武系变质岩主要为古元古界大理岩、变粒岩、斜长角闪岩等,是半稳定-稳定的浅海环境下成岩作用的产物,原岩为碳酸盐岩、含钙镁质沉积物的沉基性火山岩或白云质杂砂岩、中基性火山岩、泥质岩、粉砂质泥岩、石英砂岩、长石石英砂岩等(林文蔚等, 1998),形成时代晚于~2 100 Ma(刘平华等, 2011),其峰期高压麻粒岩相变质时代为1 900~1 850 Ma(Wan *et al.*, 2006; Zhou *et al.*, 2008; Tam *et al.*, 2011; 刘平华等, 2011; 刘建辉等, 2011),退变质时代为1 840~1 820 Ma(刘平华等, 2011)。白垩系陆源碎屑沉积岩为复成分砾岩、砂岩、粉砂岩等。白垩系火山岩为发育于陆内裂谷环境的一套由酸性-中基性-酸性-偏碱性火山岩、火山碎屑岩组成的陆相火山盆地沉积,分别对应4个火山活动旋回(丁正江等, 2015),从早期火山岩到晚期火山岩,其碱性物质成分逐渐增加(唐华风等,

2003；李金良等，2007；付文钊等，2014）。区内岩浆岩以晚侏罗世含石榴石弱片麻状二长花岗岩为主（160~152 Ma），被认为是地壳重熔型（S 型）花岗岩（孙丰月等，1995；丁正江等，2015）；西北部出露小面积早白垩世似斑状花岗闪长岩（117~110 Ma），为壳幔混合花岗岩（郭敬辉等，2005；丁正江等，2013）。另发育二长斑岩、闪长玢岩、煌斑岩脉岩群（116~114 Ma；谭俊，2009）。区内断裂构造发育，主要有桃村、郭城、崖子和育黎等 4 条 NE 向区域性超壳断裂，为盆地边界断裂，控制了盆地的形成与演

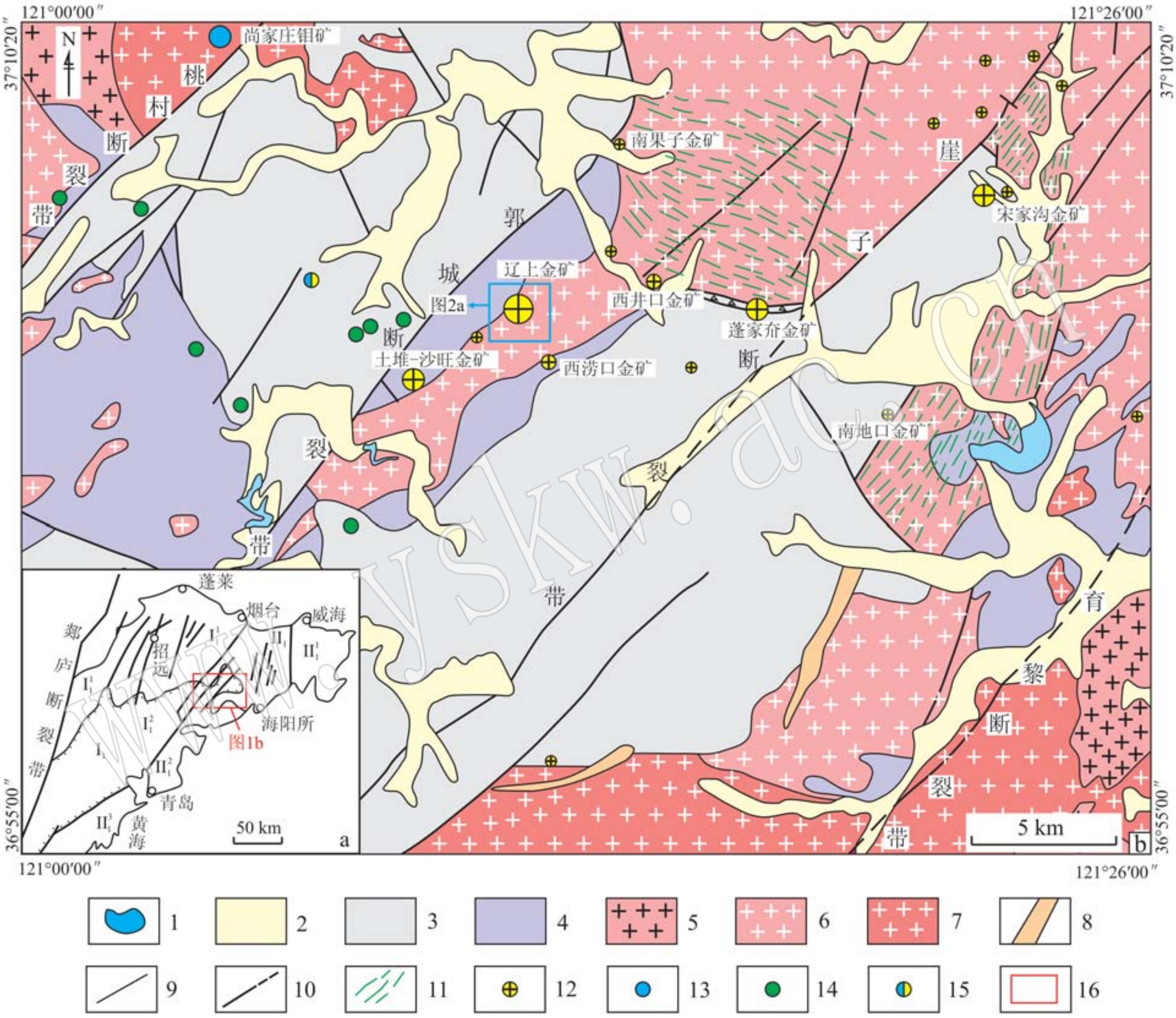

图 1　胶莱盆地东北缘大地构造位置（a）与区域矿产地质图（b）（据李国华等，2016 修改）

Fig. 1　Sketch map for geotectonic location of the northeastern margin of Jiaolai Basin (a) and mineral deposits (b) on the northeast margin of Jiaolai Basin (modified after Li Guohua *et al.*, 2016)

