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胶东院格庄岩体中辉钼矿Re−Os同位素测年及其地质意义

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提要: 院格庄花岗岩体位于烟台市牟平区境内, 是胶东地区燕山晚期伟德山超单元一个典型的复式岩体。本次研究针对花岗岩体内发育的辉钼矿开展Re−Os同位素测年, 同时对采集于花岗岩体的新鲜样品进行了主量元素、微量元素和稀土元素测试分析。结果显示, 院格庄花岗岩属于高钾富碱的钙碱性岩, 具准铝质−过铝质特征, 是壳幔混合来源的花岗岩。此外, 辉钼矿Re−Os等时线年龄为(117.8±5.7) Ma, 加权平均年龄为(118.27±0.70) Ma, 与胶东已知多个燕山晚期铜钼矿赋矿岩体特征及成矿时代一致, 显示该区可能具有良好的钼多金属成矿前景。

关 键 词: 院格庄岩体; 辉钼矿Re−Os同位素年龄; 岩石地球化学; 胶东

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Re−Os isotopic dating of molybdenites from the Yuangezhuang pluton in Jiaodong and its geological significance

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Abstract: The Yuangezhuang pluton lies in Muping block, Yantai, Shandong Province. It is a typical granitic complex of Weideshan Late Yanshanian super-unit in Jiaodong. In this study, direct Re−Os dating of molybdenites collected from the granitoids was carried out, and the major elements and trace elements in whole rock samples were also analyzed. The results show that the pluton probably belongs to a kind of granite derived from mantle−crust and is characterized by high potassium and alkali as well as metaluminous to peraluminous nature. Besides, the isochron age is 117.8±5.7 Ma, with a weighted average of 118.27±0.70 Ma, similar to data of the metallogenetic epoch and characteristics of the host rock from many known Cu−Mo deposits in Late Yanshanian period. This suggests that it probably has a good prospect for molybdenum polymetallic mineralization.

Key words: Yuangezhuang pluton; molybdenites Re−Os isotopic dating; petrogeochemical characteristics; Jiaodong

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1 引 言

胶东地区是中国重要的金矿集中区之一,累计探明金资源储量超过2000 t,该区面积仅占中国陆地总面积的0.27%,但探明金资源储量和黄金产量均超过全国的25%[1−3]。前人对胶东金矿亦研究颇多,矿床特征、地球化学特征、成矿时代、成矿物质来源、成矿模式和找矿预测等均有涉及[1, 4−11]。同时,胶东地区也发育一些大中型铜钼多金属矿床,可以划分为胶西北成矿带、栖蓬福成矿带和牟乳成矿带(图1),金矿主要分布在胶西北成矿带和牟乳成矿带,而有色金属矿床则主要集中于栖蓬福成矿带内。有色金属的成因类型包括矽卡岩型(福山邢家山钨钼矿床,牟平孔辛头铜钼矿床,牟平杏山北铜钼矿床),斑岩型(栖霞香夼铅锌矿床,栖霞尚家庄钼矿床,荣成冷家钼矿床),似层状热液交代型(福山王家庄铜矿床),条带状铁建造(昌邑铁矿床)等[13−16]。

从20世纪80年代开始,前人陆续对该区有色金属矿床就有所研究,例如,赵伦华[17]初步总结了胶东地区钼矿床的类型和成矿特征,将钼矿分为接触交代(矽卡岩)型、斑岩型和岩浆热液型,并简要概括了其矿床特征;孔庆友等[18]较全面地总结了胶东地区钼矿的地质工作程度、开发利用状况,并划分出3种矿床类型,即接触交代(矽卡岩)型、斑岩(细脉浸

