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胶东大尹格庄金矿床铅同位素地球化学[*]

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Abstract The gold deposits of the Jiaodong Peninsula define the China's largest gold province. Disseminated- and stockwork-style gold deposit, which accounts for 90% of the proved reserves in Jiaodong Peninsula, is the most important deposit type. Its giant source of gold is a striking and key scientific issue. Zhaoping fault zone, whose proved reserves exceed 1500t Au, is the largest fault-metallogenic belt in Jiaodong Peninsula. Dayingezhuang gold deposit, a typical disseminated- and stockwork-style gold deposit, whose proved reserves are about 125t Au, located in the central part of Zhaoping metallogenic belt. Its exploration depth is nearly −800m. NNE-trending Zhaoping fault and NNW-trending Dayingezhuang fault are the main ore-controlling structures. The Zhaoping fault develops along the contacts between the Jiaodong Group and Linglong granite and controls the occurrence of the gold orebodies in Dayingezhuang gold deposit. Linglong granite locates in the footwall of Zhaoping fault. Generally, it underwent pyrite-sericite-quartz alteration and hosts most part of the gold orebodies. Wall rocks in the hanging wall, which underwent intensive carbonation, comprise migmatization biotite-plagioclase-granulite, carbonate schist and amphibolite of Archaean Jiaodong Group, and garnet-sillimanite-biotite schist and biotite schist in the Lugezhuang Formation of Paleoproterozoic Jingshan Group. The gold mineralization is closely related to sericitization, pyritization and silication. The gold orebodies are located in the pyrite-sericite-quartz altered rock and pyrite-sericite-quartz altered cataclasite in footwall of Zhaoping fault. The main metallic mineral is pyrite, followed by galena, sphalerite and chalcopyrite. Frequently, pyrite is symbiotic with galena and sphalerite. The No. I and II orebodies, located in the south and north of the Dayingezhuang Fault respectively, account for 85% of the proved reserves in Dayingezhuang gold deposit. Comparing with the No. II orebody, the No. I orebody possesses more galena, sphalerite and higher silver grades. Nine sulfide samples selected from ores of No. I orebody yield ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb of 17.2638 ~ 17.3585, 15.4663 ~ 15.6116 and 37.858 ~ 38.3328 respectively. Six sulfide samples selected from ores of No. II orebody yield ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb of 17.2157 ~ 17.3286, 15.4595 ~ 15.5084 and 37.8900 ~ 38.0004 respectively. They are radiogenic and anomalous lead, who underwent three stages of evolution. The crust-mantle differentiation occurred at about 3.4Ga when the Pb isotope between the lower crust and upper mantle mixed and formed the normal lead. At about 0.8Ga, the lead escaped from the reservoirs of the second stage. Then it mixed with a certain amount of radiogenic lead. Finally, it was trapped in the gold-bearing sulfide at ca. 130Ma. All these reveal that ore-forming material may mainly be derived from the Mesozoic remobilization of metamorphic rock of the Jiaodong Group. The No. I orebody underwent intensive water-rock reaction accompanied by the mixing of more substance of the upper crust, when the gold deposited from the ore-forming fluids in the brittle faults of upper crust. In contrast, the No. II orebody keeps more information about the initial ore-forming materials and fluids.

Key words Lead isotope; Ore-forming material source; Remobilization; Dayingezhuang gold deposit; Jiaodong Peninsula

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摘　要　胶东是我国最重要的金矿集区，破碎带蚀变岩型金矿床是其最重要的金矿床类型，该类型金矿床已探明金矿资源量占全区的90%以上，其巨量金的来源是引人瞩目的关键科学问题。招平断裂带是胶东金矿集区内规模最大的断裂-成矿带，其内已探明金资源量1500余吨，大尹格庄金矿床位于招平金矿带中段，是该金矿带最具代表性的破碎带蚀变岩型金矿床之一，目前勘探深度近-800m，已探明金金属量约125t。NNE向招平断裂带和NWW向大尹格庄断裂是区内主要控矿构造，其中招平断裂带沿胶东群与玲珑花岗岩接触带发育，控制了大尹格金矿床的产出。招平断裂带下盘为玲珑黑云母花岗岩，是金矿床的主要赋矿围岩，普遍发育黄铁绢英岩化蚀变；招平断裂带上盘为太古宇胶东群混合岩化黑云斜长变粒岩、碳酸盐片岩和斜长角闪岩及古元古代荆山群禄格庄组石榴矽线黑云片岩和黑云片岩，发育强烈的碳酸盐化。金矿化与绢云母化、黄铁矿化和硅化关系密切，金矿体赋存在招平断裂带下盘的黄铁绢英岩和黄铁绢英岩化花岗质碎裂岩中，主要金属矿物为黄铁矿，其次为方铅矿、闪锌矿和黄铜矿，且黄铁矿常与方铅矿和闪锌矿共生。以大尹格庄断裂为界，其南、北两侧分别为Ⅰ号和Ⅱ号矿体，它们是占大尹格庄金矿床探明储量的85%。相对于Ⅱ号矿体，Ⅰ号矿体具有更多的方铅矿和闪锌矿及更高的银含量。I号矿体9件矿石硫化物$^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$、$^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$和$^{208}\mathrm{Pb}/^{204}\mathrm{Pb}$分别为17.2638~17.3585、15.4663~15.6116和37.858~38.3328；II号矿体6件矿石硫化物$^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$、$^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$和$^{208}\mathrm{Pb}/^{204}\mathrm{Pb}$分别为17.2157~17.3286、15.4595~15.5084和37.8900~38.0004，为放射性成因的异常铅，经历了三阶段演化史。其中，3.4Ga左右壳幔分离，铅在地壳下部和上地幔得到充分混合，形成均一的正常铅；0.8Ga左右铅脱离第二阶段储库并与铀钍体系发生分离；其后，这种铅与不同数量的放射性成因铅发生混合，并于约130Ma金成矿时被保留在硫化物等含金矿物中。该金矿床成矿物质很可能主要来自于胶东群变质岩的再活化，成矿过程中，I号矿体中成矿流体与围岩的交换反应作用更强，有更多的上地壳物质进入成矿流体；而II号矿体则保留了更多的深部初始成矿物质与成矿流体的信息。

关键词　铅同位素；成矿物质来源；再活化；大尹格庄金矿床；胶东

中图法分类号　P597.2；P618.51

1　引言

破碎带蚀变岩型金矿是我国最重要金矿类型，占胶东已探明金矿资源90%以上（邓军等，2013①）。胶东是我国最重要的金矿集区，区内密集分布着招远-莱州、蓬莱-栖霞和牟平-乳山三个金矿区（Deng *et al.*, 2006, 2008; Yang *et al.*, 2006; Goldfarb and Santosh, 2014; Yan *et al.*, 2014），已探明大型-超大型金矿床数十处，中小型金矿床百余处（杨立强等，2000，2003；邓军等，2004；王中亮，2012），其成矿时间集中于130~120Ma（Guo *et al.*, 2013; Yang *et al.*, 2007a, 2014），具有“区域集中、规模大、富集强度高和成矿期短”的特点，然而其巨量金的来源始终是引人瞩目的关键科学问题（Yang *et al.*, 2007a）。

