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胶东型金矿*

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Abstract Jiaodong area is the only Late Mesozoic giant gold province hosted in a Precambrian metamorphic terrane in the world. The metallogenic system of Jiaodong gold province is unique with the following distinctive features: (1) It is situated in an intracontinental composite tectonic setting which has experienced multiple tectono-thermal events. The large-scale gold mineralization is controlled by the change of the subduction direction of the Paleo-Pacific plate and induced the asthenosphere upwelling, the modification of the lithospheric mantle, the transition of the tectonic regime from compression to transpression, and the transition of ore-controlling faults from transpression to transtension regime at 120±2Ma. (2) Multiple ore-controlling structures and diverse ore-hosting formations collectively control the development of gold deposits with various scales and types, which result in the formation of six NE-trending gold belts, namely Sanshandao, Jiaojia, Zhaoping, Qixia, Guoji and Muru, together with an EW-trending gold-rich corridor, namely Sanshandao-Qixia. These belts give rise to different mineralization types of gold deposits (Jiaojia-type/altered rock type in fractured zones, Linglong-type/quartz vein type, Pengjiakuang-type/altered conglomerate ± breccia type, Liaoshang-type/pyrite-carbonate vein type), and each exhibiting distinct geological-geochemical characteristics. (3) The main mineralized elements of the belt include Au, Ag, Cu, Pb and Zn, all of which meet the requirements of industrial utilization. Furthermore, it is an area with super-enrichment of many coexisting critical metals. (4) The Pb isotopic composition of gold-bearing sulfides in different gold belts is linearly correlated to the proven gold reserves and the distance to the Tanlu fault zone, suggesting that the proximity to the main channel of mantle-derived fluids leads to the more radiogenic Pb content and mantle-derived components in sulfides and higher gold mineralization intensity. (5) The Δ^{199}Hg value (averaged at ~0.012‰) is relatively uniform in the region, and the negative correlation between Δ^{199}Hg/Δ^{201}Hg and the gold grade indicate that its ore-forming fluids is derived from the metasomatic lithospheric mantle, and the intensity of mantle metasomatism by subducted oceanic slab and its overlying sediments controls the gold grade. (6) The constant Δ^{33}S isotopic composition (~0‰) of gold-bearing pyrites excludes the Archean metamorphic basement and its remelting granite as the initial gold source. The heavy δ^{34}S (averaged at 9.0±3.7‰) is attributed to the devolatilization of the subducted Paleo-

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Pacific plate and its overlying sediments. The $\Delta^{33}S/\delta^{34}S$ of different gold belts is linearly correlated to the known gold reserves and their distance to the Tanlu fault zone, reflecting that the degree of crustal extension during the mineralization period controls the gold mineralization intensity. (7) The regional He-Ar and H-O isotope compositions show the characteristics of crust-mantle mixing. The isotopic compositions of ore-forming fluids of the Jiaojia-type gold deposits resemble mantle value, while those of the Linglong-type gold deposits are distributed in the transition zone between mantle and crust. The Sanshandao, Jiaojia and Zhaoping gold belts exhibit fluid isotopic compositions similar to mantle-derived fluids, whereas the Guoji gold belt has a relatively open tectonic environment. Hydrogen-oxygen isotope composition positively correlates with the known gold reserves, suggesting a gradual decrease in ore-forming fluid flux and fluid-rock reaction intensity from west to east. Based on these findings, we propose a genetic model for Jiaodong-type gold deposits and clarify the key factors for the formation of the metallogenic system, such as the metallogenic geodynamic background and deep driving force, the source of giant gold and fluids and metal complexes, the channel and mode of transport, the process and mechanism of source-to-sink, the post-mineralization changes and preservation. The exploration idea of 'detachment fault system and basement activation zone and mantle-derived fluid channel composite ore-controlling' and a 'four-step' exploration model are established. The identification characteristics of different scales of Jiaodong gold deposits and the key factors of its formation are different from other types of gold deposits in the world. It is difficult to be explained by the existing metallogenic model. Thus, it belongs to a new type of gold deposit: The Jiaodong type. Its genetic model is universal for gold deposits in North China, South China, Siberia, the Yilgarn block of western Australia, Wyoming of South America, and Guyana of South America. Numerous prospecting breakthroughs validate the rationality and applicability of the genetic model and the proposed exploration model. The Jiaodong-type gold deposits emerge as a significant research focus and exploration direction, with disseminated gold deposits being the primary exploration target in Jiaodong area due to their large resources and stable occurrence.

Key words Geological-geochemical features of the deposits; Metallogenic system; Spatio-temporal; Metallogenetic dynamics; Ore-controlling factors; Genetic and exploration model; Jiaodong-type gold deposits

摘 要 胶东是全球唯一已知赋存于前寒武纪变质地体中的晚中生代巨型金矿省,其成矿系统独具特色,具体表现为:(1)位于陆内复合构造域,经历了多期重大构造-热事件,大规模金成矿作用受控于120±2Ma古太平洋板块俯冲方向变化及其诱发的软流圈上涌、岩石圈改造和伸展-挤压变形交替及控矿断裂剪压-剪张转换;(2)多重控矿构造和多样赋矿建造联合控制了不同规模和类型金矿的发育,形成了三山岛、焦家、招平、栖霞、郭即和牟乳六条NE向金矿带和三山岛-栖霞EW向富金廊带,导致了金矿化类型(焦家式/破碎带蚀变岩型、玲珑式/石英脉型、蓬家夼式/蚀变砾岩±角砾岩型、辽上式/黄铁矿-碳酸盐脉型)及其地质-地球化学特征的多样性;(3)主要矿化元素Au、Ag、Cu、Pb和Zn均达到工业利用要求,并有多种共/伴生关键金属超常富集;(4)不同金矿带中硫化物Pb同位素组成与探明金资源储量及到郯庐断裂带的距离线性相关,反映距离幔源流体主通道越近、金属硫化物中放射性成因Pb含量和幔源组分占比越多、金成矿强度越大;(5)区域总体相对均一的$\Delta^{199}Hg$(平均~0.012‰)及$\Delta^{199}Hg/\Delta^{201}Hg$与金品位呈线性负相关,表明成矿物质来源于富集岩石圈地幔、且地幔被俯冲洋壳及其上覆沉积物交代的程度控制了金品位的高低;(6)区域恒定的$\Delta^{33}S$同位素组成(~0‰)排除了巨量金源自太古宙变质基底及其重熔花岗岩的可能,重的$\delta^{34}S$(平均9.0±3.7‰)来源于俯冲的古太平洋板片及其上覆沉积物的脱挥发份;不同金矿带$\Delta^{33}S/\delta^{34}S$与探明金资源储量及其到郯庐断裂带距离线性相关,反映成矿期地壳伸展程度控制了金成矿强度;(7)区域He-Ar和H-O同位素组成显示壳幔混合特征,焦家式金矿的成矿流体组成更靠近地幔、玲珑式金矿位于地幔与地壳过渡带;三山岛、焦家和招平金矿带的成矿流体相对接近幔源流体,而郭即金矿带具有相对开放的构造环境;不同金矿带氢-氧同位素组成和探明金资源储量正相关,可能表征了从西到东成矿流体通量和流体-岩石反应强度逐渐降低。基于对上述特征的总结,提出了胶东型金矿的成因模式,明确了其成矿地球动力学背景和深部驱动、巨量金属和流体及络合物来源、输运通道和方式、源→汇过程和机制、成矿后变化和保存等成矿系统形成的关键因素,确立了"拆离断裂系与基底活化带及幔源流体通道复合控矿"的勘查思路和"四步式"的勘查模型。综上,胶东金矿不同尺度的鉴别特征及其形成的关键因素明显不同于全球已知的其他金矿类型,难以被已有成矿模式所涵盖,属于一种新的金矿类型——胶东型,其成因模式对华北、华南、西伯利亚、西澳伊尔岗、北美怀俄明和南美圭亚那等陆内金矿床具有普适性;系列找矿突破则验证了该成因模式与勘查模型的合理性和适用性。因此,本文认为胶东型金矿是全球研究热点和重要的金矿勘查方向,而该地区找矿的主攻目标是资源量大且品位和产状稳定的破碎带蚀变岩型金矿。

关键词 矿床地质-地球化学特征;成矿系统;时-空结构;成矿动力学;控矿因素;成因及勘查模型;胶东型金矿

中图法分类号 P618.51

胶东是全球唯一已知赋存于前寒武纪变质地体中的晚中生代巨型金矿省(Goldfarb *et al.*, 2019; Groves *et al.*, 2020a; Groves and Santosh, 2021; Goldfarb and Pitcairn, 2023),其内已发现金矿床240余处,探明金资源储量近5800t,成矿强度实属罕见(Yang *et al.*, 2016a, 2022, 2024; Deng *et al.*, 2023)。然而,胶东金成矿系统独具特色,难以被已有成矿模式所涵盖,可能代表一类独特的、尚未被完全系统描述和定义的金矿类型(Goldfarb and Santosh, 2014; Deng *et al.*, 2015a,

2022)。“胶东型”一词21世纪初见于地质文献,强调了其非造山型金矿成因(翟明国等,2004)。之后,为明确与其他金矿类型的不同,胶东型金矿的成矿特征和成矿机制等逐渐被广为论述(杨立强等,2014;Deng *et al.*,2015b,2020a,2022,2023;Li *et al.*,2015;Yang *et al.*,2016b,2017,2022;宋明春等,2020,2022,2023,2024);但对于胶东型金矿的成因仍有很大争议,目前还缺乏被广泛接受的成因模式和勘查模型,特别是尚未见关于其鉴别特征和形成关键因素的系统报道。为此,本文在论述胶东型金矿不同尺度鉴别特征的基础上,提出了其形成的五个关键因素,探讨了其成因模式及其普适性、勘查模型及其找矿成效和推广前景,以期为发展该类型金矿成矿理论和提升找矿成效提供有力支撑。

1 鉴别特征

1.1 成矿动力学背景

胶东位于华北克拉通东南缘与苏鲁造山带的复合域,经历了太古宙至古元古代的克拉通化、古元古代东-西古陆的碰撞拼贴、晚古生代古特提斯洋的板块俯冲造山、三叠纪华南-华北的陆陆碰撞和深俯冲、晚中生代古太平洋板块俯冲的远程效应等多期岩浆、变质和构造-热事件(李三忠等,2003;Zheng *et al.*,2013,2019;Zhao *et al.*,2019;翟明国等,2020;Deng *et al.*,2023)。