1—水库；2—第四系；3—下白垩统陆相沉积岩、火山岩；4—古元古界变质岩；5—前寒武系侵入岩；6—晚侏罗世二长花岗岩；7—早白垩世花岗闪长岩；8—燕山晚期岩脉；9—地质界线；10—断裂；11—韧性剪切带；12—金矿床（点）；13—钼矿床；14—铜矿点；15—铅锌矿点；16—胶莱盆地东北缘地区位置；Ⅰ—华北板块；Ⅰ$_1$—胶莱-胶北断隆；Ⅰ$_1^1$—胶北断隆；Ⅰ$_1^2$—胶莱断陷；Ⅱ—秦岭-大别-苏鲁碰撞造山带；Ⅱ$_1$—胶南-威海断隆；Ⅱ$_1^1$—文登-威海断拱；Ⅱ$_1^2$—胶莱断陷；Ⅱ$_1^3$—胶南-临沭断隆

1—lake; 2—Quaternary; 3—Lower Cretaceous continental sedimentary and volcanic rocks; 4—Paleoproterozoic metamorphic rock; 5—Precambrian intrusive rock; 6—Late Jurassic monzonite granite; 7—Early Cretaceous granodiorite; 8—Late Yanshanian dyke; 9—geological boundary; 10—fault; 11—ductile shear zone; 12—Au deposit (ore spot); 13—Mo deposit; 14—Cu ore spot; 15—Pb-Zn ore spot; 16— northeast margin of Jiaolai Basin; Ⅰ—North China Plate; Ⅰ$_1$— Jiaolai-Jiaobei falut-uplift; Ⅰ$_1^1$—Jiaobei falut-uplift; Ⅰ$_1^2$—Jiaolai fault depression; Ⅱ—Qinling-Dabie-Sulu collision orogenic belt; Ⅱ$_1$—Jiaonan-Weihai falut-uplift; Ⅱ$_1^1$—Wendeng-Weihai falut-uplift; Ⅱ$_1^2$—Jiaolai fault depression; Ⅱ$_1^3$—Jiaonan-Linshu falut-uplift

化，同时也是深部岩浆作用的重要通道。这些深大断裂不仅影响岩浆岩的空间定位，而且控制着金及多金属矿床的形成与分布，目前已发现有辽上、郭城、蓬家夼、宋家沟、西井口等数个（特）大-中型金矿床和尚家庄中型钼矿。新发现的特大型黄铁矿碳酸盐脉型辽上金矿床即位于金矿集中区郭城断裂的下盘（图 1b）。

2 矿床地质特征

辽上金矿区赋矿围岩主要为前寒武系大理岩、变粒岩，晚侏罗世二长花岗岩及少量燕山晚期脉岩（图 2a）。区内矿体受构造控制明显，对围岩无明显选择性，控矿构造呈 NE 走向，倾向 SE，上陡下缓，发育于荆山群与晚侏罗世二长花岗岩接触带附近，由多条近平行构造组成（图 2b，Ⅲ、Ⅳ）。

Ⅲ号构造蚀变带：地表出露长约 960 m，宽约 1～14 m；走向及倾向上均呈舒缓波状，总体走向 50°±，倾向 SE，倾角 42°；自－300 m 标高往下蚀变带变宽变厚，最大控制厚度可达 285 m（图 2b）。带内浅部发育黄铁矿化、碳酸盐化，少量硅化、绢英岩化、钾长石化、绿泥石化等蚀变，蚀变带与围岩呈渐变过渡，无明显边界；深部主要发育黄铁矿化、碳酸盐化。

Ⅳ号构造蚀变带：位于Ⅲ号构造蚀变带上侧，二者间距约 100～150 m，大致平行（图 2b）；断续出露长约 980 m，地表宽约 1～10 m，于－200 m 标高向深部略变宽变厚。总体走向 40°～56°，倾向 SE，倾角 23°～58°。蚀变带内特征与Ⅲ矿化蚀变带基本一致，矿化强度稍弱。

区内已发现主要金矿体 4 条、次要矿体 3 条，主要赋存在－500 ～－1 000 m 标高（矿体向下未封闭；图 2b）。矿体多呈透镜状、似层状、脉状、楔状及马鞍状等，总体走向 37°，倾向 SE，倾角在 5°～55°之间，大多数倾角 10°～40°；矿体水平延伸 80～550 m，倾向延深 42～271 m，厚 1.36～42.93 m，矿石品位 1.36～22.68 g/t。