铅同位素组成除受放射性衰变和混合作用影响外，不会在物理、化学和生物作用过程中发生变化，即在矿质运移和沉淀过程中铅同位素组成保持不变（沈渭洲和黄耀生，1987）。而且，黄铁矿、方铅矿、闪锌矿等硫化物中基本不含U、Th等放射性成因铅的母体放射性元素，硫化物一旦结晶形成，其铅同位素比值基本保持不变（张静等，2009）。硫化物（尤其是黄铁矿）是胶东金矿床的主要载金矿物（Wang *et al.*, 2014; 张潮等, 2014），其微量元素地球化学研究表明，铅与金关系密切，具正相关关系（李兆龙和杨敏之，1993）。因此，矿石硫化物铅同位素组成是示踪胶东金成矿物质来源最直接、最有效的一种方法。

招平断裂带是胶东金矿集区内规模最大的断裂-成矿带，从南到北横跨矿集区，断续延伸约120km，其内已探明金资源量1500余吨（Yang *et al.*, 2014）。大尹格庄金矿床位于招平金矿带中段（图1），是典型的破碎带蚀变岩型金矿床（陈光远等, 1993; Deng *et al.*, 2003a, 2009, 2011; Yang *et al.*, 2007b, 2009a, 2014; 杨立强等, 2013）。20世纪70年代以来，随着深部成矿理论及勘查技术方法发展（杨立强等, 2006, 2010, 2011a, b; Yang and Badal, 2013; Deng *et al.*, 2014），该矿床的找矿勘查工作不断取得进展，目前勘探深度近-800m，已探明金金属量约125t（Yang *et al.*, 2014）。与找矿勘探的进展相比，该金矿床地质研究程度较低，仅在控矿构造和矿化空间结构（李卫革等，2003；李德秀等，2006；高帮飞等，2007；潘红伟等，2008）、流体包裹体（沈昆等，2000；江少卿，2007）和围岩蚀变地球化学（凌洪飞等，2002）等方面开展了相关研究，而对成矿物质来源缺乏必要探讨。为此，论文在进一步查明矿床地质特征的基础上，对不同矿体中矿石的硫化物开展了铅同位素研究，厘定了铅同位素模式年龄，探讨了成矿物质来源和不同矿体矿石硫化物铅同位素组成差异的原因，为进一步揭示其成矿机制提供理论基础。

2　区域地质

区域内前寒武纪地层发育，基底为太古界胶东群和下元古界荆山群、粉子山群（图1）。胶东群的原岩为超镁铁质-镁铁质及长英质火山岩、碎屑沉积岩，其单颗粒锆石U-Pb同位素年龄为3.4~2.6Ga（裘有守等，1988；Wang *et al.*,

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① 邓军等. 2013. 焦家金矿床构造-矿化网络结构及深部找矿预测. 中国地质大学(北京)

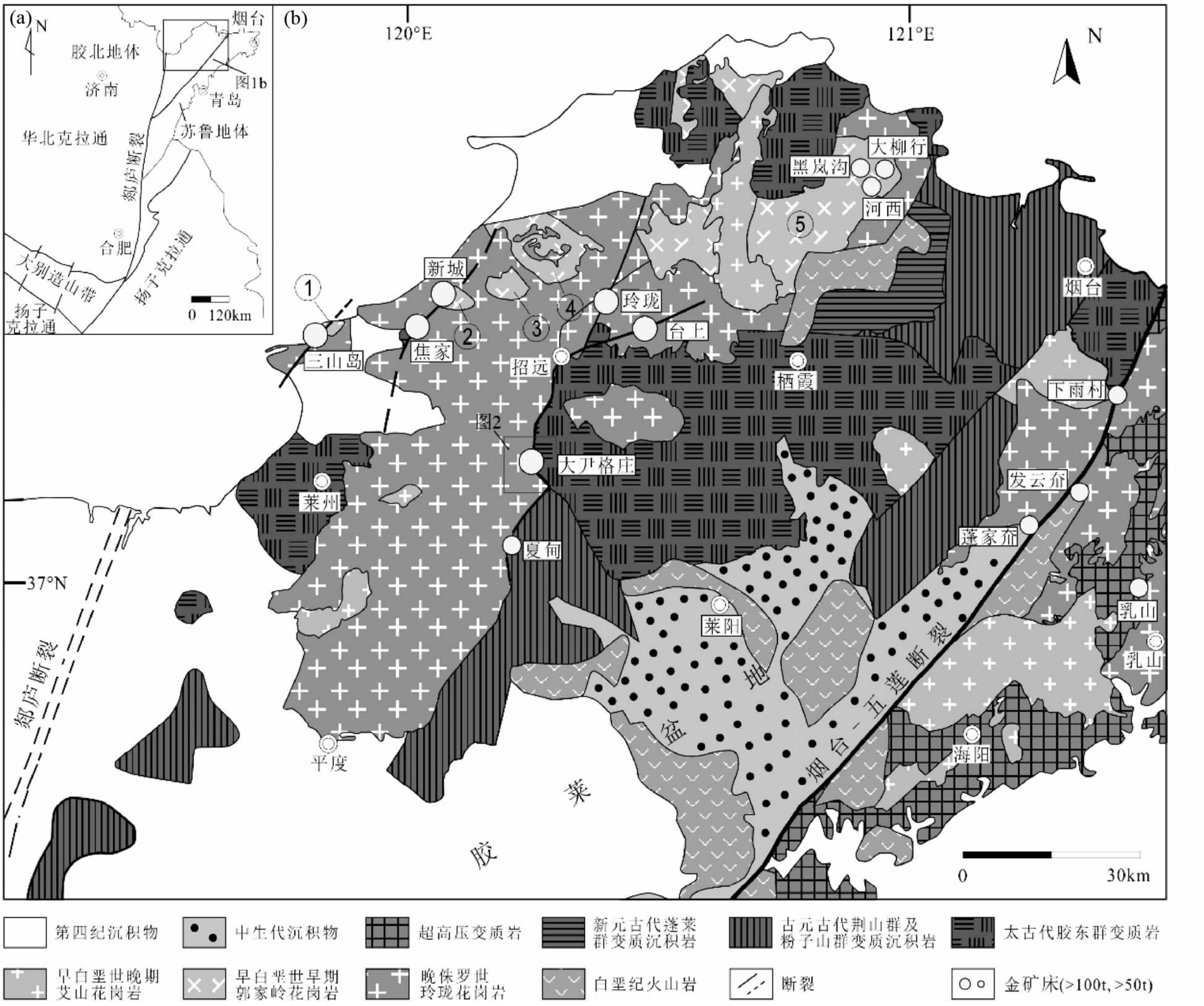

图1 招远-莱州金矿区地质图(据 Wang *et al.*, 2014 修编)