胶东主期金成矿事件集中于120±2Ma,且金成矿年龄和同成矿期中-基性岩浆岩侵位时代均具有由西向东逐渐变小的趋势,表明区域大规模金成矿作用受控于古太平洋板块俯冲-回撤的方向变化及其诱发的软流圈上涌、岩石圈改造和伸展-挤压变形交替及控矿断裂剪压-剪张转换(Deng *et al.*,2020b,c;Zhang *et al.*,2020a;Ni *et al.*,2024)。

1.2 主要控矿因素

胶东已发现金矿床受构造和建造的双重控制,主要沿区域NE向拆离断裂系与近EW向基底构造带复合部位产出,具有NE呈带、EW呈行的分布特征(Yang *et al.*,2014;杨立强等,2014,2019;Deng *et al.*,2019;宋明春等,2022)。

1.2.1 EW向基底构造带

EW向基底构造带主要包括蓬莱-龙口(N37°50′)、栖霞(N37°20′)和平度-石岛(N36°50′)三条相距约60km的构造带,以EW向花岗岩带、地堑盆地、基底褶皱及其伴生断裂带构造复杂的不连续褶-断带(图1)。其形成始于前寒武纪基底逆冲和褶皱、在三叠纪华北和华南陆-陆碰撞和苏鲁超高压变质带形成的南北向挤压过程中再活化,并被NE-NNE向断裂带切割和改造(Deng *et al.*,2019)。其中,栖霞构造带的三山岛-玲珑段长五十余千米、宽十几千米,已发现近100个金矿床,集中了胶东约3/4的探明金资源储量,成矿强度实属罕见。

1.2.2 NE-NNE向容矿断裂带

NE向拆离断裂系总体由II-IV级NE-NNE向容矿断裂带组成(图1)。其中,主拆离断裂整体沿前寒武纪变质岩与晚中生代花岗岩的接触带产出、局部切穿岩体,主断面以发育10~30cm厚的灰黑色(±灰白色)断层泥为特征;总体走向NE30°~50°,倾向SE或NW、倾角30°~50°,沿走向和倾向呈舒缓波状、膨胀夹缩和分支复合特征明显(杨立强等,2014,2019)。断裂内部具有明显的分带结构,由中心向两侧依次发育断层泥(砾)带(局部见糜棱岩)、挤压片理带、构造透镜体带、密集裂隙带和稀疏裂隙带(邓军等,2010);其内次级断裂和裂隙走向总体与主带近平行或小角度斜交,而倾角由中心向外逐渐变陡、直至反倾,形成系列羽状裂隙(Deng *et al.*,2019)。绝大多数金矿床集中于三山岛、焦家、招平、栖霞、郭即和牟乳六条高产的NE向构造-金矿带(图1),具体如下所述。

三山岛带探明金矿床5处,包括超大型的新立、三山岛、西岭和北部海域金矿床以及大型的仓上金矿床,累计探明金资源储量1400余吨(Zhang *et al.*,2020b);矿体均赋存于三山岛断裂带及其下盘派生的次级断裂-蚀变带中(图1)。

焦家带探明金矿床近60处,包括新城、焦家、寺庄和望儿山等系列大型-超大型金矿床,累计探明金资源储量1700余吨(宋明春等,2022);矿体均赋存于焦家断裂带及其旁侧派生的侯西、河西、望儿山、灵山沟-双目顶等次级断裂-蚀变带中(图1)。

招平带探明金矿床40余处,包括玲珑、台上、大尹格庄和夏甸系列大型-超大型金矿床,累计探明金资源储量超过1500吨(宋明春等,2022);矿体均赋存于招平断裂带及其旁侧派生的玲珑、旧店等次级断裂-蚀变带中(图1)。

栖霞带探明金矿床60余处,包括大型的笏山、黑岚沟、庄官金矿床3处,其他均为中-小型金矿床,累计探明金资源储量450余吨(宋明春等,2022);矿体均赋存于NNE向的五十里堡和肖古家边界断裂带围限区内的次级断裂-蚀变带中(图1)。

郭即带探明金矿床40余处,包括大型的辽上、西涝口、蓬家夼、发云夼和土堆金矿床5处,其他均为中-小型金矿床,累计探明金资源储量约200t(宋明春等,2022);矿体均赋存于郭城和崖子断裂带及其旁侧派/伴生的次级断裂-蚀变带中(图1)。

牟乳带探明金矿床50余处,包括大型的乳山(金青顶)、牟平(邓格庄)、三甲和蓝家庄金矿床4处,其他均为中-小型金矿床,累计探明金资源储量250余吨(宋明春等,2022);矿体均赋存于牟乳断裂带及其旁侧派/伴生的青虎山-唐家沟、石沟-巫山、将军石-曲河庄及马家庄-葛口等次级断裂-蚀变带中(图1)。

其他NE-NNE向断裂带金矿化程度较低,如郯庐、五莲-烟台、栾家河、肖古家和桃村断裂带等,只发现零星的小型金矿床或矿点(图1)。

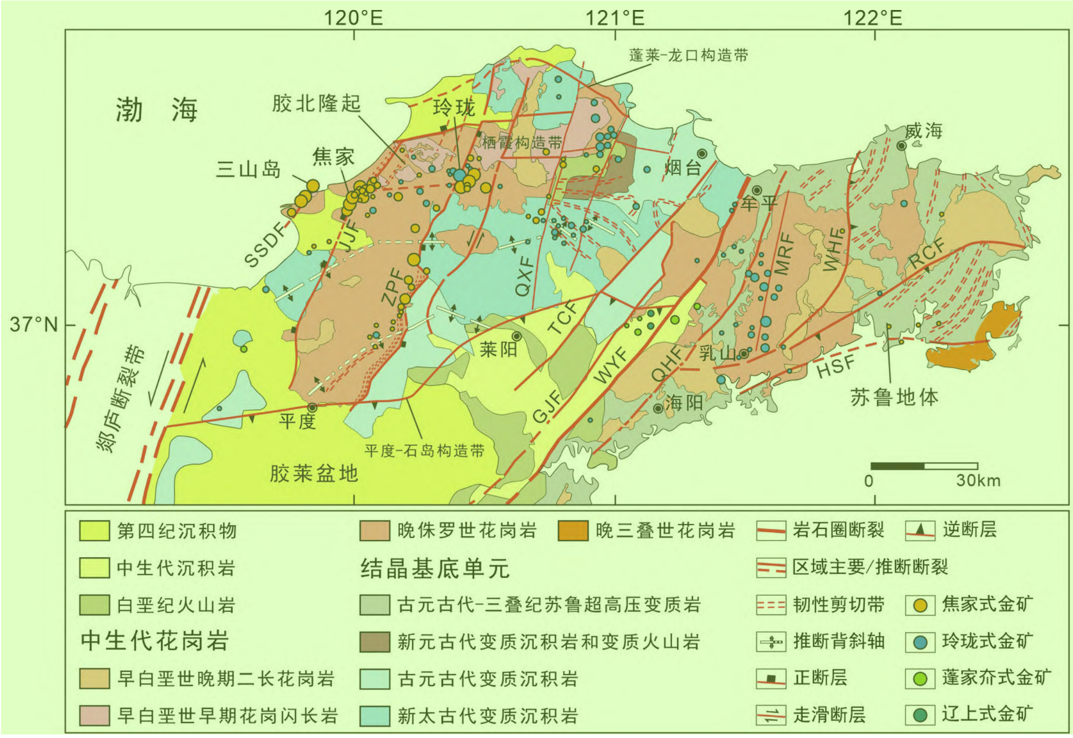

图1　胶东金矿省地质与金矿床分布简图(据杨立强等,2024)
GJF-郭即断裂;HSF-海阳-石岛断裂;JJF-焦家断裂;MRF-牟乳断裂;QHF-青岛-海阳断裂;QXF-栖霞断裂;RCF-荣成断裂;SSDF-三山岛断裂;TCF-桃村断裂;WHF-威海断裂;WYF-五莲-烟台断裂;ZPF-招平断裂

Fig.1　Simplified geological map of Jiaodong gold province showing the distribution of gold deposits (after Yang *et al.*, 2024)

1.2.3　赋矿围岩的物理-化学属性

除上述控矿构造之外,赋矿建造的物理-化学属性是控制金矿床产出的另一关键因素(图2)。其中,能干性(如抗张强度)越强的岩石越易于发生脆性破裂,越有利于为成矿流体运移提供特定的通道;反应活性指数(如Fe×[Fe×Fe+Mg+Ca])越高的岩石越富铁,越有利于流体-岩石反应(如硫化反应)的发生,从而成为最优选的赋矿围岩(Groves *et al.*, 2020b)。

胶东金矿主要的赋矿围岩为晚侏罗世钙碱性花岗岩、早白垩世早期高钾钙碱性花岗岩、前寒武纪变质岩和早白垩世莱阳群底砾岩,它们分别赋存约77%、10%、11%和2%的金矿床(宋明春等,2018)。最重要的矿石类型为黄铁绢英岩,此外,中-基性脉岩与金矿脉的时空分布紧密相伴,而太古代TTG片麻岩和古元古代片麻岩则往往不利于金矿床的产出,这种情况的出现可能均受控于它们的物理-化学属性(图2)。其中,黄铁绢英岩和中-基性脉岩具有最强的抗张强度和很高的反应活性指数,符合其属于胶东金矿最重要矿石类型及与金矿脉时空紧密相伴的特征;晚侏罗世玲珑黑云母花岗岩和早白垩世早期郭家岭花岗闪长岩具有很强的抗张强度和中等的反应活性指数,在成矿过程中易发生脆性破裂而具有更高的流体通量,且流体致裂会引起流体压力从超静岩压力到静水压力的骤降(Sibson, 1992; Cox *et al.*, 2001),从而导致流体不混溶和巨量金沉淀富集(Loucks and Mavrogenes, 1999),这也与大型-超大型金矿床均产出于其中的事实一致。而太古代胶东群变质岩具有最高的反应活性指数和最低的抗张强度,虽然能够通过硫化反应(Phillips and Groves, 1983; Böhlke, 1988)或/和其他水-岩反应导致金沉淀(Evans, 2010),但往往规模不大,与其内仅产出有小型金矿床的现象吻合。