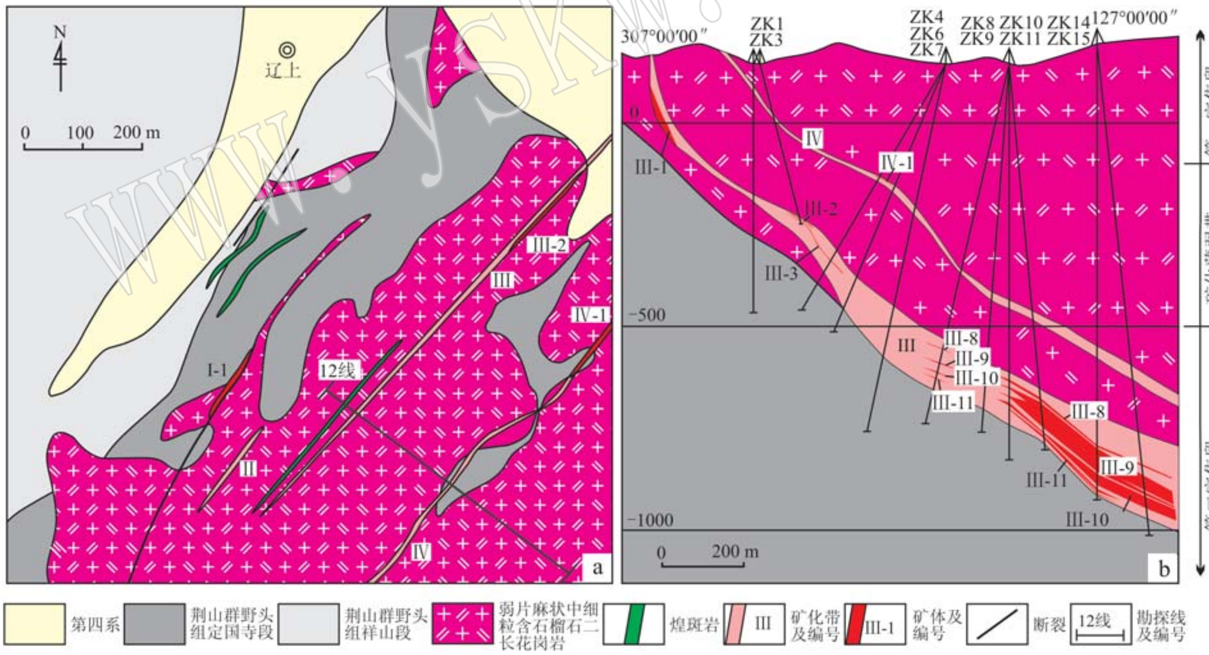

图 2 辽上金矿区地质简图（a，据山东省第三地质矿产勘查院，2014❶修改）与 12 线剖面图（b，据纪攀等，2016 修改）

Fig. 2 Geological map (a, modified after No. 3 Exploration Institute of Geology and Mineral Resources, 2014❶) and geological section along No. 12 line (b, modified after Ji Pan *et al.*, 2016) of the Liaoshang gold deposit

辽上金矿床以充填方式成矿，含金黄铁矿碳酸盐（细）脉体沿围岩裂隙充填，对围岩没有明显选择性，形成 3 种主要矿石类型（丁正江等，2015；李国华等，2016），分别为黄铁矿碳酸盐脉花岗岩型（图 3a）、黄铁矿碳酸盐脉变质岩型（图 3b）和黄铁矿碳酸盐脉型（图3c），其中第3种金品位最高，前两类

❶ 山东省第三地质矿产勘查院. 2014. 山东省牟平区辽上金矿深部及外围详查报告.

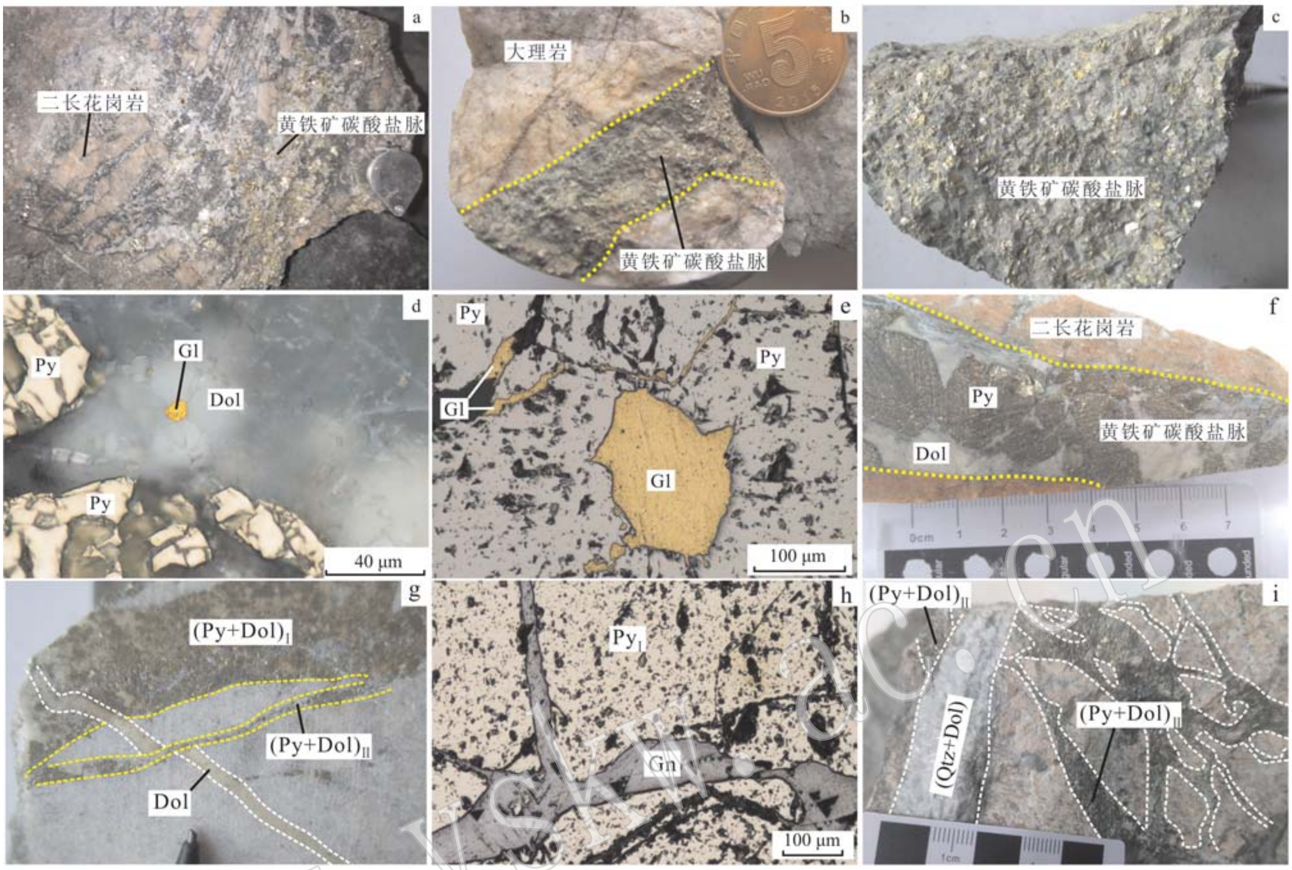

图 3　辽上金矿石类型及矿物特征

Fig. 3　Ore types and mineral characteristics of the Liaoshang gold deposit

a—黄铁矿碳酸盐脉花岗岩型矿石；b—黄铁矿碳酸盐脉变质岩型矿石；c—黄铁矿碳酸盐脉型矿石；d—白云石中的包体金(反射光)；e—黄铁矿中的包体金与裂隙金(反射光)；f—黄铁矿碳酸盐脉沿二长花岗岩裂隙充填；g—Ⅰ阶段黄铁矿碳酸盐脉与Ⅱ段黄铁矿碳酸盐脉穿切关系；h—方铅矿交代Ⅰ阶段黄铁矿(反射光)；i—Ⅲ阶段石英-碳酸盐脉穿切Ⅱ阶段黄铁矿碳酸盐脉；Py—黄铁矿；Gn—方铅矿；Gl—自然金；Dol—白云石；Qtz—石英(矿物缩写符号据沈其韩，2009)