①-三山岛;②-上庄;③-北截;④-丛家;⑤-郭家岭

Fig. 1 Geological map of the Zhaoyuan-Laizhou gold field (modified after Wang *et al.*, 2014)

①-Sanshandao; ②-Shangzhuang; ③-Beijie; ④-Congjia; ⑤-Guojialing

1998);下元古界荆山群和粉子山群不整合于上太古界胶东群之上,为一套含碳质富铝的泥质碎屑岩和富镁碳酸盐岩建造,形成于2.5~1.9Ga(Wang *et al.*, 1998)。这些前寒武纪基底岩石在1.8Ga左右发生了区域变质作用(Tang *et al.*, 2007; Jahn *et al.*, 2008; Zhou *et al.*, 2008)。上元古界蓬莱群碎屑岩和碳酸盐岩不整合于下元古界荆山群和粉子山群之上,二者之间缺失中元古界地层(王中亮等,2011)。在胶莱盆地中,堆积了中新生代巨厚的陆相碎屑岩和火山岩,整个古生代地层缺失(图1)。

区域内花岗质岩石覆盖了2/3以上的基岩露头,可分为玲珑型、郭家岭型和艾山型等3种类型(Sun *et al.*, 2007; Ma *et al.*, 2014; Wang *et al.*, 2014; 图1)。玲珑型花岗岩体以黑云母花岗岩为主,呈NNE向带状分布于焦家断裂与招平断裂之间(图1),被认为是加厚的下地壳(主要是上太古界胶东岩群岩石)部分熔融的产物,没有任何地幔的成分加入(Zhang *et al.*, 2010; Jiang *et al.*, 2012);锆石LA-ICP MS U-Pb年代学研究表明其形成于166~149Ma(Jiang *et al.*, 2012; Yang *et al.*, 2012)。郭家岭型花岗岩体由石英二长岩、二长花岗岩和花岗闪长组成,呈近EW向岩株状侵入到玲珑型花岗岩体中(图1),自东向西包括郭家岭、丛家、北截、上庄和三山岛五个侵入体,其锆石LA-ICP MS U-Pb年龄为132~126Ma(Hou *et al.*, 2007; Yang *et al.*, 2012)。最近地质地球化学研究表明,郭家岭型花岗岩体是由胶东基底岩石(主要是上太古界胶东岩群岩石)部分熔融形成的酸性岩浆和新生的基性下地壳部分熔融形成的中性岩浆混合形成,同时岩浆上升过程中受到上地壳(主要是玲珑黑云母花岗岩)的混染(Wang *et al.*, 2014)。艾山型花岗岩体由二长花岗岩和正长花岗岩组成,呈NE向侵入到玲珑型或郭家岭花岗岩体中(Yang *et al.*, 2014; 图1),其锆石LA-ICP MS U-Pb年龄为118~110Ma(Goss *et al.*, 2010)。其中,玲珑型和郭

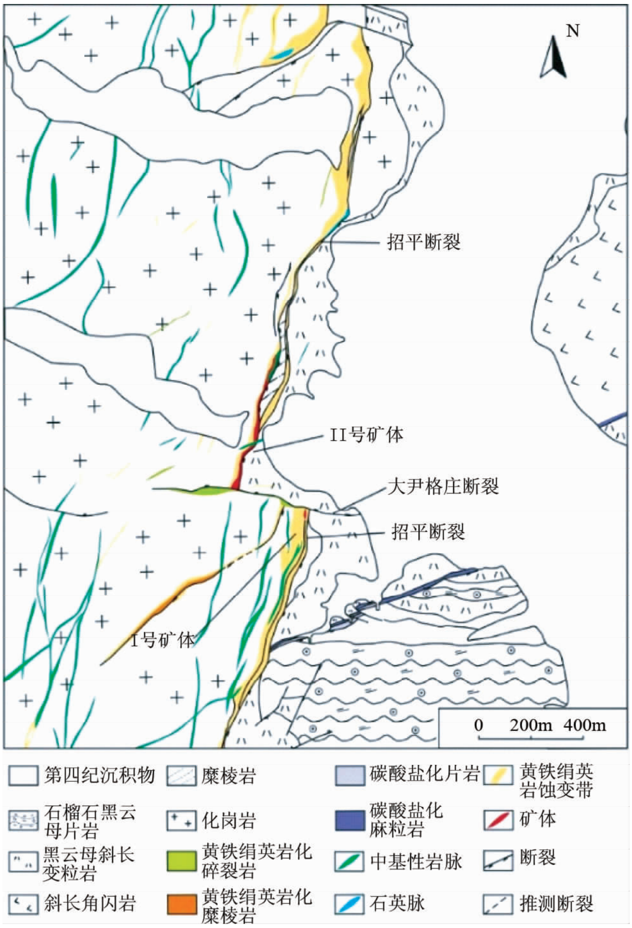

图2　大尹格庄金矿床地质简图(据 Yang *et al.*，2009a，2014)

Fig. 2　General geological map of the Dayingezhuang gold deposit (after Yang *et al.*，2009a，2014)

家岭型花岗岩体内赋存了95%的胶东金资源量，为胶东地区金矿床的主要赋矿围岩(Deng *et al.*，2003b，2009；Yang *et al.*，2008，2009b，2014)。

区域构造格架为EW向构造带和NNE-NE向断裂带(图1)。EW向构造带既是燕山运动前基底构造，又是燕山运动以来长期活动的构造系统，其构造形迹是褶皱和韧性剪切带(Deng *et al.*，2000；邓军等，2010)。NNE-NE向断裂带主要由一系列沿玲珑型花岗岩体和胶东群变质岩接触带发育的NNE-NE向断裂(自西向东依次为三山岛断裂、焦家断裂和招平断裂)以及发育在玲珑型花岗岩体和郭家岭型花岗岩体中的较小规模的NNE-NE向断裂节理组成，其控制了胶东金矿床的产出(Yang *et al.*，2003，2004；杨立强等，2014a，b；王中亮等，2013；张良等，2013；郭林楠等，2014；图1)。