总之,多重控矿构造和多样赋矿建造联合控制了不同规模和不同类型金矿化的发育,导致了金矿床工业类型及其地质-地球化学特征的多样性,具体如下所述。

1.3　矿床地质特征

胶东金矿的主要矿化样式包括焦家式(破碎带蚀变岩型)、玲珑式(石英脉型)、蓬家夼式(蚀变砾岩/角砾岩型)、辽上式(黄铁矿-碳酸盐脉型)四种,其中前两者占全区探明金资源储量的90%以上、后两者属于焦家式的特殊类型(图3)。

1.3.1　焦家式金矿

焦家式金矿主要有两种产出状态(杨立强等,2019,2024;宋明春等,2020,2023):(1)沿早前寒武纪变质岩系(或莱阳群底部砾岩)与晚中生代花岗岩类接触界面展布的主拆离断层下盘的蚀变碎裂(花岗)岩中,构造-蚀变-矿化仅发育于主断裂下盘、具有明显的单侧分带结构;(2)沿晚中生代不

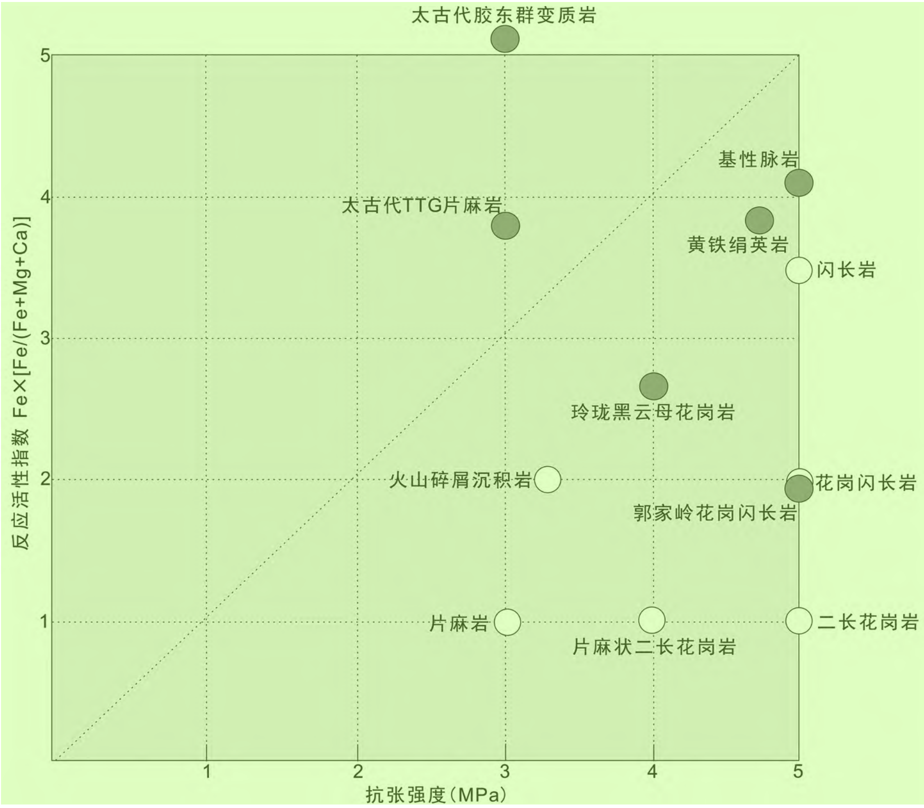

图 2 胶东金矿赋矿围岩的物理-化学属性图解(据 Groves *et al.* ,2020b 修改)

由于难以获得具有代表性的量化值,X 轴和 Y 轴经验性地编号为 1 ~5. Fe × [Fe × Fe + Mg + Ca] :1 = 0.5 ~ 0.6 ;2 = ~ 1.0 ;3 = 2.3 ~ 2.7 ;4 = 3.2 ~ 55 ;5 = 9 ~ 28. 岩石地球化学数据来源于 Yang *et al.* (2016a) , Deng *et al.* (2020a) , 刘向东等(2019) , Wang *et al.* (2024a) ;岩石力学参数来源于水利水电科学研究院(1991) , 山东省地质矿产局第六地质大队(1996①)

Fig. 2 Illustration of the physical-chemical properties of the ore-hosting wall rocks of the Jiaodong gold deposits (modified from Groves *et al.* ,2020b)

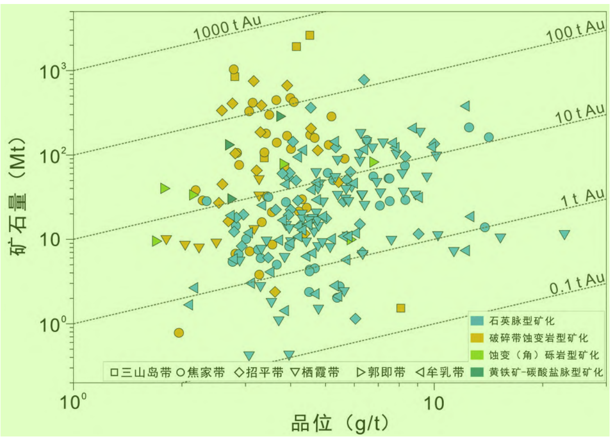

图 3 胶东不同金矿带和矿化类型的品位-吨位图

Fig. 3 Grade-tonnage diagram of different gold belts and mineralization types in Jiaodong

同期次或不同岩相花岗岩类接触界面展布的次级断裂两侧的蚀变碎裂岩中,断裂上、下盘发育似对称的构造-蚀变-矿化分带结构(但下盘强度往往略大于上盘):由以断层泥为标志的主裂面至远离主裂面,构造变形强度逐渐减弱,构造岩类型由断层泥→碎裂岩→花岗质碎裂岩→碎裂花岗岩变化,蚀变类型由黄铁绢英岩化→绢英岩化-硅化→钾长石化-绢英岩化变化,矿化样式由细脉-浸染状→细脉-网脉状→脉状变化。

焦家式金矿的矿体数量少,单个矿体规模大;矿体形态总体较为简单,多为脉状、透镜状和似层状。靠近主裂面的矿体产状总体与其一致,长度可达 1000 ~ 1200m,延深可达 800 ~ 1500m,矿化连续稳定;远离主裂面逐渐出现与之斜交和/或反倾的矿体。控矿断裂产状变化、次级断裂发育和断裂交汇及分支部位均是有利赋矿空间。主要发育黄铁绢英岩、黄铁绢英岩化花岗质碎裂岩和黄铁绢英岩化花岗岩三类金矿石;矿石构造主要为浸染状、网脉状和(细)脉状等;主要金属矿物为黄铁矿、方铅矿、闪锌矿、黄铜矿、磁黄铁矿和毒砂等,脉石矿物主要为石英、绢云母、钾长石和方解石等。金品位整体相对稳定,一般不具特高值(图 3)。

① 山东省地质矿产局第六地质大队. 1996. 焦家金矿床地质勘探-生产勘探总结报告

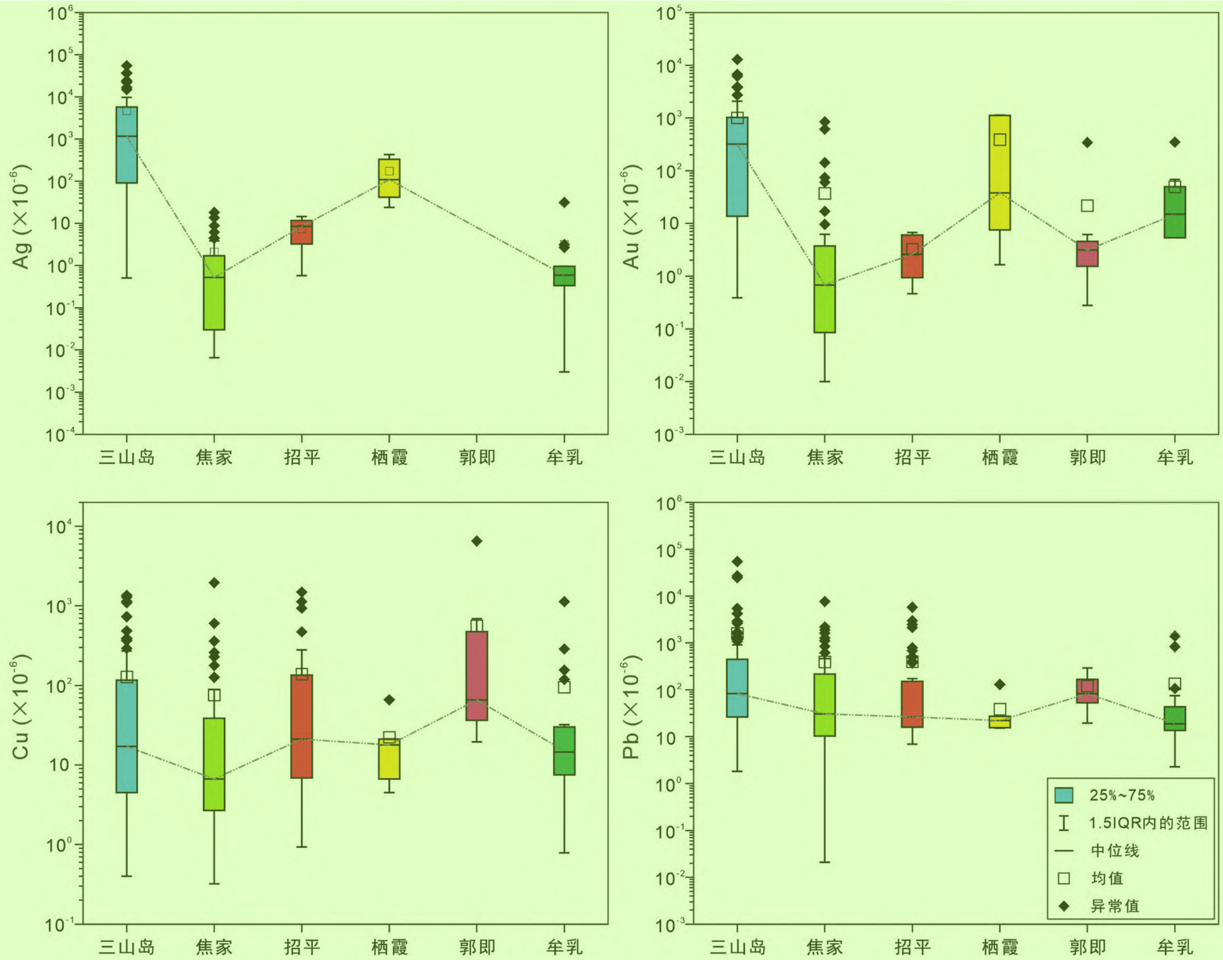

图4 胶东不同金矿带金矿石和蚀变岩中成矿元素含量箱线图

全岩地球化学数据来源:三山岛金矿带来源于邓军等(2010), Li *et al.* (2013),赵睿等(2015),高建伟等(2023);焦家金矿带来源于张炳林等(2014),张潮等(2016),卫清等(2018),刘向东等(2019),袁月蕾等(2023);招平金矿带来源于张炳林等(2017),杜泽忠等(2020),于昆(2014);栖霞金矿带来源于智云宝等(2020);郭即金矿带数据(未收集到Ag含量)来源于孙兴丽(2014);牟乳金矿带来源于李旭芬等(2011),陈海燕等(2012),王真(2013),倪璋懿(2022). 图5数据来源同此图