a—pyrite-carbonate vein granite type ore; b—pyrite-carbonate vein metamorphic rock type ore; c—pyrite-carbonate vein type ore; d—inclusion gold within dolomite (reflected light); e—inclusion gold and fissure gold in pyrite (reflected light); f—pyrite-carbonate vein filling the fissure of monzogranite; g—perforation relationship between stage Ⅰ pyrite-carbonate vein and stage Ⅱ pyrite-carbonate vein; h—galena replacing stage Ⅰ pyrite (reflected light); i—stage Ⅲ quartz-carbonate vein crossing stage Ⅱ pyrite-carbonate vein; Py—pyrite; Gn—galena; Gl—native gold; Dol—dolomite; Qtz—quartz (mineral abbreviation after Shen Qihan, 2009)

矿石含金量与其所含黄铁矿碳酸盐细脉的多少呈正相关。断裂带中黄铁矿碳酸盐脉矿石主要由自然金、黄铁矿、白云石组成，含少量方解石、黄铜矿、方铅矿、闪锌矿等矿物。自然金矿物粒度 5~350 μm 不等(集中在 20~50 μm)，主要以裂隙金、粒间金、包裹金和共生金的形式赋存在白云石(图 3d)和黄铁矿中(图 3e)。根据矿物共生组合及形成的先后顺序，将“辽上式”金矿成矿过程划分为 3 个成矿阶段(纪攀等, 2016)：Ⅰ阶段，粗粒黄铁矿-白云石-金阶段，脉体宽大，主要产出大颗粒黄铁矿，粒度 3~20 mm，自形程度好(图 3f；五角十二面体)，金矿物产出较多且粒度粗大[图 3g；$(Py+Dol)_{Ⅰ}$]；Ⅱ阶段，细粒黄铁矿-白云石-(少量)金阶段[图 3g；$(Py+Dol)_{Ⅱ}$]，脉体细小，细脉状、网脉状，主要产出细粒半自形黄铁矿，少量黄铜矿、方铅矿、闪锌矿等，金矿物产出粒度较细小，方铅矿交代Ⅰ阶段黄铁矿(图 3h)；Ⅲ阶段，石英-碳酸盐脉阶段，生成细粒碳酸盐(白云石为主)和少量石英，呈脉状切割Ⅱ阶段黄铁矿碳酸盐细脉(图 3i)，不含金。

3　样品采集及分析方法

3.1　样品采集

采集辽上金矿床黄铁矿碳酸盐脉矿石样品 18 件，黄铁矿碳酸盐脉宽为 2~3 cm，黄铁矿颗粒粗大，粒径为 3~8 mm，晶型呈五角十二面体。采集标本

后,室内使用切割机去除大部分二长花岗岩围岩,以保证研究目标黄铁矿碳酸盐脉中黄铁矿、碳酸盐矿物的同期性和同源性。初步处理后的样品粉碎至40~80目,淘洗后进行初选,然后在双目镜下挑选出黄铁矿、白云石分别用于S、Pb和C、O同位素测试,X射线物相分析结果表明黄铁矿和白云石的纯度大于99%。

3.2 分析方法

白云石C、O和黄铁矿S、Pb同位素分析测试工作均在核工业北京地质研究院分析测试中心完成。白云石C、O同位素分析,用玛瑙研钵将白云石单矿物研磨至200目,烘箱105℃烘烤样品2 h,去除吸附水。75℃下烘烤在Gasbench线制样设备的样品管,烘干后将0.1 mg样品放入样品管中并封盖。用高纯氦气将样品管中的空气排出。用酸泵酸针向样品管中加过量的100%磷酸。磷酸和碳酸盐样品反应产生CO_2气体。用高纯氦气将生成CO_2气体带入MAT253质谱仪测试C、O同位素组成。C、O同位素测试以PDB为标准,分别标记为$\delta^{13}C_{V\text{-}PDB}$和$\delta^{18}O_{V\text{-}PDB}$,分析精度优于±0.2‰(刘汉彬等, 2013)。黄铁矿S同位素分析,将单矿物和氧化亚铜按一定比例研磨、混合均匀后,在真空达10^{-2} Pa和980℃状态下加热进行氧化反应使矿物中的硫转化生成SO_2。然后用液氮冷冻剂收集并纯化SO_2,用Delta V Plus分析SO_2中硫同位素组成,测量结果以V-CDT为标准,分析精度优于±0.2‰。黄铁矿Pb同位素样品先用混合酸溶样,然后用树脂交换法分离出铅,蒸干后用热表面电离质谱法进行铅同位素测量,仪器型号为ISOPROBE-T,对1 μg铅的$^{204}Pb/^{206}Pb$测量精度<0.05%,$^{208}Pb/^{206}Pb$≤0.005%。

4 同位素地球化学特征

4.1 白云石C、O同位素组成

18件辽上金矿床主成矿阶段白云石样品的C、O同位素测试结果见表1。白云石的C同位素变化范围小,分布集中,$\delta^{13}C_{V\text{-}PDB}$值为-4.6‰~-3.6‰,平均值-4.22‰;白云石的O同位素变化范围小,分布集中,$\delta^{18}O_{V\text{-}SMOW}$值集中在9.6‰~10.6‰,平均值10.1‰。

表1 辽上金矿床白云石碳氧同位素组成 ‰

Table 1 Carbon and oxygen isotopic compositions of dolomites from the Liaoshang gold deposits

样品号	$\delta^{13}C_{V\text{-}PDB}$	$\delta^{18}O_{V\text{-}PDB}$	$\delta^{18}O_{V\text{-}SMOW}$
2015LS-01	-4.5	-20.5	9.7
2015LS-02	-4.4	-20.3	9.9
2015LS-03	-4.5	-20.2	10.1
2015LS-04	-4.1	-20.5	9.7
2015LS-05	-3.7	-20.0	10.2
2015LS-06	-4.5	-20.4	9.8
LS-07	-4.5	-19.7	10.6
LS-08	-4.4	-19.8	10.4
LS-09	-4.5	-19.8	10.5
LS-10	-4.3	-19.9	10.4
LS-11	-4.4	-20.1	10.2
LS-12	-4.1	-19.8	10.5
6 474	-3.6	-20.5	9.8
H179	-4.2	-20.4	9.9
H173	-4.6	-20.6	9.6
17B25	-3.8	-20.0	10.3
B23	-3.8	-19.9	10.4
17B26	-4.0	-20.0	10.2