3　矿床地质

大尹格庄金矿床位于招平断裂带中段(图1)，其内出露地层为太古宇胶东群和古元古代荆山群禄格庄组变质岩(图2)；其中，太古宇胶东群岩性主要为混合岩化黑云斜长变粒岩、碳酸盐片岩和斜长角闪岩，分布于矿区的东部，招平断裂带的上盘；古元古代荆山群禄格庄组主要由石榴矽线黑云片岩和黑云片岩组成，出露于矿区中、东部(图2)。矿区内花岗岩类出露广泛，分布于招平断裂下盘的大部分地区，岩性主要为玲珑黑云母花岗岩，为大尹格庄金矿床的主要赋矿围岩。此外，矿区内中基性脉岩十分发育，呈NNE向近平行分布于玲珑黑云母花岗岩内(图2)。

矿区内构造以断裂为主，褶皱基本不发育。断裂构造主要有招平断裂带和大尹格庄断裂。其中，招平断裂带沿胶东群与玲珑花岗岩接触带发育，下盘普遍发育黄铁绢英岩化蚀变，上盘具有强烈的碳酸盐化，是大尹格金矿床的主要控矿构造。该断裂在大尹格金矿床内总体走向20°，倾向南东，倾角21°~58°，宽40~78m，最宽达140m，由糜棱岩、碎裂岩、碎斑岩及少量断层泥和角砾岩等组成。大尹格庄断裂走向280°，倾向北东，倾角43°~60°，宽1.8~35m，由碎裂岩、角砾岩及断层泥组成，呈波状弯曲，局部分枝复合；其错断招平断裂，上盘相对向左滑动，水平断距260~300m；显示其成矿晚期左行压扭性特征。此外，大尹格庄断裂上盘的玲珑黑云母花岗岩亦发育黄铁绢英岩化蚀变，表明该断裂至少经历了两期活动。

大尹格庄金矿床金矿化与绢云母化、黄铁矿化和硅化关系密切。金矿体受控于NNE向招平断裂(图2)，赋存在其下盘黄铁绢英岩和黄铁绢英岩化花岗质碎裂岩中，矿石中主要金属矿物为黄铁矿，其次为方铅矿、闪锌矿和黄铜矿，且黄铁矿常与方铅矿和闪锌矿共生。Ⅰ号和Ⅱ号矿体是大尹格庄金矿床的重要组成部分，占大尹格庄金矿床探明储量的85%(Yang *et al.*，2014)，分别位于大尹格庄断裂的南边和北边。Ⅰ号矿体主要集中于招平断裂下盘60m范围内(图2)，走向NE 20°，倾向南东，倾角27°~40°，矿体厚2~10m，长450~990m，金品位2~4.06g/t，平均2.69g/t。Ⅱ号矿体亦主要分布于招平断裂下盘60m范围内(图2)，走向NE 20°，倾向南东，倾角28~53°，矿体厚10~30m，长260~1057m，金品位2.1~3.73g/t，平均2.56g/t。相对于Ⅱ号矿体，Ⅰ号矿体含有更高的银含量和更多的Pb、Zn硫化物，该银矿化在大尹格庄断裂附近增强，而接近招平断裂部位相对较弱。大尹格庄金矿床Ⅰ号矿体含有大量银矿物这一特征使其不同于Ⅱ号矿体和胶东其他金矿床内的金矿体。

4　铅同位素分析

4.1　样品采集及分析方法

本研究在大尹格庄金矿床不同中段内系统采集了15件I号和II号矿体的矿石样品用于铅同位素分析。其中，9件矿石采自I号以金为主的含银矿体；6件矿石采自II号单金矿体。样品经粉碎、过筛，在双目镜下挑选40~60目、纯度

表1 大尹格庄金矿床矿石矿物铅同位素组成及源区特征值

Table 1 Lead isotope composition and parameters of sulfide for Dayingezhuang gold deposit

序号	样品号	测试对象	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	μ	ω	Th/U	t(Ma)	Δα	Δβ	Δγ
I 号矿体												
1	Y55-210K	方铅矿	17.2638	15.4663	37.8580	9.36	39.60	4.09	832	60.43	13.40	47.36
2	Y61-210-1B	黄铁矿	17.3102	15.5010	37.9775	9.42	40.21	4.13	837	63.72	15.71	50.90
3	Y61-210-2B	黄铁矿	17.2914	15.4901	37.9407	9.40	40.05	4.12	839	62.70	15.01	49.95
4	Y61-210-3B	黄铁矿	17.3153	15.5023	37.9818	9.42	40.21	4.13	835	63.84	15.78	50.92
5	Y61-290-1	黄铁矿	17.2669	15.5176	38.0333	9.47	40.96	4.19	885	65.40	17.22	54.73
6	Y61-290-4	黄铁矿	17.3585	15.6116	38.3328	9.65	42.76	4.29	920	74.3	23.7	64.73
7	Y62-210A	黄铁矿	17.3187	15.5412	38.1201	9.50	41.26	4.20	874	67.59	18.67	56.61
8	Y62-210B	黄铁矿	17.2840	15.4946	37.9539	9.41	40.21	4.14	849	63.14	15.39	50.79
9	Y62-290C	黄铁矿	17.2853	15.5053	37.9899	9.44	40.49	4.15	859	64.18	16.18	52.29
II 号矿体												
10	Y75-247-1A	黄铁矿	17.2301	15.4773	37.8900	9.39	40.1	4.13	868	61.56	14.42	49.93
11	Y75-247-4A	黄铁矿	17.3286	15.5084	38.0004	9.43	40.27	4.13	832	64.41	16.16	51.3
12	Y75-247-5A	黄铁矿	17.2756	15.4965	37.9157	9.42	40.11	4.12	857	63.34	15.58	50.11
13	Y75-247-6A	黄铁矿	17.2949	15.4819	37.9441	9.38	39.96	4.12	827	61.9	14.38	49.52
14	Y79-356K	闪锌矿	17.2359	15.4860	37.9198	9.4	40.29	4.15	873	62.4	15.04	51.01
15	Y79-356K	方铅矿	17.2157	15.4595	37.8306	9.35	39.73	4.11	859	59.86	13.18	47.86

注：t 为单阶段模式年龄；$\mu = {}^{238}U/{}^{204}Pb$，$\omega = {}^{232}Th/{}^{204}Pb$；$\Delta\alpha = [({}^{206}Pb/{}^{204}Pb)_d(t)/({}^{206}Pb/{}^{204}Pb)_m(t) - 1] \times 1000$，$\Delta\beta = [({}^{207}Pb/{}^{204}Pb)_d(t)/({}^{207}Pb/{}^{204}Pb)_m(t) - 1] \times 1000$，$\Delta\gamma = [({}^{208}Pb/{}^{204}Pb)_d(t)/({}^{208}Pb/{}^{204}Pb)_m(t) - 1] \times 1000$，d 与 m 分别代表成矿时代 t 时刻矿石 Pb 与地幔 Pb（朱炳泉，1998）；地幔 Pb 同位素组成计算参照（Chen *et al.*，1982）地幔增长公式，$\mu = 7.8$，${}^{232}Th/{}^{238}U = 4.04$，$t_0 = 4.57Ga$，原始 Pb 组成：$({}^{206}Pb/{}^{204}Pb)_0 = 9.307$，$({}^{207}Pb/{}^{204}Pb)_0 = 10.294$，$({}^{208}Pb/{}^{204}Pb)_0 = 29.476$