Fig. 4 Box plots of ore-forming element contents in gold ores and altered rocks from different gold belts in Jiaodong

1.3.2 玲珑式金矿

玲珑式金矿常产于远离主拆离断裂下盘系列近平行、等间距、左行右阶式排列的次级陡倾张性断裂和大型节理裂隙中(Deng *et al.*, 2019;杨立强等, 2019;Sai *et al.*, 2020;宋明春等, 2020, 2022;何江涛, 2021)。金矿体主要赋存在赋矿构造走向转折部位或倾角陡-缓变化部位形成的构造扩容空间内,通常由单条或多条含金石英脉群组成;矿体产状与控矿断裂一致,分枝复合、尖灭侧现和尖灭再现特征明显,单个矿体的规模一般较小。矿体形态、产状和规模随含金石英脉的形态、产状、规模和组合样式而变;其中,厚大且矿化连续的含金石英单脉中矿体呈脉状,有时因石英脉中矿化强度和连续性的差异导致矿体呈透镜状和扁豆状。围岩蚀变主要以含金石英脉两侧的不连续脉状绢英岩化和硅化蚀变及较为连续的钾化蚀变为特征,蚀变带分布范围有限、多为2~3m。

矿石类型主要为含金石英-硫化物脉和黄铁矿-石英-方解石脉,发育致密块状、团块状、浸染状和细脉-网脉状构造。矿石矿物主要为黄铁矿,其次为黄铜矿、方铅矿、闪锌矿、磁黄铁矿,以及少量银金矿、自然金、碲金银矿、自然银和碲铋矿等;脉石矿物主要为石英、方解石、绢云母和钾长石等。应该特别指出的是,牟乳带还可见梳状和角砾状构造,且其硫化物(黄铁矿、方铅矿和闪锌矿等)含量明显高于胶北地体中的同类金矿(亦称邓格庄式/硫化物-石英脉型)。其金品位明显高于焦家式金矿、特别是矿脉复合或脉体膨大部位具特高值,变异性较大(图3)。

1.3.3 蓬家夼式金矿

蓬家夼式金矿产于莱阳群底部砾岩中的低角度层间滑脱带内(聂爱国等, 1999;邹为雷等, 2001;杨立强等, 2019)。矿体呈透镜状、层状或似层状,单体规模较大,矿体厚度0.8~4.5m,走向70°~110°、延伸较为稳定,倾向SE或S、倾角45°~60°(随地层产状而变化)。

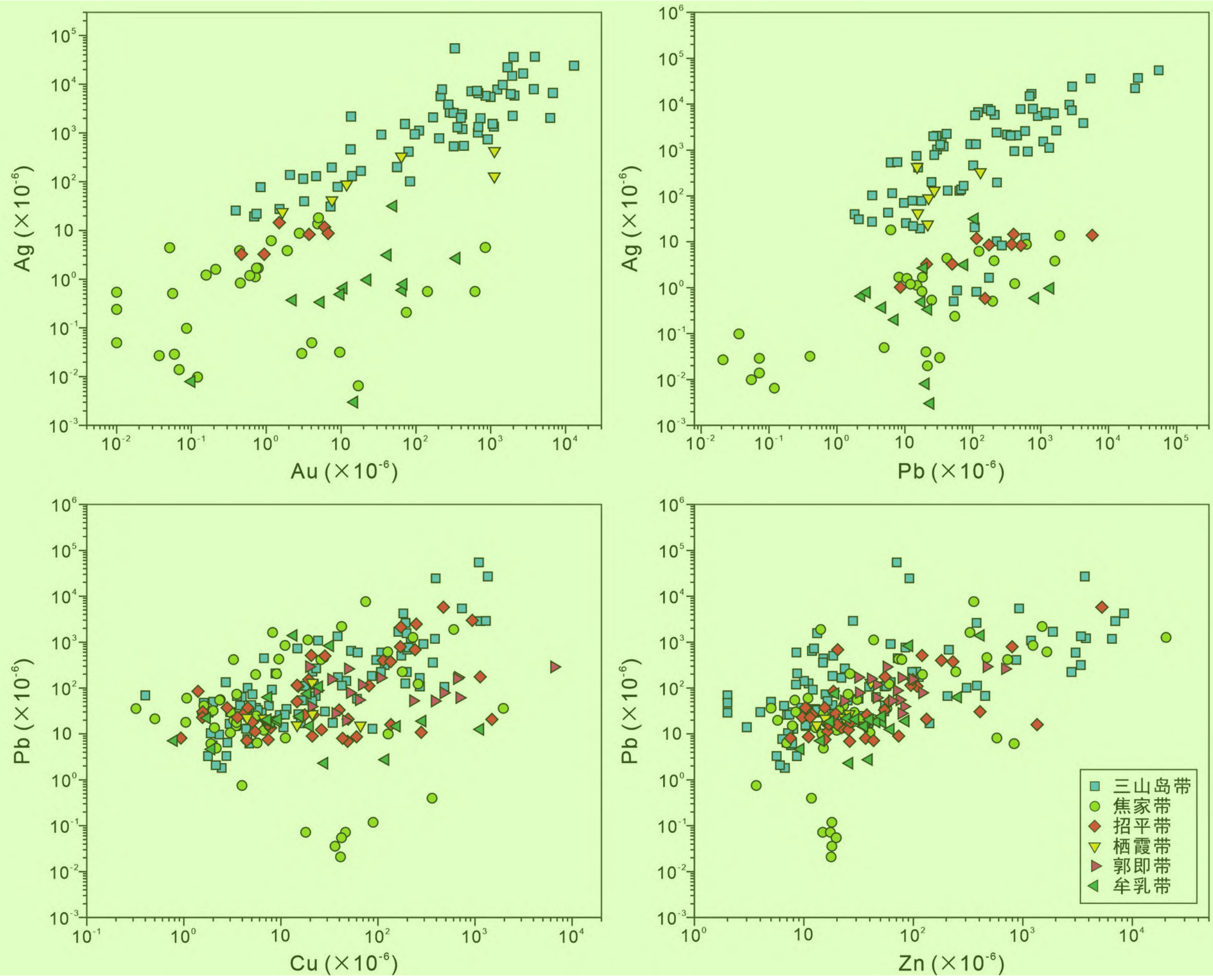

图 5 胶东不同金矿带金矿石和蚀变岩中成矿元素相关性图解

Fig. 5 Correlation diagrams of ore-forming elements in gold ore and altered rock from different gold belts in Jiaodong

主要矿石类型为黄铁矿化构造角砾岩和黄铁矿化底砾岩(含少量砂岩),角砾和砾石由硅化大理岩(偶见长英质)构成,胶结物为热液黄铁矿-石英脉;矿石构造主要为角砾状,其次为浸染状、条带状和网脉状。矿石矿物主要有黄铁矿、磁黄铁矿、黄铜矿、方铅矿、闪锌矿、毒砂和银金矿等,脉石矿物主要为方解石、石英和绿泥石等。矿石品位为 1.69 ~ 6.79g/t,整体较为稳定,和焦家式吻合(图 3)。

1.3.4 辽上式金矿

辽上式金矿产于沿荆山群变质岩与晚侏罗世弱片麻状二长花岗岩接触界面及其下盘系列陡倾次级断裂-裂隙中(丁正江等,2015;李国华等,2017;王志新等,2017;梁辉等,2022),矿体主要呈似层状、透镜状、楔状和马鞍状。

金矿石以含黄铁矿-碳酸盐(细)脉为特征,主要有含黄铁矿-碳酸盐脉花岗岩、含黄铁矿-碳酸盐脉变质岩和黄铁矿-碳酸盐脉三种类型,后者的金品位最高。矿石构造主要有浸染状、稠密浸染状、脉状、角砾状和团块状。金属矿物主要为黄铁矿,其次为黄铜矿、磁黄铁矿、方铅矿、磁铁矿和自然金等;不同矿石类型中的脉石矿物组合不同,主要有白云石、方解石、石英、绢云母和透辉石等。金品位 1.0 ~ 5.5g/t,整体较为稳定,和焦家式一致(图 3)。

1.4 矿床地球化学

1.4.1 矿化元素

胶东金矿石和蚀变岩中主要矿化元素包括 Au、Ag、Cu、Pb 和 Zn(达到伴生矿工业利用要求,并有多种共/伴生关键金属超常富集;杨立强等,2020,2022),其含量均具有明显的空间非均一性。六条金矿带中,三山岛金矿带具有最高的 Au、Ag 和 Pb 元素含量,焦家金矿带中 Au 和 Ag 含量最低;Au 和 Ag 含量从西到东呈基本一致的"W"字形变化趋势;西部三条带中 Au、Ag 和 Cu 呈相似的"V"字形变化趋势;东部三条带中 Au 含量亦呈"V"字形变化,而 Cu 和 Pb 的变化趋势相反(图 4)。

各成矿元素间具较好相关性,特别是 Au-Ag、Ag-Pb、Zn-Pb 和 Pb-Cu 的相关性更强(图 5),表明这些亲硫元素在金成矿作用过程中的地球化学行为类似(Pokrovski *et al.*,2014)。