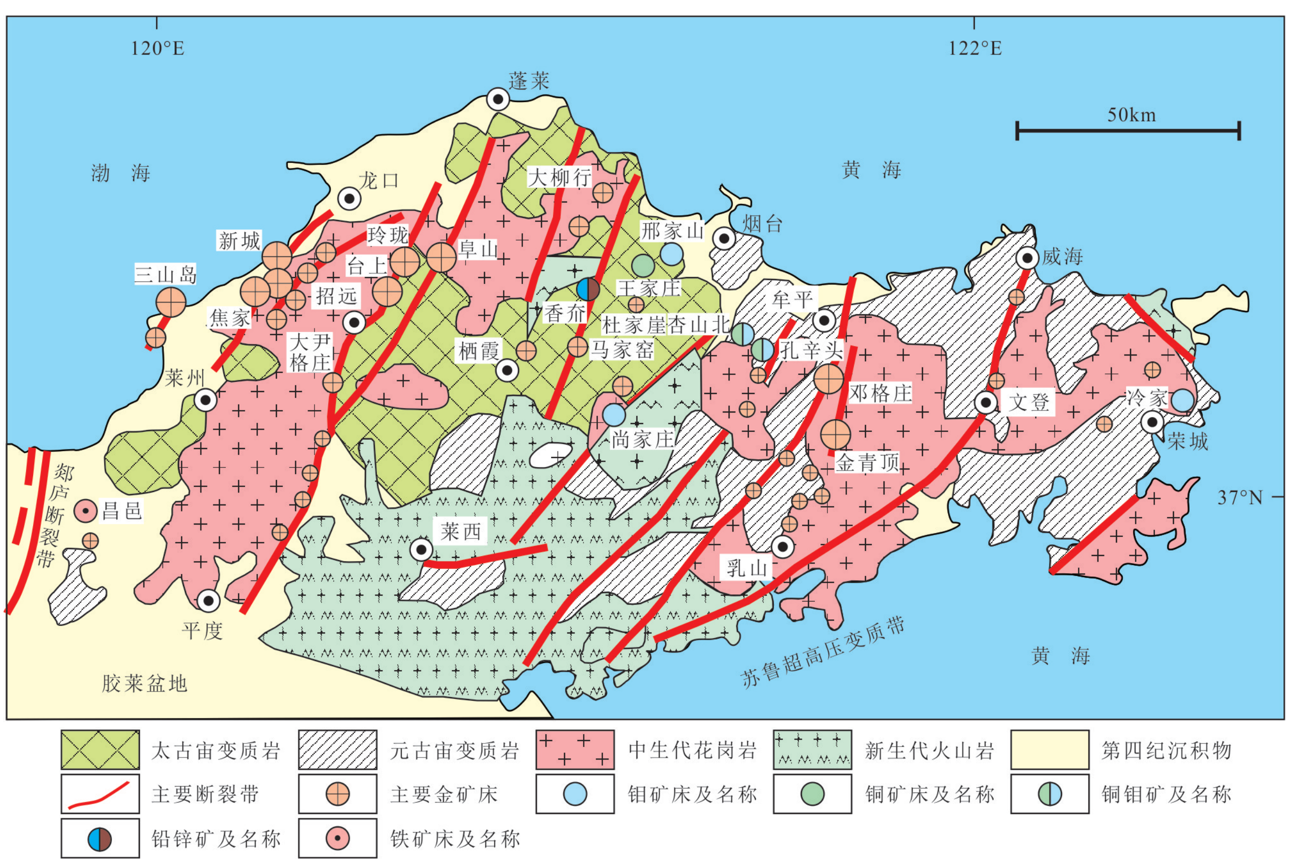

图1 胶东地区地质图及主要贵金属、有色金属矿床分布图(转引自参考文献[12])

Fig.1 Geological map and distribution of precious and nonferrous metal deposits in Jiaodong region (modified after reference [12])

染)型和热液充填型,阐述了邢家山、尚家庄、孔辛头等主要矿床的地质特征;王奎峰[19]详细探讨了栖霞香夼铅锌矿床的地质特征和成因,认为该矿床属典型的与花岗闪长斑岩岩浆有关的斑岩型矿床;孙丰月等[20]初步讨论了福山区北部斑岩成矿系统,将与斑岩成矿有关的有色金属矿床划分为邢家山式、王家庄式和隆口式,找矿方向主要为邢家山式;王奎峰等[16, 19]详细总结了胶东地区铅锌矿和铜矿的矿床类型及典型矿床特征,并根据其成矿地质背景、时空分布特征圈定出成矿远景区;薛玉山等[21]对邢家山钼矿地质地球化学特征作了详细分析,由此得出邢家山钼成矿过程可划分为岩浆热液期(包括矽卡岩阶段、石英硫化物阶段和碳酸盐化阶段)和表生氧化期,邢家山钼矿成矿与幸福山岩体有关,属于传统的岩浆接触交代成因;柳振江、李杰、成少博等[22−24]对胶东地区钼矿进行过Re−Os辉钼矿测年,结果显示钼成矿与金矿形成时代大体一致。

院格庄岩体位于烟台市牟平区院格庄村和莱山镇南部,前人曾经针对其成岩年龄、地球化学特征以及侵位机制方面开展过工作,取得了许多重要成果。张田和张岳桥[25]在2007年测得院格庄岩体黑云母 Ar−Ar 等时年龄为(116.8±1.4) Ma,锆石SHRIMP年龄为(113.4±2.5) Ma,即成岩时代为早白垩世。金秉福[26]在1997年对院格庄岩体进行过岩石地球化学分析,认为燕山运动晚期,太平洋板块下插欧亚板块,形成上地幔与下地壳物质同熔,底辟作用下岩浆沿北东向深大断裂上侵混染分异,形成了现在的花岗岩体。笔者于2011年在院格庄岩体野外考察时发现有辉钼矿化,随后针对岩体东北缘发育的杏山北和孔辛头矽卡岩型铜钼矿区开展了研究工作。本文主要对发育在院格庄岩体中的辉钼矿进行了精确的Re−Os同位素测年工作,并开展了岩石地球化学分析工作,结合前人研究成果,进一步探讨该岩体的成因机制和铜钼成矿机制,该成果对解释杏山北和孔辛头铜钼矿区成矿时代、成因机制具有重要意义,对该区域的铜钼有色金属找矿勘查工作也有所裨益。