大于99%的黄铁矿、方铅矿及闪锌矿单矿物样品5~10mg。挑纯后的单矿物在玛瑙钵里研磨至200目以下，送中国科学院地质与地球物理研究所岩石圈构造演化国家重点实验室分析。铅同位素比值测量采用德国Finnigan公司MAT262固体源质谱计，同位素质量分馏校正系数为每质量单位1‰。本次研究获得的铅同位素比值分析相对误差小于0.04%。具体测试方法参见李磊等(2013)。

4.2 分析结果

大尹格庄金矿床I号和II号矿体的15件矿石样品的硫化物铅同位素分析结果及按H-H单阶段演化模式（Faure，1986）计算的模式年龄、μ、ω和Th/U值见表1。从表1中可以看出，I号和II号矿体的矿石硫化物铅同位素组成基本相似，变化范围较小，但相对于I号矿体，II号矿体的矿石硫化物铅同位素组成$^{206}Pb/^{204}Pb$、$^{207}Pb/^{204}P$和$^{208}Pb/^{204}Pb$值相对较低，反映了I号矿体矿石所含的放射成因铅比II号矿体稍高。

5 讨论

5.1 铅同位素模式年龄

大尹格庄金矿床15件矿石样品的硫化物铅同位素组成$^{206}Pb/^{204}Pb$、$^{207}Pb/^{204}Pb$和$^{208}Pb/^{204}Pb$的变化范围分别为0.1428%、0.1521%、0.5022%，均不超过0.1%（表1），可能属于正常铅范围。然利用单阶段正常铅H-H演化模式年龄计算公式$[({}^{207}Pb/{}^{204}Pb - b_0)/({}^{206}Pb/{}^{204}Pb - a_0)] = [(e^{\lambda5T} - e^{\lambda5t})/(e^{\lambda8T} - e^{\lambda8t})]/137.88$（$T$为地球年龄，$a_0$，$b_0$为地球初始铅同位素组成，$t$为欲求模式年龄，$\lambda_8$、$\lambda_5$分别为$^{238}U$、$^{235}U$的衰变常数）（Faure，1986）得到的模式年龄变化于827~920Ma，明显低于胶东群变质岩的原岩年龄（3.4~2.6Ga，裘有守等，1988；Wang *et al.*，1998）、荆山群地层的形成年龄（2.5~1.9Ga，Wang *et al.*，1998）及胶东群和荆山群岩石发生变质作用的年龄（约1.8Ga，Tang *et al.*，2007；Jahn *et al.*，2008；Zhou *et al.*，2008），但又高于区内玲珑黑云母花岗岩的侵位年龄（166~149Ma，Jiang *et al.*，2012；Yang *et al.*，2012）、郭家岭型花岗岩的侵位年龄（132~126Ma，Hou *et al.*，2007；Yang *et al.*，2012）和大尹格庄金矿床的矿化年龄（134~126Ma，Yang *et al.*，2014）。此外，在$^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$图解上，铅同位素比值投影点均不沿着单阶段增长曲线分布（图3a）；矿石铅μ和ω值分别为9.35~9.65和39.60~42.76，明显高于正常铅μ值（8.686~9.238）和正常铅ω值（35.55±0.59）。因此，大尹格庄金矿床内矿石铅并非单阶段正常铅，应为放射性成因的异常铅，铅同位素演化比较复杂。

在$^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$图解中（图3a），硫化物铅同位素组成构成了线性关系良好的直线。其中，II号矿体矿石样品的铅同位素数据点沿斜率为0.3161、截距为10.027的直线分布（相关系数为0.6806），不具备混合线的高斜率特征（Andrew *et al.*，1984）；通过对6个硫化物样品^{204}Pb误差线

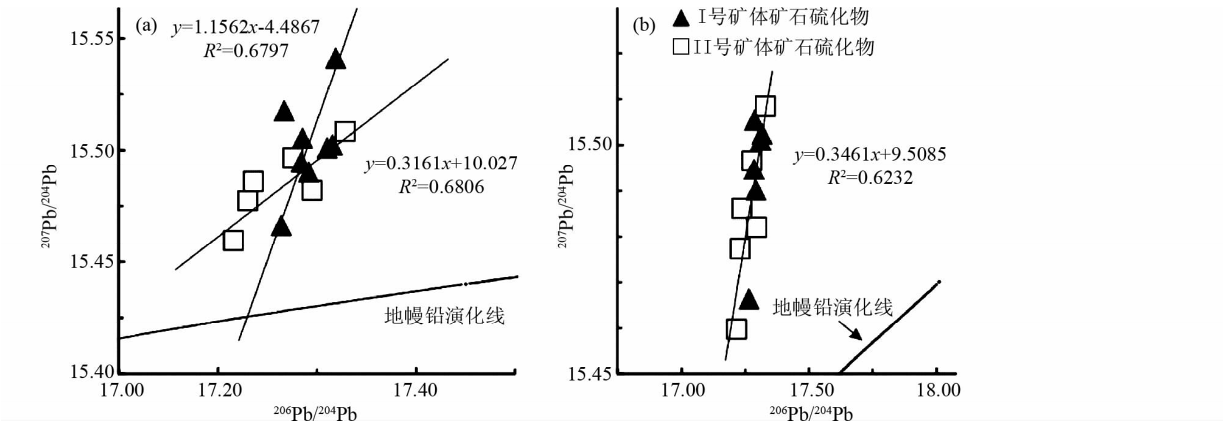

图 3 大尹格庄金矿床铅同位素^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb 图解(底图据 Faure, 1986)

Fig. 3 ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram for the Dayingezhuang gold deposit (after Faure, 1986)

表 2 大尹格庄金矿床岩/矿石同位素年代学数据

Table 2 Geochronology data of Dayingezhuang gold deposit

样品号	岩性	测试对象	测试方法	年龄(Ma)	数据来源
9880304	玲珑黑云母花岗岩	全岩	K-Ar	144 ±7	Xu, 1999
9880302	成矿前伟晶岩脉	全岩	K-Ar	129 ±6	
9880302	钾长石化花岗岩	全岩	K-Ar	126 ±6	
9692611	绢英岩化花岗岩	全岩	K-Ar	126 ±6	
/	成矿后闪长玢岩	全岩	K-Ar	129 ±2	郭振一等, 1990
Y745380KI	黄铁绢英岩矿石	绢云母	Ar-Ar	130.52 ±0.52 (P)	Yang *et al.*, 2014
Y745350KII	黄铁绢英岩矿石	白云母	Ar-Ar	128.67 ±0.50 (P)	
Y725245K	黄铁绢英岩矿石	绢云母	Ar-Ar	133.37 ±0.56 (P)	
Y61250K	黄铁绢英岩银多金属矿石	绢云母	Ar-Ar	126.8 ±0.59 (P)	