4.2 黄铁矿S、Pb同位素组成

辽上金矿床主成矿阶段14件黄铁矿的S-Pb同位素测试结果见表2。辽上金矿床黄铁矿$\delta^{34}S$值除LS-1(3.4‰)之外,较为集中,为+7.3‰~+9.4‰,均值为+8.2‰。黄铁矿$^{206}Pb/^{204}Pb$值为17.027~17.576,$^{207}Pb/^{204}Pb$值为15.435~15.503,$^{208}Pb/^{204}Pb$值为37.706~38.205。

5 讨论

5.1 成矿流体来源

前人研究表明,热液碳酸盐矿物中的碳、氧同位素组成是示踪成矿流体来源的有效手段(Taylor, 1986; 黄智龙等, 2004)。一般来说,岩浆和深部来源碳在自然界中$\delta^{13}C_{V\text{-}PDB}$变化范围分别为-9‰~-3‰和-5‰~+2‰,海相碳酸盐类$\delta^{13}C_{V\text{-}PDB}$约为-3.0‰~+2.0‰(Hoefs, 1997),有机碳$\delta^{13}C_{V\text{-}PDB}$的变化范围为-30‰~-15‰,蒙阴金刚石$\delta^{13}C_{V\text{-}PDB}$的变化范围为-6.4‰~-0.4‰(张宏福等, 2009),大理岩类$\delta^{13}C_{V\text{-}PDB}$的变化范围为-5.7‰~+3.8‰(王炳成等, 1992❶)。辽上金矿床黄铁矿碳酸盐脉矿石

❶ 王炳成, 等. 1992. 胶东金矿稳定同位素地球化学及找矿(科研报告).

表 2　辽上金矿床黄铁矿 S 同位素组成

Table 2　S compositions of pyrites from the Liaoshang gold deposit

样品号	$\delta^{34}S_{V\text{-}CDT}$/‰	$^{206}Pb/^{204}Pb$	2σ	$^{207}Pb/^{204}Pb$	2σ	$^{208}Pb/^{204}Pb$	2σ
LS-01	8.0	17.316	0.001	15.475	0.001	37.883	0.003
LS-02	9.4	17.576	0.003	15.503	0.002	38.205	0.006
LS-03	8.4	17.106	0.001	15.435	0.001	37.750	0.003
LS-04	7.7	17.260	0.002	15.465	0.001	37.827	0.003
LS-05	9.1	17.317	0.002	15.486	0.002	38.013	0.005
LS-06	7.3	17.282	0.002	15.460	0.001	37.910	0.003
LS-1	3.4	–	–	–	–	–	–
LS-2	7.4	–	–	–	–	–	–
6 474	–	17.156	0.003	15.449	0.003	37.819	0.008
H179	–	17.137	0.004	15.443	0.003	37.794	0.008
H173	–	17.222	0.002	15.470	0.024	37.947	0.006
17B25	–	17.100	0.004	15.441	0.003	37.798	0.008
B23	–	17.027	0.003	15.454	0.003	37.706	0.008
17B26	–	17.151	0.004	15.498	0.004	38.017	0.009

中白云石碳同位素 $\delta^{13}C_{V\text{-}PDB}$ 值为 −4.60‰～−3.60‰，平均值−4.22‰（表 1），位于岩浆系统总碳、幔源蒙阴金刚石、大理岩类碳同位素组成变化范围内（图 4），但与区内具有海相碳酸盐特征的荆山群大理岩（$\delta^{13}C_{PDB}$ = 0.24‰～1.70‰；杨敏之等，1996；张连昌等，2002）相比，$\delta^{13}C$ 出现亏损，而且辽上金矿白云石 $\delta^{18}O_{V\text{-}SMOW}$ 值集中在 9.6‰～10.6‰，与海相碳酸盐（$\delta^{18}O_{SMOW}$ = 20‰～24‰）、荆山群大理岩（11.93‰～16.6‰；张连昌等，2002）相比亦出现不同程度的亏损，而接近于岩浆碳酸岩（5.5‰～14.5‰；Deines and Gold，1973），上述特征表明辽上金矿床原始流体中的碳主要来源于深部岩浆热液。在 $\delta^{13}C-\delta^{18}O$ 图解（图 5）上，辽上金矿床样品集中落于岩浆岩范围内，表明辽上金矿床原始成矿流体中碳的来源主要与深部岩浆热液有关。

5.2　成矿物质来源

S 同位素是热液脉型金矿床中成矿物质来源示踪的重要方法之一（Yang *et al.*，2016；Zu *et al.*，2020）。热液硫化物中的 S 同位素受热液流体中总 S 同位素组成、pH 值和 Eh 值、沉淀时的温压条件以及硫化物形成时空间体系的开放程度等多种因素影响（裴英茹等，2016）。郑永飞等（2000）认为在低氧逸度环境下，热液矿物组合多为黄铁矿、磁黄铁矿、方解石、石墨等矿物，此时黄铁矿中的 $\delta^{34}S$ 值基本等于热液中的 $\delta^{34}S$ 值；在高氧逸度环境下，会出现重晶石等硫酸盐矿物，而此时重晶石中的 $\delta^{34}S$ 值大于流体中的总 S 同位素组成。而辽上金矿床的主要载金矿物为黄铁矿和白云石，未出现重晶石等硫酸盐矿物，因此，认为辽上金矿床中黄铁矿 $\delta^{34}S$ 值基本代表了热液流体中的 $\delta^{34}S$ 值，可以示踪其成矿物质来源。

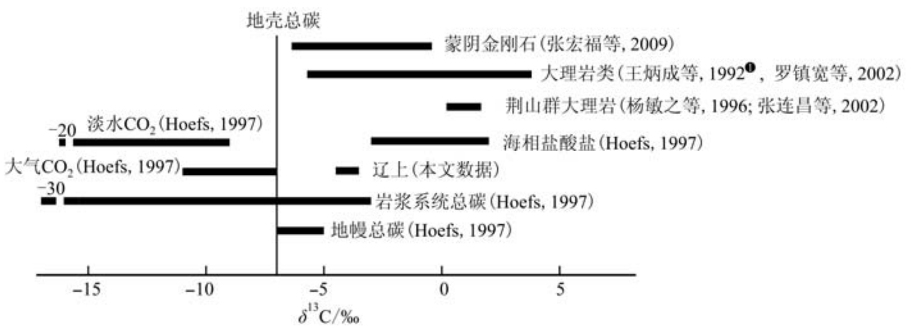

图 4　辽上金矿及相关碳储库（$\delta^{13}C$）

Fig. 4　The Liaoshang gold deposit and its associated carbon reservoir（$\delta^{13}C$）

❶ 王炳成，等. 1992. 胶东金矿稳定同位素地球化学及找矿（科研报告）.