2　区域地质背景

院格庄岩体大地构造位置处于沂沭断裂带(郯庐断裂带)以东,苏鲁超高压变质带以西,胶莱盆地以北,胶北地体的北部,牟乳成矿带西部(图1)。区内地层复杂,岩浆岩分布广泛,断裂构造发育。

2.1 地层

区域内地层主要出露古元古界荆山群(Pt_1j)、粉子山群(Pt_1f)、中生界白垩系(K)及新生界第四系(Q)(图2)。古元古界荆山群(Pt_1j)地层出露于岩体东北部和东部,分布较广,包括禄格庄组(Pt_1jl)、野头组(Pt_1jy)和陡崖组(Pt_1jd),主要是黑云母片岩夹透辉岩、大理岩、透辉岩、斜长角闪岩和变粒岩等;古元古界粉子山群(Pt_1f)地层出露于岩体西北部,面积较小,主要为黑云母变粒岩等。已有研究表明,荆山群与粉子山群为同时异相的古元古界沉积变质岩组合[27]。中生界白垩系(K)出露于岩体东部,面积不大,主要是莱阳群(K*l*)的巨砾岩、粗砾岩等盆地边部的洪积扇沉积岩相。新生界第四系(Q)出露广泛,主要为残坡积含砾黏土、冲积泥质砂和含砾砂等沉积物。

2.2 构造

区域内构造主要为断裂构造,NE向断裂是区域上的主要断裂,以桃村—东陡山断裂为代表。牟平—即墨断裂带有6条主要断裂,其中包括桃村—东陡山断裂,该断裂带由一系列NNE向斜列的断层及其所夹变质岩−岩浆岩组成[28],每条断裂以脆性变形为特征,切割基底变质岩系、燕山期花岗岩体。牟平—即墨断裂带晚侏罗世—白垩纪运动学的历史和构造应力场的演化较完整地记录了中国东部晚中生代构造体制转换过程[29, 30]。NW向断裂属后期断裂构造,为压扭性断裂。

2.3 岩浆岩

区域内岩浆岩发育,分布广泛,中酸性−酸性岩浆活动频繁。西南部主要发育有中生代伟德山超单元似斑状二长花岗岩、花岗岩,中东部中生代玲珑超单元弱片麻状二长花岗岩、伟晶不等粒花岗岩,中北部新太古代栖霞超单元云英闪长岩。其中的中生代伟德山超单元岩浆活动形成了院格庄岩体。脉岩主要有煌斑岩、闪长玢岩等。