的斜率 R′和质量分辨率误差线斜率 R″的计算(Franklin *et al.*, 1983),也排除了^{204}Pb 误差线的可能性。因此,II 号矿体矿石样品的铅同位素组成所构成的直线应为常规等时线,反映了放射性成因异常 Pb 的特征。与 II 号矿体的矿石硫化物铅同位素组成基本相似的 I 号矿体,其铅同位素数据点沿斜率为 1.1562、截距为 -4.4867 的直线分布(相关系数为 0.6797),亦不具备混合线的高斜率特征(Andrew *et al.*, 1984)。此外,根据异常铅直线的斜率(1.1562)及大尹格庄金矿床的矿化年龄(约 130Ma)计算获得的成矿物质来源区原岩的年龄 t_r = 5.4Ga,远大于地球的年龄,说明 I 号矿体矿石硫化物数据点的趋势线不是常规等时线,其事实上应是^{204}Pb 误差线。

实际上,I 号和 II 号矿体矿石的硫化物 Pb 同位素比值投影点基本重合(图 3a),指示其成矿物质来源、成矿物理化学条件以及成矿流体与围岩相互作用的一致性。从图 3b 中可以看出,I 号矿体的 9 个硫化物数据点中,除了含放射性成因铅较高的 3 个异常点外(表 1 中 5、6、7),其他 6 个硫化物数据点与 II 号矿体 6 个硫化物数据点有很好的线型分布趋势,构成了一条等时线,这也进一步证明了 I 号矿体的 6 个含放射性成因铅低的样品最具代表性。利用最小二乘法求得该等时线斜率为 0.3461,截距为 9.5085,直线方程为^{207}Pb/^{204}Pb = 0.3461(^{206}Pb/^{204}Pb) + 9.5085,其相关显著性检验值(Significance F)为系数为 0.002,远小于 0.01。考虑到大尹格庄金矿床中铅可能经历了区域变质作用以及后期的构造-岩浆活动,该铅等时线为二次等时线,其与 Staecy-Kramers 两阶段演化模式(Stacey and Kramers, 1975)中第二阶段曲线分别在 3.4Ga 和 0.8Ga 处相交。其中,3.4Ga 相当于铅源年龄,与胶东群变质岩的原岩年龄(3.4 ~2.6Ga)基本一致;0.8Ga 代表了铅脱离第二阶段储库并与铀、钍分离的年龄,与胶北地体 0.8Ga 左右明显的地质事件一致(李兆龙和杨敏之,1993),相当于华北地台发育的晚元古代蓟县运动(0.85 ~0.80Ga)。

为了确定大尹格庄金矿床的形成时代,本研究系统搜集了与金矿体具有切割关系的地质体的形成年龄和大尹格庄金矿床与矿石矿物共生热液蚀变矿物的同位素年龄数据(表 2)。被金矿脉切割的玲珑黑云母花岗岩全岩 K-Ar 年龄为 144 ±7Ma,成矿前伟晶岩脉全岩 K-Ar 年龄为 129 ±6Ma,钾长石化花岗岩及绢英岩化花岗岩全岩 K-Ar 年龄均为 126 ±6Ma,成矿后闪长玢岩脉全岩 K-Ar 年龄为 129 ±2Ma(郭振一等,1990①);此外,大尹格庄金矿床矿石的 1 件白云母和 3

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① 郭振一等. 1990. 胶东地区金矿控矿构造地球化学特征及找矿方向. 山东省地质科学院

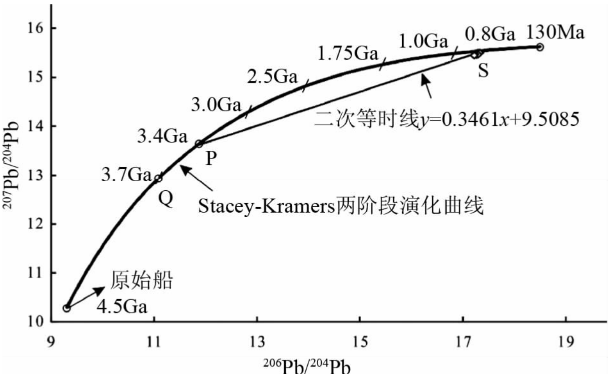

图4 大尹格庄金矿异常铅演化图(演化曲线据 Stacey and Kramers, 1975)

Fig. 4 Evolution of the anomalous Pb in Dayingezhuang gold deposit (the evolution curve after Stacey and Kramers, 1975)

件绢云母样品的^{40}Ar/^{39}Ar 年龄分别为 128.67 ± 0.50Ma、130.52 ± 0.52Ma、133.37 ± 0.56Ma 和 126.8 ± 0.59Ma。根据这些与成矿有关的年龄,厘定了大尹格庄金矿床 130 ± 4Ma 的成矿年龄,明显早于区域上 120 ± 5Ma 的金成矿作用事件(Yang and Zhou, 2001; Li *et al.*, 2003, 2006)。由此可见,大尹格庄金矿床矿石铅同位素基本上经历了三阶段演化史,图4是该研究区硫化物铅三阶段演化图解。其中,3.4Ga 左右壳幔分离,铅在地壳下部和上地幔得到充分混合,形成均一的正常铅,该阶段属铅正常演化阶段;0.8Ga 左右铅脱离第二阶段储库并与铀钍体系发生分离;其后,这种铅与不同数量的放射性成因铅发生混合,并于约 130Ma 金成矿时被保留在硫化物等含金矿物中。

5.2 成矿物质来源

大尹格庄金矿床 I 号和 II 号矿体的矿石硫化物铅同位素比值没有明显差别(表1),显示其铅源的统一性,即不同矿体的成矿物质来源一致。在 Zartman and Doe(1981)的 ^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb 同位素模式和构造环境图解中,大尹格金矿床矿石铅同位素大多数投影点均落在造山带和上地幔演化线之间,位于克拉通化地壳铅范围内(图5);在朱炳泉(1998)矿石铅同位素的 $\Delta\gamma$-$\Delta\beta$ 成因分类图解中(图6),除了两个样品点落在上地壳来源铅的范围内外,其他均落在其与造山带铅的交界区域内;说明矿石铅可能来源于富含上地幔物质的古老结晶基底岩石,并不同程度的混入了上地壳和上地幔物质。结合大尹格庄金矿床矿石的铅源年龄为 3.4Ga,其相当于胶东群变质岩的原岩年龄,因此,大尹格庄金矿床矿石铅很可能主要来自于胶东群基底岩石。