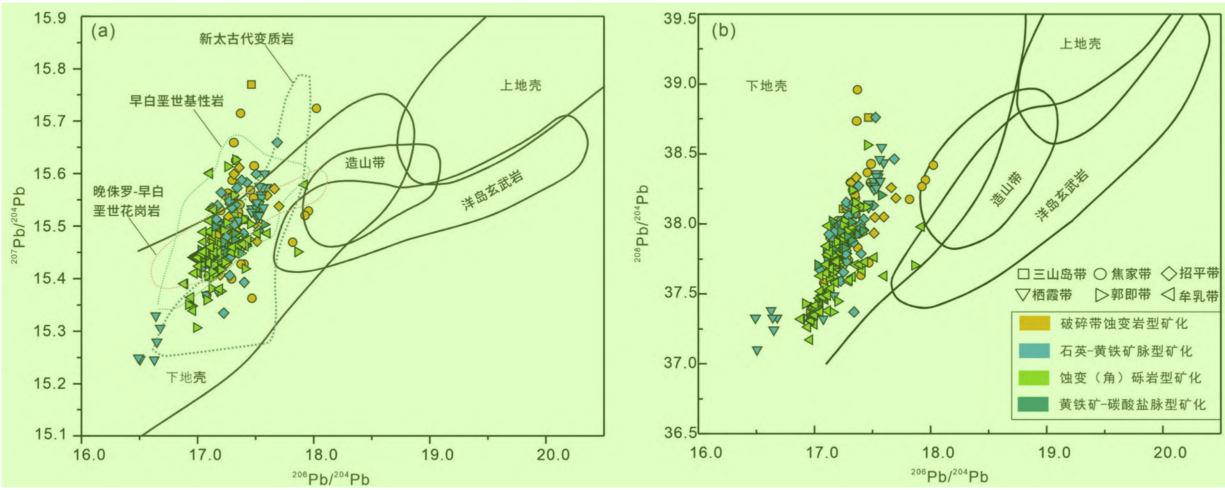

图 6 胶东金矿金属硫化物和不同地质体的 Pb 同位素组成图解(底图据 Zartman and Doe, 1981)

数据来源:金属硫化物的数据来自于 Deng *et al.* (2020a)及其中的相关文献,薄军委等(2021)和 Tian *et al.* (2022, 2023);晚侏罗-早白垩世花岗岩数据来自 Liu *et al.* (2021), Wu *et al.* (2020)和宋英昕等(2020);白垩纪基性岩数据来源于 Ma *et al.* (2014)和龙群(2017);新太古代变质岩数据来自 Deng *et al.* (2020a)及其中的相关文献. 图 7 数据来源同此图

Fig. 6 Diagram of Pb isotopic compositions of metal sulfides in gold deposits and different geological bodies in Jiaodong (base map after Zartman and Doe, 1981)

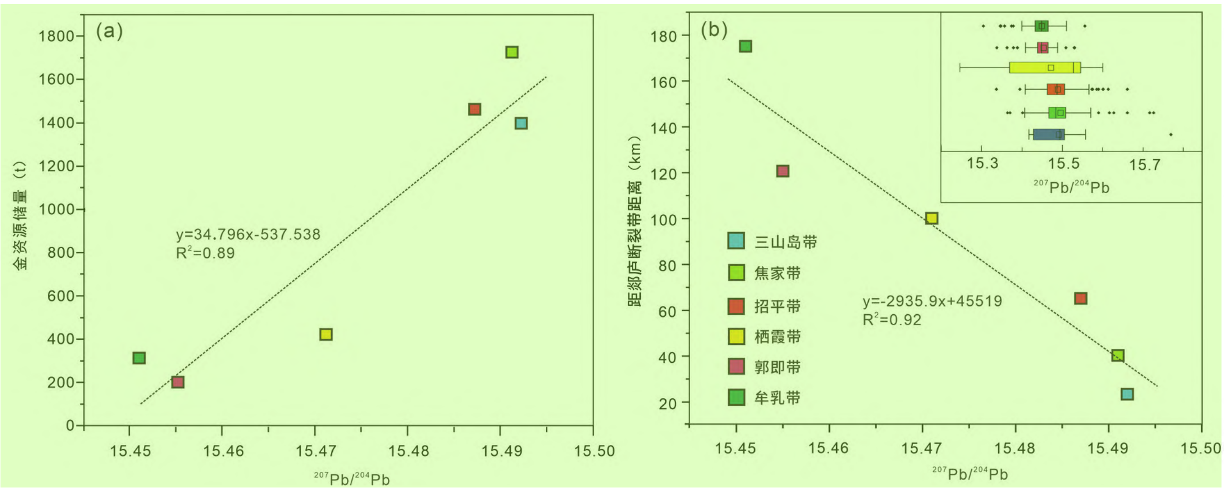

图 7 胶东不同金矿带中金属硫化物^{207}Pb/^{204}Pb 与金资源储量图解(a)及^{207}Pb/^{204}Pb 与金矿带距郯庐断裂带距离相关性图解(b)

Fig. 7 Correlation diagrams of ^{207}Pb/^{204}Pb of metal sulfides with gold resource reserves (a) and ^{207}Pb/^{204}Pb of metal sulfides with the distance from the Tanlu fault zone (b) in different gold belts in Jiaodong

1.4.2 铅同位素

六条金矿带和四种矿化样式中金属硫化物 Pb 同位素整体组成相似、局部略显分散,表明其成矿物质的来源总体相同(图 6)。金属硫化物的^{206}Pb/^{204}Pb(16.49 ~ 18.02)、^{207}Pb/^{204}Pb(15.25 ~ 15.77)和^{208}Pb/^{204}Pb(37.1 ~ 38.96)绝大部分落在下地壳区,少部分具有更强的放射性 Pb 同位素组成而落在下地壳之外,反映成矿物质具有混合来源(下地壳为主,外加一个更具放射性 Pb 的源区)。金属硫化物与古老下地壳部分熔融的晚侏罗世花岗岩(Yang *et al.*, 2018)和壳幔混源的早白垩世花岗岩(Li *et al.*, 2018; Song *et al.*, 2020)及富集岩石圈地幔部分熔融的早白垩世基性脉岩(龙群, 2017; Wang *et al.*, 2024b)三者的 Pb 同位素组成基本重合,说明更具放射性 Pb 的源区可能为富集岩石圈地幔,即胶东金矿成矿物质主要来自于被交代地幔改造的古老下地壳(杨立强等, 2014; Dong *et al.*, 2023)。

不同矿化样式中金属硫化物 Pb 同位素组成整体一致,而不同金矿带的略有差异、且与各带探明金资源储量和到郯庐断裂带的距离相关性较好(图 7)。如自西向东各金矿带

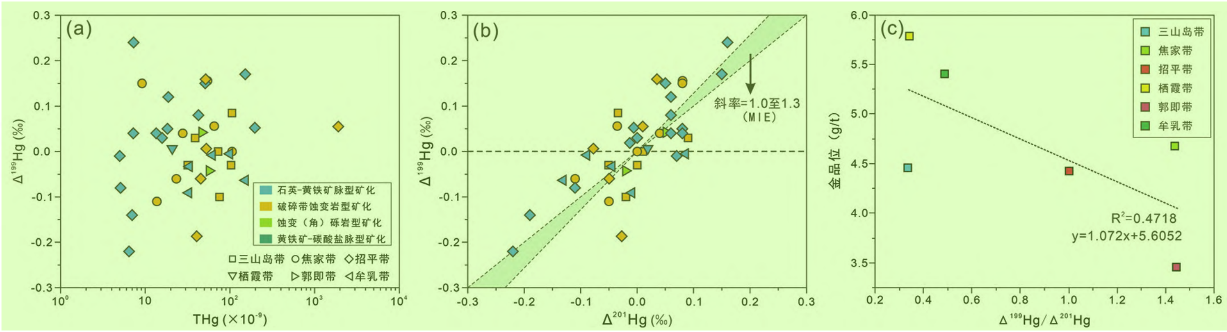

图 8　胶东不同金成矿带和矿化类型中载金黄铁矿的汞同位素图解

(a) Δ^{199}Hg 与 THg 图；(b) Δ^{199}Hg 与 Δ^{201}Hg 图解；(c) Δ^{199}Hg/Δ^{201}Hg 与金品位相关图．数据来源：Wang *et al.* (2024a) 和 Zhang *et al.* (2024)

Fig. 8　Diagrams of mercury isotope in gold－bearing pyrites from different gold belts and mineralization types in Jiaodong

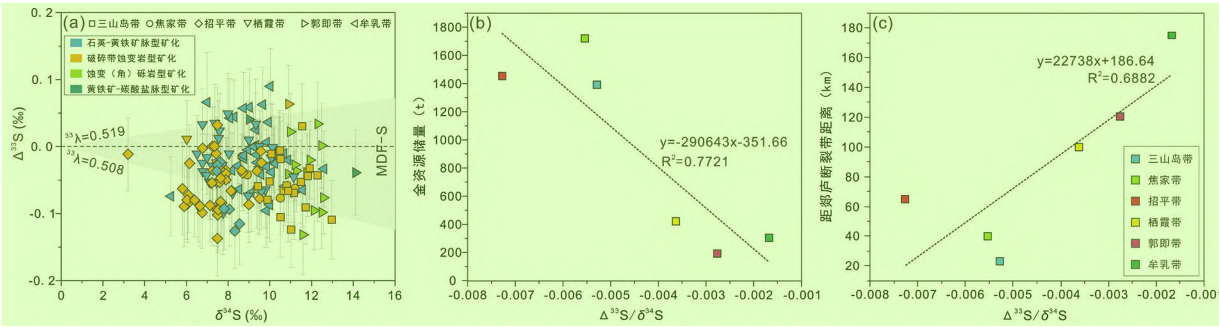

图 9　胶东不同金成矿带和矿化类型的黄铁矿多硫同位素图解

(a) Δ^{33}S 与 δ^{34}S 图解，灰色三角形表示 LaFlamme *et al.* (2018) 定义的硫同位素质量相关分馏范围($^{33}\lambda$ 范围从 0.508 到 0.519)、MDF-S 为硫的质量分馏(用 δ^{34}S 进行监测)；(b) Δ^{33}S/δ^{34}S 与金属量相关图解；(c) Δ^{33}S/δ^{34}S 与金矿带与郯庐断裂带之间距离的相关图解．多硫同位素数据来源于 Qiu *et al.* (2023)