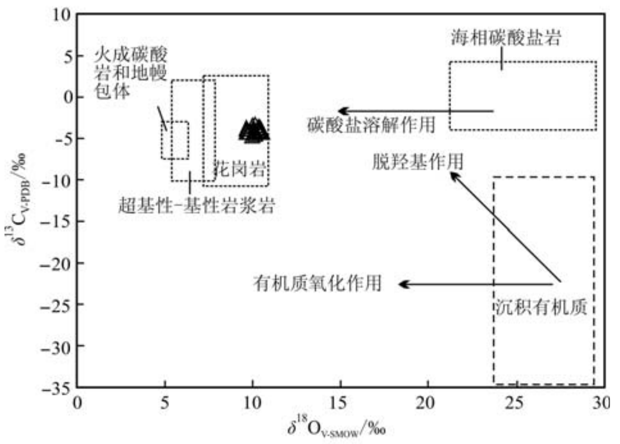

图 5　辽上金矿床 $\delta^{13}C_{V-PDB}-\delta^{18}O_{V-SMOW}$ 相关图解（底图据刘建明等，1997）

Fig. 5　Correlation diagram of $\delta^{13}C_{V-PDB}-\delta^{18}O_{V-SMOW}$ in the Liaoshang gold deposit (after Liu Jianming *et al.*, 1997)

通过辽上金矿床与胶东典型金矿床硫同位素对比发现(图6)，胶西北矿集区(三山岛金矿床)、牟乳成矿带(金青顶金矿床)、胶莱盆地东北缘矿集区(辽上、蓬家夼、宋家沟、土堆-沙旺等金矿床)均以富 ^{34}S 为特征，相对于陨石硫、玄武岩硫同位素组成偏高；胶莱盆地东北缘地区赋矿围岩荆山群 $\delta^{34}S$ 值高于胶西北赋矿围岩胶东群 $\delta^{34}S$ 值，相对应辽上金矿床 $\delta^{34}S$ 值略高于三山岛金矿床 $\delta^{34}S$ 值。胶东地区中基性脉岩、郭家岭花岗岩、玲珑花岗岩等不同的地质体 $\delta^{34}S$ 值也比较相近，尤其是具有幔源特征的中基性脉岩 $\delta^{34}S$ 值也远高于玄武岩、地幔 $\delta^{34}S$ 值。这表明胶东地区金矿床成矿物质与流体可能源于深源岩浆热液，同时流体上升过程有地壳物质混入，使得硫同位素发生分馏。

辽上金矿床 $\delta^{34}S$ 值较陨石硫偏高，均以富 $\delta^{34}S$ 为特征，与胶东地区荆山群、玲珑花岗岩、郭家岭花岗岩、胶东中基性脉岩相近；但也有 $\delta^{34}S$ 值(LS-1 号 $\delta^{34}S$ 值为 3.4‰)低于胶东中基性脉岩 $\delta^{34}S$，与具有幔源性质的玄武岩相近，表明硫同位素在流体演化过程发生较大分馏。而一般认为较高的 $\delta^{34}S$ 值表明可能存在大气降水循环淋滤作用使得硫同位素发生较大程度的分馏(张连昌等，2002)，因此辽上金矿床硫的来源一部分可能源于深源岩浆热液，深源流体上升过程中随着地壳物质成分的不断加入或在地壳浅部大气降水的混入，硫同位素发生分馏，最终表现出高 $\delta^{34}S$ 值特征。

侯明兰等(2006)在研究胶东金矿时对比了煌斑岩与矿石铅同位素组成，认为矿石铅与煌斑岩具有相同的源区，为壳幔混合的产物。从辽上金矿床黄铁矿 $^{206}Pb/^{204}Pb-^{207}Pb/^{204}Pb$ 同位素构造环境判别图(图7)上可以看出，黄铁矿铅同位素较为集中，其投点主要落于造山带和地幔演化曲线之间，表明辽上金矿铅也以壳幔混合为主，铅来源与盆缘发云夼、蓬家夼、大庄子等金矿床具有相似的铅同位素特征(孙