为进一步追索大尹格庄矿床金矿化与区内出露的花岗岩及胶东群变质岩等地质体的关系,本文系统搜集了胶东群变质岩、玲珑黑云母花岗岩和郭家岭花岗闪长岩的全岩及钾长石的铅同位素组成(表3),并将其与大尹格庄金矿床矿石硫化物的铅同位素数据一起进行铅同位素模式图和构造环境判别图(图5)投图。从图5可以看出,胶东群变质岩的铅同位素数据点主要位于造山带铅和地幔铅平均演化线之间,克拉通化地壳区,说明变质岩的铅为幔、壳混合源铅;玲珑黑云母花岗岩和郭家岭花岗岩的投影点均位于造山带铅演化曲线和地幔铅演化曲线之间或地幔铅演化线附近,克拉通化地壳区,为幔、壳混合源铅(图5),结合该花岗岩主要是由胶

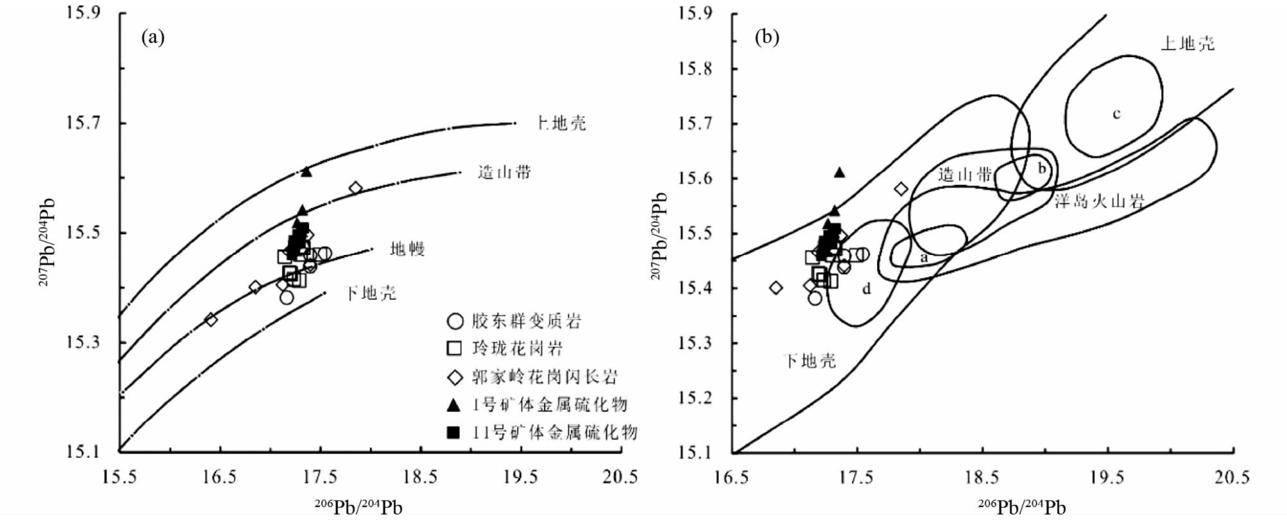

图5 大尹格庄金矿床矿石及区域主要地质体铅同位素模式图(a)及构造环境判别图(b)(底图据 Zartman and Boe, 1981)

数据来源见表1及表2;a、b、c、d 为各区域中样品相对集中区

Fig. 5 The plumbotectonic model (a) and lead isotope diagram for discriminating tectonic setting (b) for the Dayingezhuang gold deposit and the main regional geological body (after Zartman and Doe, 1981)

The data are listed in Table 1 and Table 2; a, b, c, d represent the centralized areas

表3 胶东地区胶东群变质岩及花岗岩铅同位素组成

Table 3 Lead isotopes of the metamorphic rock of Jiaodong Group and granitoids in Jiaodong Peninsula

样品号	岩性	测试对象	铅同位素组成			数据来源
			$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	
T1-15	胶东群变粗玄岩	全岩	17.164	15.382	37.376	杨士望,1986
T1-17	胶东群磁铁二辉麻粒岩	全岩	17.546	15.462	37.472	
T1-18	胶东群辉石斜长片麻岩	全岩	17.156	15.328	37.286	
T1-21	胶东群绿帘斜长角闪岩	全岩	17.396	15.438	37.34	
J190-08	胶东群斜长角闪岩	全岩	17.32	15.474	37.756	敬成贵,1988
Jx-75	胶东群斜长角闪片麻岩	全岩	17.399	15.459	37.445	李兆龙等,1990
87L-13	玲珑石榴石花岗岩	钾长石	17.301	15.460	37.815	李兆龙等,1990
87L-15	玲珑黑云母花岗岩	钾长石	17.143	15.456	37.855	
86jc-4	玲珑钾长石化花岗岩	钾长石	17.205	15.425	37.678	
86jc-3	玲珑钾长石化花岗岩	钾长石	17.407	15.404	37.689	
s-47	栾家河花岗岩	钾长石	17.321	15.474	37.835	
84-250	栾家河花岗岩	钾长石	17.325	15.472	37.587	
J100	玲珑黑云母花岗岩	全岩	17.288	15.413	37.625	敬成贵,1988
r-04	玲珑黑云母花岗岩	全岩	17.233	15.415	37.752	李兆龙和杨敏之,1993
A0-17	玲珑黑云母花岗岩	全岩	17.494	15.46	38.043	
Lja-1	栾家河花岗岩	全岩	17.190	15.427	37.814	
/	郭家岭斑状花岗闪长岩	长石	16.408	15.342	36.645	陈振胜等,1994
/	郭家岭斑状花岗闪长岩	长石	17.188	15.466	37.909	
/	郭家岭斑状花岗闪长岩	长石	17.851	15.581	38.394	
/	郭家岭斑状花岗闪长岩	长石	17.256	15.485	37.869	
/	郭家岭斑状花岗闪长岩	长石	17.124	15.405	37.571	
/	郭家岭斑状花岗闪长岩	长石	17.386	15.409	37.624	马振东,1998
87sp-1	郭家岭花岗闪长岩	钾长石	17.235	15.471	37.810	李兆龙等,1990
87sp-2	郭家岭花岗闪长岩	钾长石	17.370	15.496	37.904	
Gj-01	郭家岭花岗闪长岩	全岩	17.396	15.441	37.922	李兆龙和杨敏之,1993