Fig. 9　Diagrams of multi-sulfur isotopes of pyrite from different gold belts and mineralization types in Jiaodong

的 ^{207}Pb/^{204}Pb 组成整体呈线性升高趋势；反映距离郯庐断裂带越近，金矿带金属硫化物中放射性成因 Pb 含量和幔源组分占比越多，金资源储量越大。

1.4.3　汞同位素

胶东金矿中载金黄铁矿的 THg 浓度在招平金矿带中变化较大($4.99\times10^{-9}\sim1908\times10^{-9}$)，其他金矿带中波动较小(图 8a)。$\Delta^{201}$Hg 与 Δ^{199}Hg 值之间存在正相关关系，比值接近 1(图 8b)，这与水相汞(II)光还原过程中观察到的结果一致(Bergquist and Blum，2007)。六条金矿带和四种矿化样式中的载金黄铁矿总体显示相对均一的 Δ^{199}Hg 值(接近 ~0‰，平均值 ~0.012‰)，与原始地幔和幔源岩浆型汞矿具有相似的 MIF-Hg 信号，表明岩石圈地幔控制了胶东金矿总体的 Hg 收支、成矿物质可能来源于交代岩石圈地幔(Wang *et al.*，2024a；Zhang *et al.*，2024)；少数样品显示正或负的 Δ^{199}Hg 偏移(>0.1‰或<－0.1‰)，反映了洋壳或陆壳物质对于交代岩石圈地幔的贡献(Wang *et al.*，2024a；Zhang *et al.*，2024)。Δ^{199}Hg/Δ^{201}Hg 与金品位的二元图揭示了两者之间具有一定的负相关性(图 8c)，表征了深部俯冲洋壳及其上覆沉积物对浅部金矿化品位的控制，即再循环的洋壳俯冲物质对交代岩石圈地幔的贡献越大、越有利于高品位金矿的产出。

1.4.4　多硫同位素

胶东典型金矿床矿石中的黄铁矿多硫同位素分析结果表明(Qiu *et al.*，2023)，Δ^{33}S 在 －0.14‰～＋0.09‰之间变化，平均值为 －0.04±0.09‰；δ^{34}S 较高，变化范围为 3.2‰～14.1‰，平均值为 9.0±3.7‰(图 9a)。所有样品均具有相对恒定的 Δ^{33}S 同位素组成(接近 ~0‰，平均值 －0.04‰)，未识别出 MIF-S 信号，排除了太古宙变质基底及其重熔花岗岩作为巨量金来源的可能性，表明含金流体来自更深部源区。δ^{34}S 值变化明显(3.2‰～14.1‰)且相对较重(平均 9.0±3.7‰)，不同于地幔硫而显示壳源物质信号，其中重的 δ^{34}S 可能来源于俯冲的古太平洋板片及其上覆沉积物(Qiu *et al.*，2023)。

六条金矿带黄铁矿 Δ^{33}S/δ^{34}S 比值与已知金属量(图 9b)及金矿带到郯庐断裂带距离之间具有良好的线性相关(图 9c)，结合区域载金黄铁矿相对恒定的 Δ^{33}S 同位素组成，

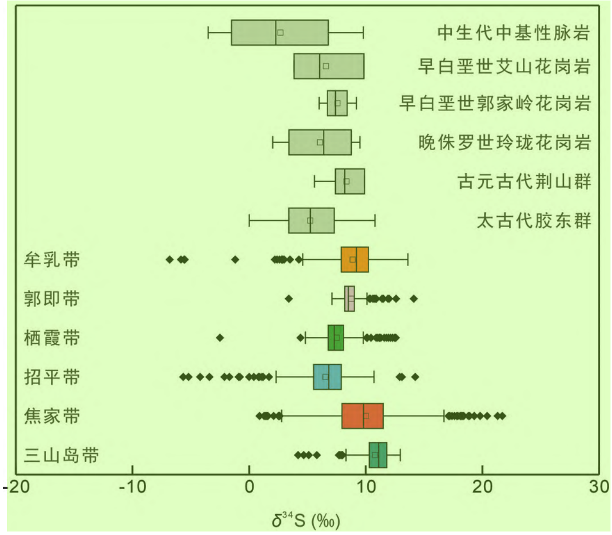

图 10 胶东不同金矿带中金属硫化物 $\delta^{34}S$ 组成变化

数据来源：Deng *et al.*（2020a）及其中的参考文献，Hu *et al.*（2020），Zhang *et al.*（2020b），朱照先等（2020），Liu *et al.*（2021），Wu *et al.*（2021），Yao *et al.*（2021），薄军委等（2021），黄鑫（2021），李杰等（2021），李逸凡等（2021），毛兴强等（2022），许杨等（2021），Bao *et al.*（2022），Chi *et al.*（2022），Li *et al.*（2022，2023），Sun *et al.*（2022），Xu *et al.*（2022），Du *et al.*（2023），Qiu *et al.*（2023），Tian *et al.*（2023），Wang *et al.*（2024a，b）

Fig. 10 Diagram of $\delta^{34}S$ composition variation of metal sulfides from different gold belts in Jiaodong

反映这种线性关系可能与 $\delta^{34}S$ 值的变化有关：自西向东成矿期伸展程度的减弱导致成矿强度明显降低（Deng *et al.*，2023；Qiu *et al.*，2023）。

六条金矿带金属硫化物 $\delta^{34}S$ 组成总体近似、变化范围相对较窄（5.53‰～11.8‰），且与其直接围岩的 $\delta^{34}S$ 一致（图 10），表明其硫具有相同来源、并在复杂的壳幔交换过程中达到了同位素体系的均一化（Mao *et al.*，2008）。而从西到东 $\delta^{34}S$ 值具有先降后升的变化趋势，可能揭示了金成矿条件的细微差别（王义文等，2002；侯明兰等，2006；Deng *et al.*，2015a，2020a；李杰等，2022）；整体较重的 $\delta^{34}S$ 反映深部幔源流体源区受到了地壳物质的混染（Chen *et al.*，2005；Mao *et al.*，2008；杨立强等，2014；Deng *et al.*，2020a；Hu *et al.*，2022）；招平和栖霞金矿带较低的 $\delta^{34}S$ 值说明其可能经历了强烈的成矿流体不混溶或流体-岩石反应，与其赋矿围岩具有高反应活性指数的特征一致（图 2）。

1.4.5 氦-氩同位素

六条金成矿带中热液黄铁矿流体包裹体的大部分 He-Ar 同位素数据投影在地壳与地幔流体过渡带（图 11），显示壳幔混合组成特征。其中，栖霞金矿带的 ^3He-^4He（0.041～11.4）、牟乳金矿带的 R/Ra（0.037～3.612）和招平金矿带的 $^{40}Ar/^{36}Ar$（365.9～7935.12）变化范围最大，牟乳金矿带的部分数据点落在地壳流体区中（图 11b）。由于矿石位于地壳寄主岩中，且这些数据可能包括次生流体的贡献，因此目前对这些数据的意义尚不清楚；唯一重要的因素被认为是来自 0%～30% 范围内数据的地幔成分，异常值高达 100%（Zhang *et al.*，2012；Shen *et al.*，2013；Xue *et al.*，2013）。

三山岛、焦家、招平和牟乳金成矿带成矿流体 $^{40}Ar/^{36}Ar$ 比值明显偏离大气饱和水的氩同位素组成（图 11b），而郭即金矿带成矿流体 $^{40}Ar/^{36}Ar$ 比值接近于大气饱和水氩的同位素组成（张连昌等，2002；张运强等，2012；薛建玲等，2013），

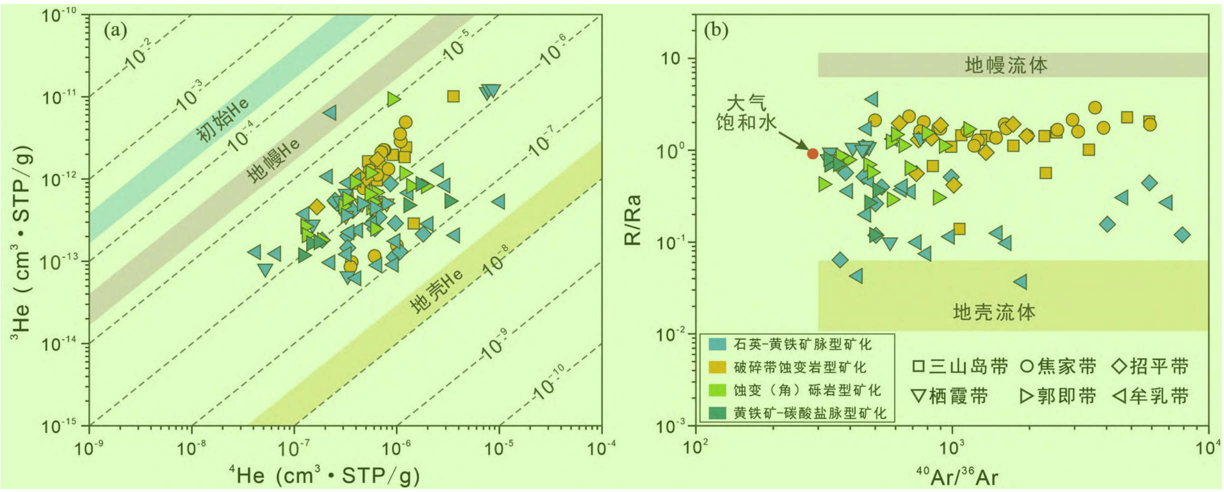

图 11 胶东不同金成矿带和矿化类型中热液黄铁矿流体包裹体 ^3He-^4He（a）和 R/Ra-$^{40}Ar/^{36}Ar$（b）图

主要储层组成区域资料来自 Mamyrin and Tolstikhin（1984）；氦-氩同位素来源于 Deng *et al.*（2020a）及其中的参考文献，Li *et al.*（2023）和 Xu *et al.*（2023）

Fig. 11 ^3He vs. ^4He（a）and R/Ra vs. $^{40}Ar/^{36}Ar$（b）diagrams of fluid inclusions in hydrothermal pyrite from different gold belts and mineralization types in Jiaodong