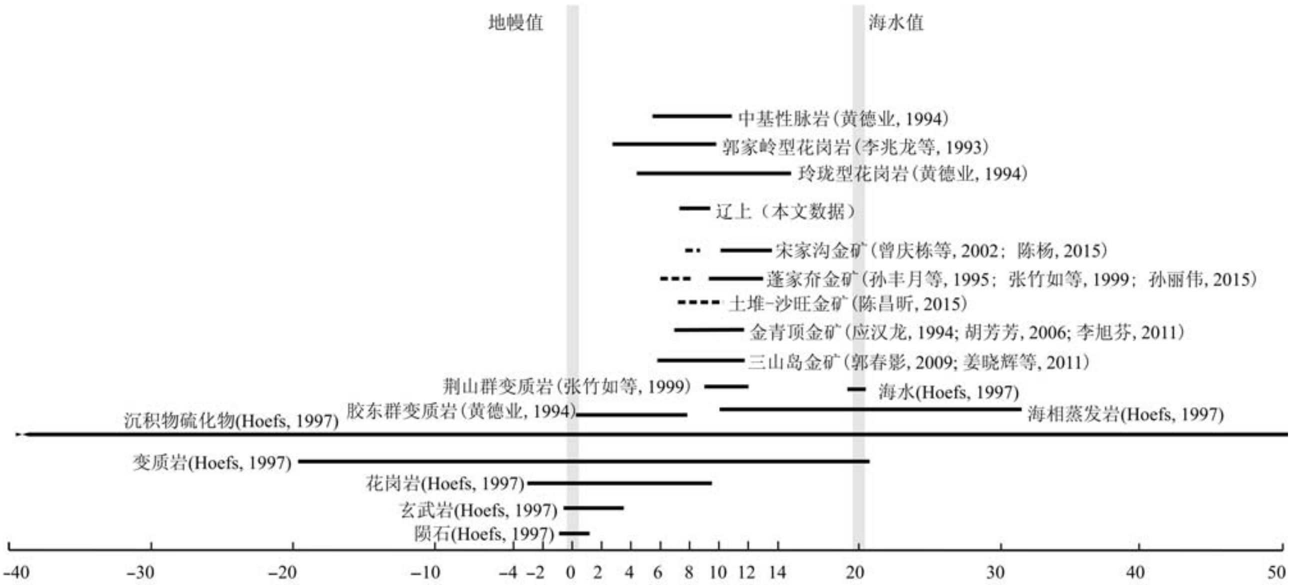

图 6　曲型矿床硫化物 $\delta^{34}S$ 值分布图

Fig. 6　Distribution of sulfide $\delta^{34}S$ values of typical deposits

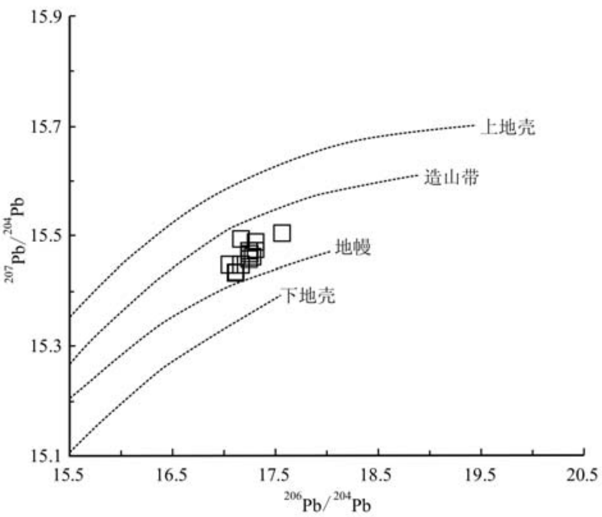

图 7　辽上金矿床 $^{207}Pb/^{204}Pb$ -$^{206}Pb/^{204}Pb$ 同位素构造环境判别图(底图据曾庆栋等, 2002)

Fig. 7　Discrimination diagram of $^{207}Pb/^{204}Pb$ -$^{206}Pb/^{204}Pb$ isotope tectonic environment in the Liaoshang gold deposit (after Zeng Qingdong *et al*., 2002)

丰月等, 1995; 杨金中等, 2001; 张连昌等, 2001; 曾庆栋等, 2002)。关于成矿物质来源,徐述平等(2008)总结了荆山群变质岩中金元素丰度,大量数据显示荆山群金含量较低,小于地壳中金的丰度值 4 $\times 10^{-9}$,不能直接为区内成矿提供如此巨量金元素。Yang 等(2015)从成矿时间方面给出了金矿成矿物质源于深部岩浆系统的佐证,认为胶东金成矿时间与区内火山活动时间基本一致,为火山活动同期产物;而部分学者从同位素特征方面研究认为区内发云夼、蓬家夼金矿床成矿作用与胶莱盆地中火山-次火山岩浆活动有关(杨金中等, 2001; 曾庆栋等, 2002);李红梅等(2010)对区内土堆-沙旺金矿床 S、Pb 同位素分析认为成矿物质与伴生脉岩均来自深部壳幔岩浆混合源区,初始岩浆热液流体为地幔流体衍生物;Tan 等(2012)对土堆-沙旺金矿床研究也认为金矿成矿物质与辉绿岩具有同源性,成矿物质源于深部岩浆系统。与区内土堆-沙旺、发云夼、蓬家夼、大庄子等金矿床相比,辽上金矿床与其有相似的铅同位素特征,表明区内金矿床具有相同或相似的铅源,应为同一成矿背景下发生的成矿作用,其成矿物质为壳幔混合作用产物,与深部岩浆活动存在密切关系。

5.3　成矿模式

胶莱盆地是胶东地区中生代形成的陆相火山-沉积盆地,经历了莱阳期、青山期、王氏期 3 个阶段的演化(李桂群等, 1994; 陈书平等, 1998; 唐华风等, 2003; 徐贵忠等, 2004; 佟彦明, 2007; 任凤楼等, 2008; 吴冲龙等, 2009),其中,青山期区内发了大规模的火山-岩浆作用,火山活动时间大致在 125 ~100 Ma(邱检生等, 2001; 凌文黎等, 2006; 张岳桥等, 2008; 匡永生等, 2012; 周建波等, 2016),青山期基性火山岩喷发时间在 122~113 Ma,酸性火山岩喷发时间为 110~98 Ma(匡永生等, 2012),前者与区内本类型金矿化时间基本一致(Tan *et al*., 2015;黄铁矿 Rb-Sr 等时线年龄约 118 Ma,丁正江等;未发表数据)。而在 125~115 Ma 期间,太平洋板块运动方向发生转变,转由 SEE 向 NWW 向欧亚大陆俯冲,华北克拉通构造体制发生重大转折,地幔大规模上涌,岩石圈加剧拆沉减薄,壳幔强烈作用,岩浆活动频繁(翟明国等, 2003; 吴福元等, 2003; 邓晋福等, 2003; 许文良等, 2004; Xu *et al*., 2004; 周新华, 2006; 闫俊等, 2007; Ma *et al*., 2014; Fan *et al*., 2016),与此同时区域上爆发了大规模金成矿事件。