表4 胶东玲珑和蓬莱金矿区内金矿床矿石铅同位素组成

Table 4 Lead isotopes of Linglong and Penglai gold field, Jiaodong Peninsula

序号	金矿床	样数	铅同位素组成			数据来源
			$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	
1	蓬莱黑岚沟	9	17.501 17.3558 ~ 17.5958	15.5402 15.5105 ~ 15.5746	38.2735 38.0749 ~ 38.4361	侯明兰等,2006
2	蓬莱大柳行	5	17.4493 17.3653 ~ 17.5037	15.5262 15.5142 ~ 15.5355	38.2348 38.1249 ~ 38.3136	
3	蓬莱河西	5	17.3874 17.3086 ~ 17.4799	15.5441 15.5264 ~ 15.5692	38.2069 38.0642 ~ 38.3698	
4	玲珑西山	5	17.4221 17.4096 ~ 17.4431	15.5408 15.536 ~ 15.5489	38.205 38.125 ~ 38.4196	
		12	17.2346 17.142 ~ 17.379	15.4888 15.406 ~ 15.888	37.8651 37.691 ~ 38.271	李兆龙,1990
		1	17.238	15.472	37.883	马广刚,2011
5	玲珑东山	6	17.5208 17.4617 ~ 17.5951	15.5641 15.5443 ~ 15.5994	38.1772 38.1305 ~ 38.2315	侯明兰等,2006
		3	17.4167 17.358 ~ 17.481	17.5307 15.506 ~ 15.567	38.102 38.04 ~ 38.213	马广刚,2011
6	玲珑台上	5	17.5406 17.1979 ~ 17.6627	15.5738 15.5581 ~ 15.595	38.31 38.2481 ~ 38.3849	侯明兰等,2006
		4	17.548 17.460 ~ 17.636	15.577 15.486 ~ 15.735	38.311 37.995 ~ 38.730	李兆龙和杨敏之,1993

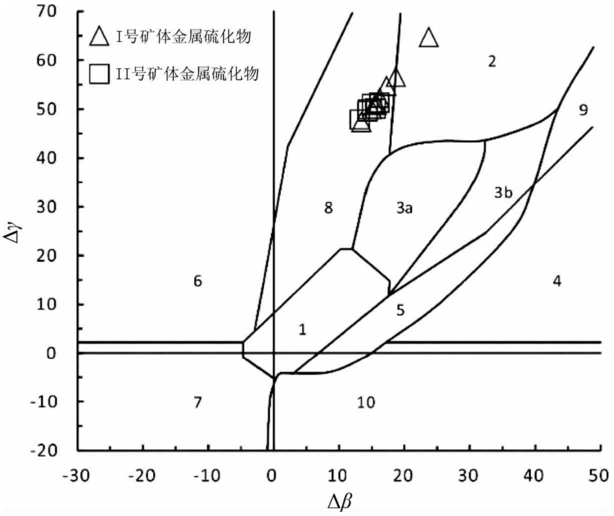

图6 大尹格庄金矿床矿石铅 Δγ-Δβ 成因判别图解(底图据朱炳泉,1998)

1-地幔源铅;2-上地壳源铅;3-上地壳与地幔混合的俯冲铅:3a-岩浆作用,3b-沉积作用;4-化学沉积型铅;5-海底热水作用铅;6-中深变质作用;7-深变质下地壳铅;8-造山带铅;9-古老页岩上地壳铅;10-退变质铅

Fig. 6 Δγ vs. Δβ genetic classification diagram showing ore minerals lead isotopic distribution in the Dayingezhuang gold deposit (after Zhu, 1998)

北地体的基底岩石(主要是胶东群)部分熔融形成(Hou *et al.*, 2007; Wang *et al.*, 2014),可以认为花岗岩中的铅来自本区的结晶基底胶东群岩石;玲珑黑云母花岗岩是大尹格金矿床的主要赋矿围岩,其与大尹格庄金矿床矿石硫化物有相似的铅同位素组成;表明了大尹格庄金矿与花岗岩及胶东群变质岩之间的渊源关系,具有明显的同源性和继承性演化特点,即大尹格庄金矿床矿石铅为再活化的下地壳铅,即胶东群变质岩铅。胶东群地层中明显高于地壳丰度值的元素有Au、Pb、Cu 和 Cr,金的丰度值在(1~920)$\times 10^{-9}$(王炳成,1991;邓军等,2001;刘玉强等,2004;王中亮,2012),且马家窑金矿床即赋存在该地层中,表明了胶东群变质岩与金矿化关系密切。据此推断大尹格庄金矿床成矿物质很可能主要来自于中生代活化再造的胶东群变质岩。

值得指出的是,在大尹格庄金矿床内,I 号和 II 号矿体虽具有相似的铅同位素组成,但相比而言,位于近 EW 向大尹格庄断裂下盘的 I 号金矿体比上盘 II 号金矿体具有较高的放射成因的铅;该现象也表现在胶东其他金矿区的金矿床内。其中,在玲珑金矿区内,自西向东从西山、东山到台上金矿,其铅同位素成^{206}Pb/^{204}Pb、^{207}Pb/^{204}Pb 和^{208}Pb/^{204}Pb 具有增高的趋势(表4);在蓬莱金矿区内,自西向东从河西、大柳行到黑岚沟金矿其放射性成因的铅亦逐渐增高(表4);其被认为是本区地层结构和岩石类型共同制约的结果,并和铅同位素的混合作用有关(林文蔚等,1999;侯明兰等,2006)。然而,在大尹格庄金矿床内,除了 Ⅰ 号矿体相对于 Ⅱ 号矿体含有更高的银含量和更多的 Pb、Zn 硫化物外,其具有相同的地质特征、赋矿围岩及蚀变-矿化类型,且金矿化均受北东向招平断裂控制;说明矿脉形成过程中,I 号矿体中成矿流体与围岩的交换反应作用更强,有更多的上地壳物质进入了成矿流体,这也可能是导致 I 号矿体发生银矿化而 II 号矿体未发生银矿化的因素;但关于其更深层次的原因比如其是否与大尹格庄断裂的金成矿晚期活动有关尚需进行进一步研究。

6 结论

(1)大尹格庄金矿床内矿石硫化物铅并非单阶段正常铅,应为放射性成因的异常铅,铅同位素演化比较复杂。

(2)大尹格庄金矿床矿石铅同位素基本上经历了三阶段演化史;其中,3.4Ga 左右壳幔分离,铅在下地壳和上地幔得到充分混合,形成均一的正常铅;0.8Ga 左右铅脱离第二阶段储库并与铀钍体系发生分离;其后,这种铅与不同数量的放射性成因铅发生混合,并于约 130Ma 金成矿时被保留在硫化物等含金矿物中。

(3)大尹格庄金矿床成矿物质很可能主要来自于中生代活化再造的胶东群变质岩。

(4)成矿流体在上地壳脆性断层带内沉淀形成矿脉的过程中,I 号矿体的成矿流体与围岩的水岩交换反应作用更强,有更多的上地壳物质进入了成矿流体;而 II 号矿体则保留了更多的深部初始成矿物质与成矿流体的信息。

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