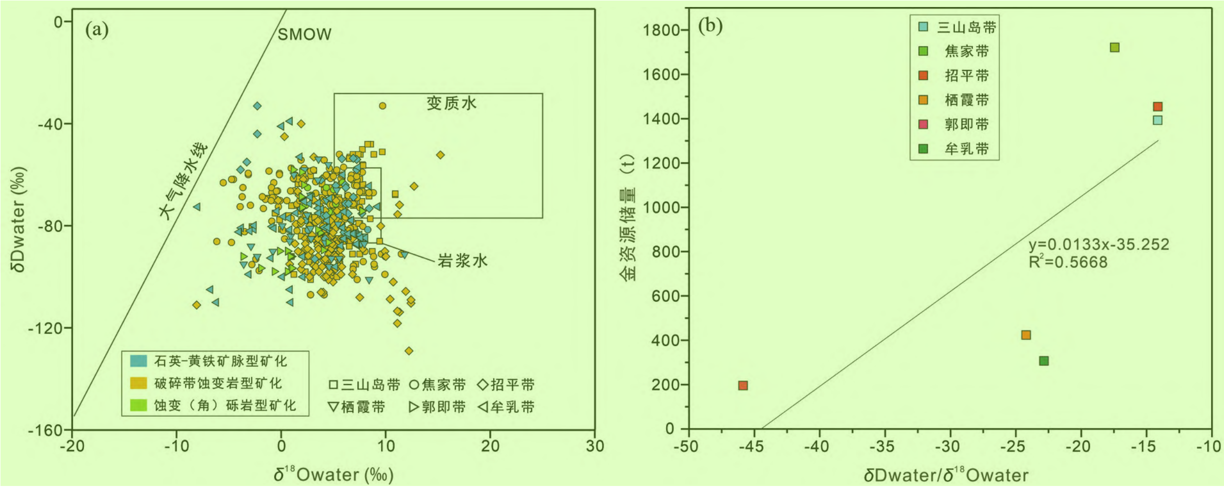

图 12　胶东不同金矿带和矿化类型中热液石英和绢云母的氢-氧同位素图解(a)及 δDwater/δ^{18}Owater 与金资源储量相关性图解(b)

数据来源：Deng *et al.* (2020a)及其中的参考文献，王金辉(2020)，魏瑜吉等(2020)，Liu *et al.* (2021)，Wu *et al.* (2021)，黄鑫(2021)，李杰等(2021)，李逸凡等(2021)，Tian *et al.* (2022)，Wang *et al.* (2022)，毛兴强等(2022)，Du *et al.* (2023)，Zhao *et al.* (2023)

Fig. 12　Hydrogen-oxygen isotopic diagram of hydrothermal quartz and sericite (a) and the correlation diagram of δDwater/δ^{18}Owater with gold resource reserves (b) from different gold belts and mineralization types in Jiaodong

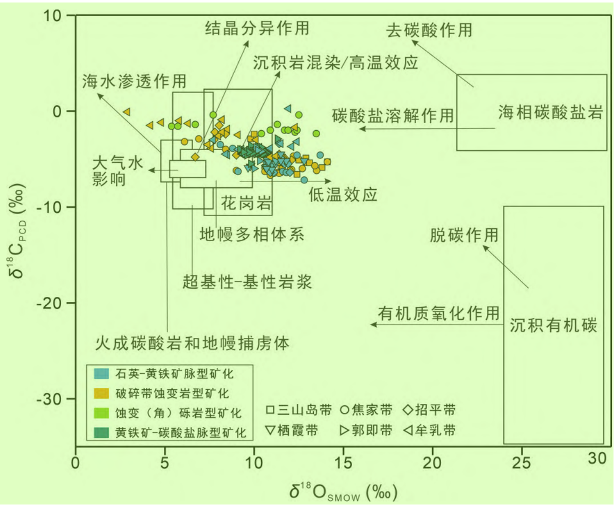

图 13　胶东不同金矿带和矿化类型中碳酸盐矿物的碳-氧同位素图解

数据来源：Deng *et al.* (2020a)及其中的参考文献，吕婧祎等(2023)，马顺溪等(2020)，王勇军等(2020)，Li *et al.* (2020)，Jiang *et al.* (2020)，魏瑜吉等(2020)，薄军委等(2021)，Wu *et al.* (2021)，Lan *et al.* (2022)，Tian *et al.* (2022)，Wang *et al.* (2022)

Fig. 13　Carbon-oxygen isotope diagram of carbonate minerals from different gold belts and mineralization types in Jiaodong

表明郭即金矿带的流体包裹体中含有较多的大气降水组分，三山岛、焦家、招平和牟乳金矿带成矿流体中幔源流体贡献较大，郭即金矿带的相对较小，栖霞金矿带介于它们之间。

不同矿化类型中热液黄铁矿流体包裹体的大部分 He-Ar 同位素组成差异明显，其中焦家式金矿的成矿流体组成更接近于地幔组成，玲珑式金矿成矿流体组成在地幔与地壳组成过渡带中具有较大的变化范围(图 11)。

1.4.6　碳-氢-氧同位素

不同金成矿带和矿化类型中热液石英和绢云母的氢-氧同位素组成整体非常相似，均分布在大气水线与变质流体和岩浆流体之间区域，这可能是由于成矿后次生流体和流体-围岩反应对原生成矿流体造成了混染，而并非深源流体与大气水的混合(Goldfarb and Groves，2015)。

六条金矿带的氢-氧同位素组成略有差异(图 12a)，其中三山岛、焦家和招平金矿带的相对接近原生岩浆水，有较小部分大气水的加入；而从栖霞经郭即至牟乳金矿带，其氢-氧同位素组成逐渐趋近于大气降水线。同时，蓬家夼式金矿相对于其他类型有较轻的氢-氧同位素组成，反映胶莱盆地北缘相对开放的构造环境。六条金矿带的氢-氧同位素组成和金资源量之间具有明显的正相关性(图 12b)，可能表征了由西向东成矿流体通量和流体-岩石反应强度逐渐降低。

胶东金矿碳酸盐矿物的 $\delta^{18}O_{SMOW}$ 值(2.9‰～14.1‰)和 $\delta^{13}C_{PDB}$ 值(－7.2‰～0.24‰)的总体变化范围不大，明显高于淡水 CO_2 和有机质的碳同位素组成、略高于地壳和大气 CO_2 的 $\delta^{13}C$ 并低于海相碳酸盐。6 条金矿带 $\delta^{18}O_{SMOW}$ 和 $\delta^{13}C_{PDB}$ 比值在多相地幔体系附近的花岗岩区域，均具有低温蚀变趋势，三山岛、焦家和招平金矿带中受低温蚀变影响更明显，说明这三条金矿带成矿晚阶段流体-岩石反应程度更强(图 13)。

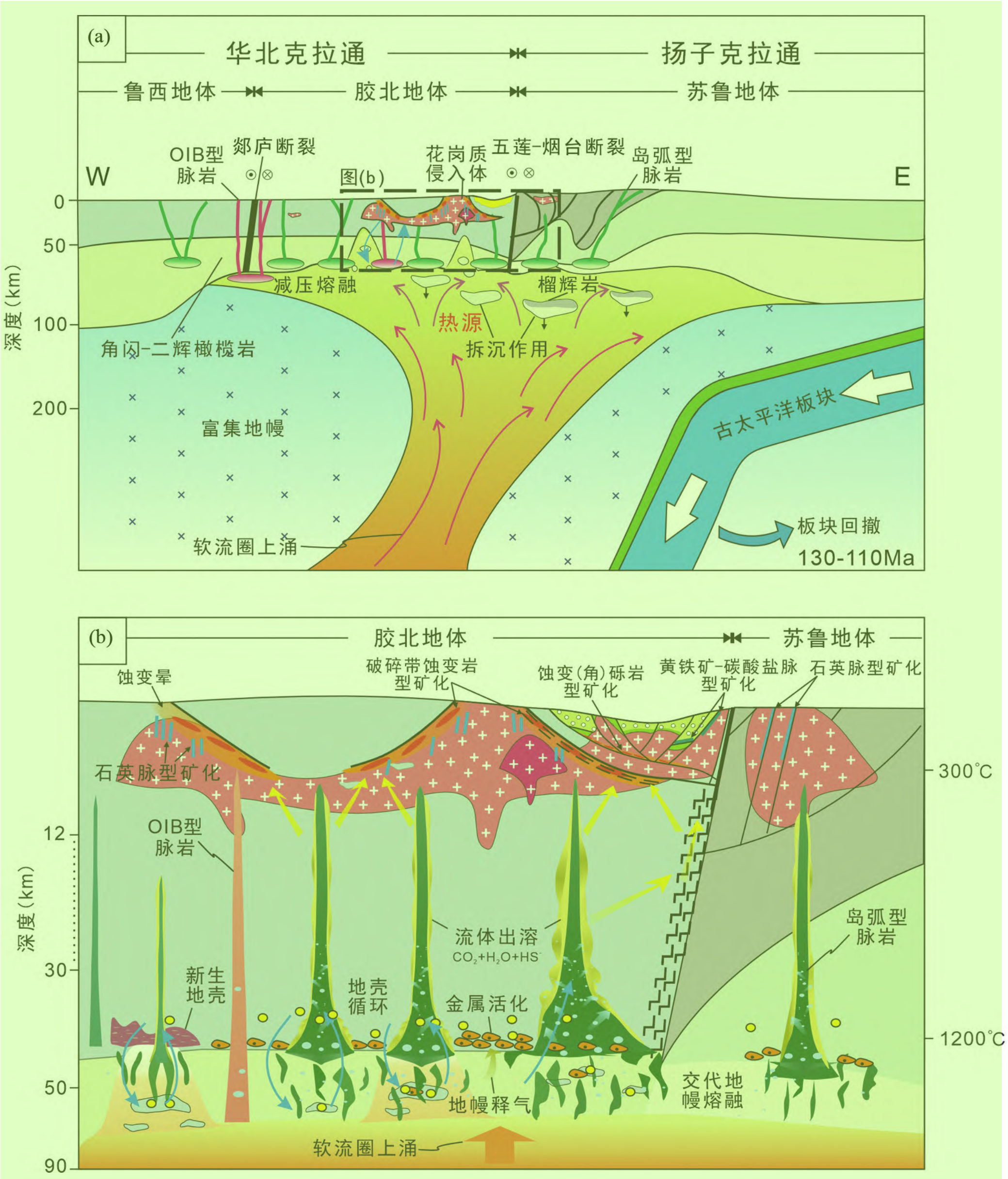

图 14 胶东型金矿成矿模型(据 Deng *et al.*, 2023 修改)