辽上金矿床位于胶东东部地区,形成于早白垩世中国东部软流圈上涌、岩石圈大规模减薄背景下,此时交代富集地幔部分熔融形成的中基性偏碱性岩浆快速上涌(Fan *et al*., 2001; Ling *et al*., 2009; 匡永生等, 2012),不仅形成了区内大量的火山岩和基性脉岩群(郭城脉岩群; 谭俊, 2009; Tan *et al*., 2012),而且带来大量成矿物质在盆缘形成了辽上式黄铁矿碳酸盐脉型金矿床。即在太平板块俯冲背景之下,软流圈上涌,分异演化形成了 C-H-O 深源含矿流体,深源含矿流体在热驱动下向上运移,并与地壳发生反应,部分地壳物质进入深源含矿流体形成壳幔混合含矿流体,壳幔混合含矿流体运移至地壳浅部,与大气降水混合,形成多源混合含矿流体并在运移过程中萃取了荆山群部分成矿物质。多源含矿流体在热液驱动下运移至盆缘滑脱构造,由于物理化学条件改变,在盆缘滑脱构造由陡变缓部位沉淀成矿(图 8)。而载金矿物白云石流体包裹体均一温度显示,辽上金矿床成矿温度在 199.8~247.1℃,平均 222.7℃(纪攀, 2016),为低温热液脉型金矿床。

6　结论

(1) 白云石 C、O 和黄铁矿 S、Pb 同位素显示,辽上黄铁矿碳酸盐脉型金矿成矿流体主要源于深部

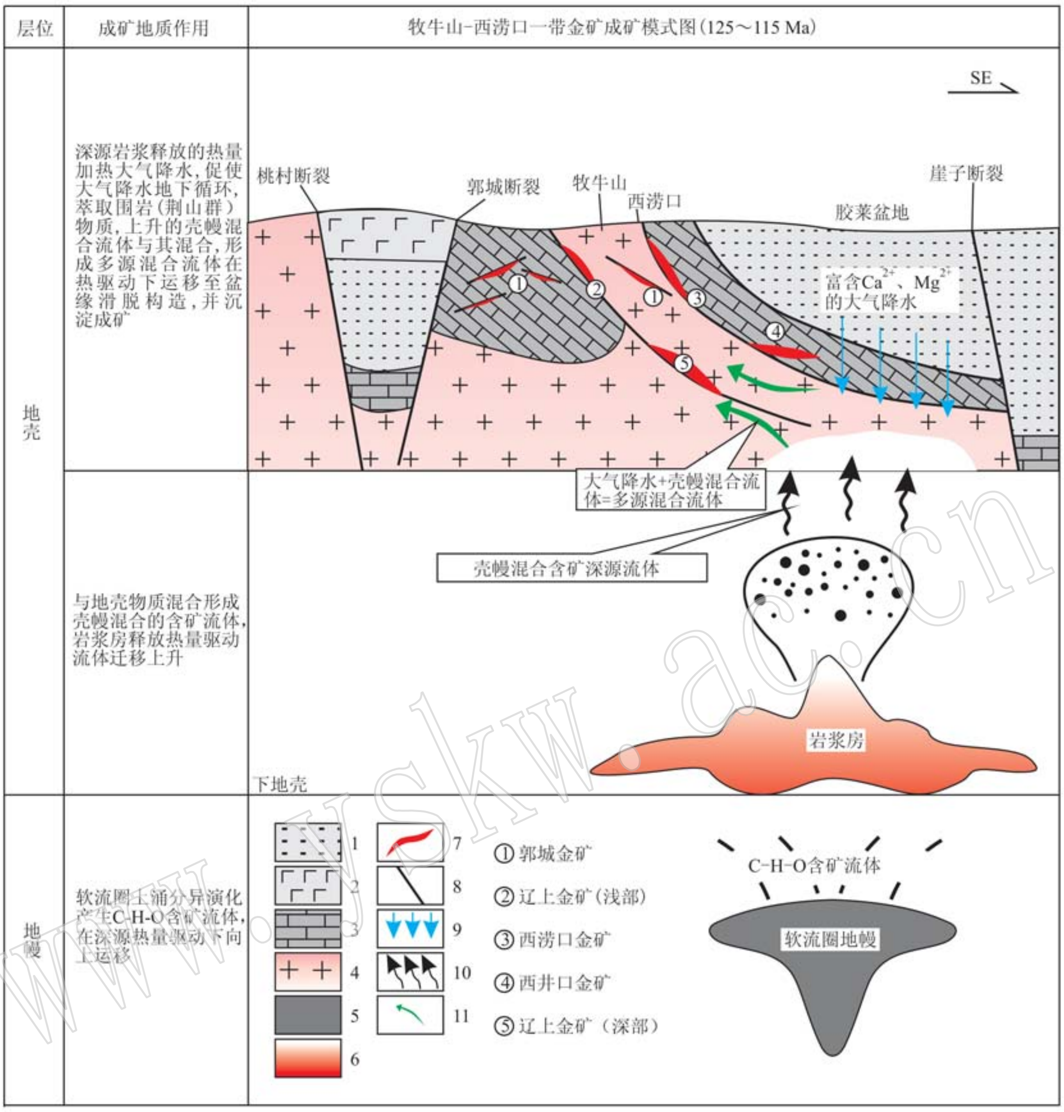

图 8 辽上金矿床成矿模式图

Fig. 8 Metallogenic model of Liaoshang gold deposit

1—莱阳群; 2—火山岩; 3—荆山群; 4—中生代玲珑花岗岩; 5—软流圈地幔; 6—岩浆储库; 7—金矿体; 8—断裂面(滑脱面); 9—大气降水; 10—壳幔混合含矿流体; 11—多源混合流体

1—Laiyang Group; 2—volcanic rocks; 3—Jingshan Group; 4—Mesozoic Linglong granite; 5—asthenospheric mantle; 6—magma reservoir; 7—gold orebody; 8—fracture surface (detachment surface); 9—meteoric water; 10—mixed ore-bearing fluids; 11— multi-sources mixed fluids

岩浆流体,后期有大气降水混入;成矿物质源于地幔,部分源于地壳,为壳幔混合作用产物,与深部岩浆作用存在密切关系,成因类型为含金黄铁矿碳酸盐脉充填型低温热液金矿床。

(2) 辽上黄铁矿碳酸盐脉型金矿床形成于太平洋板块俯冲背景之下,软流圈上涌,分异演化成 C-H-O 含矿流体,流体上升过程中混入地壳物质,在热液驱动下上升至地壳浅部,壳幔混合流体与大气降水混合,多源含矿流体运移至盆缘滑脱构造并在由陡变缓部位沉淀成矿。

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