(a)成矿期软流圈大规模上涌与富集地幔部分熔融;(b)成矿期基性岩浆和富集地幔脱气形成幔源流体,流体活化下地壳硫化物堆晶中金属产生成矿流体

Fig. 14 Metallogenic model of Jiaodong-type gold deposits (modified after Deng *et al.*, 2023)

2 成因模式

综上可见,胶东下地壳经历了活化改造和 Au 再富集作用(Deng *et al.*, 2023; Dong *et al.*, 2023),和矿石具有较为一致的同位素(Pb-S 等)组成特征(Deng *et al.*, 2020a),表明巨量金主体来源于再循环的下地壳(杨立强等, 2014);成矿流体 He-Ar 和 C-O 同位素组成与富集地幔多相体系范围一致(Li and Santosh, 2014; Deng *et al.*, 2020a),且同成矿期基性脉岩来源于被水和碳酸盐熔/流体交代的富集岩石圈地幔(Ma *et al.*, 2014; Deng *et al.*, 2017),说明成矿流体来自起源于富集岩石圈地幔(Groves *et al.*, 2020a; Deng *et al.*, 2023)。其中,古元古代东-西古陆的碰撞拼贴、晚古生代古特提斯洋板块俯冲造山、三叠纪华南-华北陆陆碰撞和深俯冲复合可能导致富集地幔岩石圈的形成和含水矿物及挥发份的聚集,成为含金流体的重要源区(Deng *et al.*, 2020b);贯通岩石圈地幔顶部与地壳深部 EW 向大陆深俯冲带和基底构造带以及地壳浅部 NE-NNE 向逆冲断层系可能是其关键控制因素,高压-超高压条件下来自不同地壳源的流体的交代作用可能是其关键机制(Deng *et al.*, 2019, 2022)。

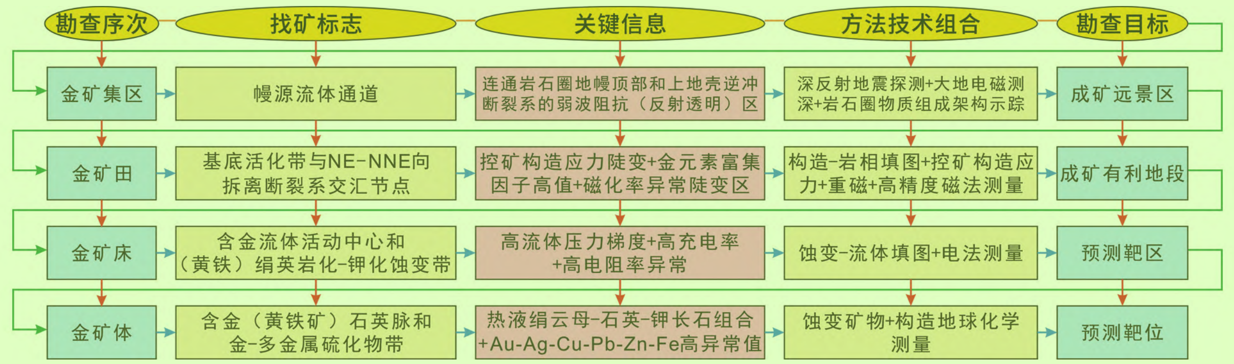

图 15　胶东型金矿勘查模型

Fig. 15　Exploration model of Jiaodong-type gold deposits

而上地壳拆离断裂带汇聚于中地壳滑脱构造带、与下地壳逆冲构造带及陡立超壳深大断裂带一起构成贯通地幔顶部和全地壳的流体输运系统(俞贵平等,2020;Deng *et al.*,2023),有利于深部含金流体的快速运移、而不会形成广泛的熔体(Goldfarb and Santosh,2014)。约 120Ma 时,古太平洋板块俯冲-回撤的方向变化及其诱发的软流圈上涌引起上覆富集岩石圈地幔部分熔融和交代置换及地壳强烈改造(图 14a),导致富集地幔和壳幔过渡带中 Au 的活化迁移与含金流体的释放,随幔源流体进入贯穿地壳的断裂系统(图 14b)。壳-幔相互作用过程中,区域挤压→伸展变形交替,诱发了赋矿围岩快速隆升和减压降温,导致控矿断裂系统的地震泵吸作用于脆-韧性转换带→脆性角砾岩带附近发生了大规模的金成矿作用(杨立强等,2014;Yang *et al.*,2016b)。贯穿岩石圈地幔和全地壳的成矿流体通道系统对金矿的形成和定位至关重要(Deng *et al.*,2023;Yang *et al.*,2024),金成矿强度与富集地幔岩石圈对地壳的改造程度及其至幔源流体主通道的距离呈线性正相关(图 7-图 9 和图 12)。

胶东中成和浅成金矿床共存,说明其成矿深度范围广、且成矿后经历了显著的差异隆升和剥蚀,已知浅成金矿床的深部可能发育中成金矿床(Zhang *et al.*,2020a;Qiu *et al.*,2023)。金矿床地质-地球化学特征和成矿深度热力学估算表明,成矿深度总体西深东浅:胶北隆起中成金矿较为发育,而苏鲁地体以浅成金矿为主(Fan *et al.*,2003;Wen *et al.*,2015;Guo *et al.*,2017);胶北地体北部发育胶东目前唯一已知浅成金锑矿床(孙绪德等,2018),牟乳金矿带具有明显的锑元素异常(张连昌等,2001)。部分岩金矿床已剥露到地表、且古河流和近海沉积物中发育大量砂金矿床(高殿海,1990),说明金矿形成后遭受了明显的剥蚀。热年代学研究表明金矿形成后整体经历了较为缓慢的隆升和剥蚀,不同区域剥蚀量介于 2～7km 不等,深部矿体保留良好(柳振江等,2010;Zhang *et al.*,2019,2020b;杨伟等,2023);相较胶北地体,苏鲁地体成矿后伸展程度低、冷却速度慢、剥蚀程度略低(Qiu *et al.*,2023)。

尽管胶东金矿不同尺度的鉴别特征及其形成的关键因素明显不同于全球已知的其他金矿类型,难以被已有成矿模式所涵盖(Goldfarb and Santosh,2014),可能属于一种新的金矿类型——胶东型(Deng *et al.*,2015a,2020c,2023),但其成因模式仍然具有一定普适性,例如华北、华南、西伯利亚、西澳伊尔岗、北美怀俄明和南美圭亚那等大陆内部大量金矿床的成矿地球动力学背景、主要控矿因素和成矿作用过程及机制等与胶东金矿一致(Yang *et al.*, 2014;Deng and Wang, 2016;Deng *et al.*,2018;McDivitt *et al.*,2020;Qiu *et al.*,2020),特别是东亚及其邻区的克拉通边缘和内部众多金矿床的成矿背景、控矿因素、成矿流体特征和成矿物质来源等均与胶东金矿吻合,可能属于同一类型金矿床(Goldfarb *et al.*,2005,2007;Deng *et al.*,2022,2023)。

3　勘查模型

由上可见,拆离断裂系＋(黄铁)绢英岩化-钾化蚀变带＋基底活化带＋幔源流体通道是胶东金成矿系统的找矿标志。据此,我们确立了“拆离断裂系与基底活化带及幔源流体通道复合控矿”勘查思路和“四步式”勘查模型(图 15):(1)利用深反射地震探测、大地电磁测深和岩石圈物质组成架构示踪结果,揭示幔源流体通道表征的大型金矿区/带可能发育的空间范围,明确区域成矿远景区(杨立强等,2023;Yang *et al.*,2024);(2)通过构造-岩相填图、控矿构造应力分析、重磁测量和高精度磁法测量,探查拆离断裂与基底活化带交汇部位约束的金矿田可能产出的空间位置,选定成矿有利地段(王偲瑞等,2020;杨立强等,2024);(3)借助蚀变-流体填图和电法测量,查明含金流体活动中心和蚀变-矿化分带空间结构,圈定矿床尺度的预测靶区(Zhang *et al.*,2020b);(4)实施蚀变矿物和构造地球化学测量,定位金矿化中心及其顶底板和预测靶位,提交隐伏金矿体的验证工程设计(邓军等,2010)。

应该特别指出的是,控矿构造和赋矿建造的多样性导致了胶东型金矿的矿化样式及其地质-地球化学特征的多样性,显然其相应的勘查技术方法也有一定差异;应用上述成

因模式和找矿标志及勘查模型指导成矿预测和工程部署的过程中,需要充分考虑它们之间紧密的时空和成因关联。三山岛、焦家、招平、栖霞、郭即和牟乳六条高产金矿带近年的系列找矿突破验证了成因模式和勘查模型的合理性和适用性(邓军等,2010;陈玉民等,2016;于学峰等,2019;宋明春等,2020,2022,2024),表明区域找矿潜力巨大,胶东型金矿是全球研究热点和重要勘查方向,主攻目标是资源量大且品位和产状稳定的蚀变岩型金矿床/体(Deng *et al.*,2023)。

4 结语

胶东金矿不同于全球其他已知的金矿床类型,不能被已有理论模型所涵盖。在系统阐释其矿床地质-地球化学特征、成矿系统时-空结构和主控矿因素及动力学背景等不同尺度鉴别特征的基础上,明确了其成矿地球动力学背景和深部驱动、巨量金属和流体及络合物来源、输运通道和方式、源→汇过程和机制、成矿后变化和保存等成矿系统形成的关键因素,提出了胶东型金矿的成因模式与勘查模型。

胶东型金矿的成矿流体来自于经历了多期改造的富集岩石圈地幔,成矿金属具有壳幔混源的特征,含金流体通道具有壳幔贯通性,成矿深度跨度大,成矿强度明显受控于距幔源流体主通道的远近和富集地幔对地壳的改造程度及含金流体中幔源组分占比(距离越近、改造越强、占比越多,则金资源储量越大),地幔被俯冲洋壳及其上覆沉积物交代的程度控制了金品位的高低(程度越强,则品位越高)。

系列找矿突破验证了成因模式和勘查模型的合理性和适用性,胶东型金矿是全球研究热点和重要勘查方向,主攻目标是资源量大且品位和产状稳定的破碎带蚀变岩型金矿。

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