3　岩体地质特征

院格庄岩体整体呈椭圆状,NW−SE向延伸,地表出露面积约90 km²,风化剥蚀很深,岩相均一稳定,大致可分为3个岩相带(图2)。

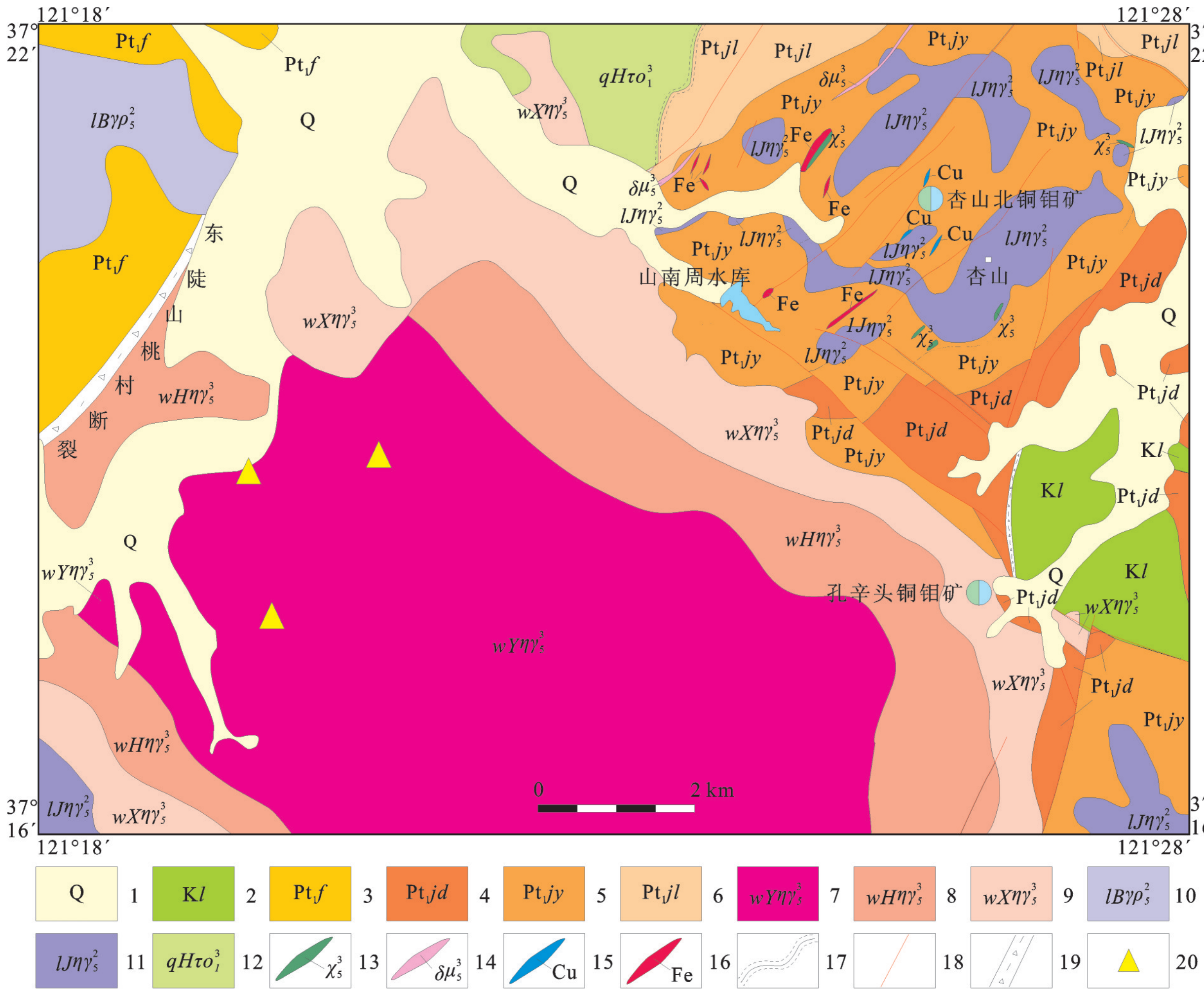

图2 院格庄岩体区域地质图❶

1—第四系; 2—白垩系莱阳群; 3—古元古界粉子山群; 4—古元古界荆山群陡崖组; 5—古元古界荆山群野头组; 6—古元古界荆山群禄格庄组; 7—中生代伟德山超单元斑状角闪二长花岗岩; 8—中生代伟德山超单元巨斑状角闪二长花岗岩; 9—中生代伟德山超单元巨斑状黑云二长花岗岩; 10—中生代玲珑超单元伟晶花岗岩; 11—中生代玲珑超单元弱片麻状二长花岗岩; 12—新太古代栖霞超单元条带状英云闪长岩; 13—煌斑岩; 14—闪长玢岩; 15—铜矿体; 16—铁矿体; 17—韧性断裂; 18—压扭性断裂; 19—断裂破碎带; 20—采样点

Fig.2 Regional geological map of the Yuangezhuang pluton❶

1−Quartnary; 2−Cretaceous Laiyang Group; 3−Paleoproterozoic Fenzishan Group; 4−Paleoproterozoic Jingshan Group Douya Formation; 5−Paleoproterozoic Jingshan Group Yetou Formation; 6−Paleoproterozoic Jingshan Group Lugezhuang Formation; 7−Mesozoic Weideshan superunit porphyritic hornblende monogranite; 8−Mesozoic Weideshan superunit megaporphyritic hornblende monogranite; 9−Mesozoic Weideshan superunit megaporphyritic biotite monogranite; 10−Mesozoic Linglong superunit giant granite; 11−Mesozoic Linglong superunit weakly gneissic monogranite; 12−Neoarchean Qixia superunit banded tonalite; 13−Lamprophyre; 14−Dioritic porphyrite; 15−Copper orebody; 16−Iron orebody; 17−Ductile fault; 18−Compresso−shear fault; 19−Fault fracture zone; 20−Sampling locations

岩石一般为灰白色,似斑状结构,块状构造。斑晶一般为钾长石,肉红色,较自形,粒径10~40 mm、1~5 cm不等,最大的甚至可以达到7 cm,有些斑晶角闪石、黑云母等暗色矿物包裹其中。岩石周围含有同源或异源暗色微粒包体(图3−a, 图3−b),斜长石斑晶粒度不一,为3~13 mm,最大者50 mm;包体岩性单一,体积较小,数量较少。后期有细晶岩脉侵入,宽20~30 mm,另有暗色基性岩脉和闪长玢岩脉侵入。岩石蚀变发育显著,主要有钾化、绿泥石化等,发育有黄铁矿化和辉钼矿化等。

通过显微镜下观察鉴定,院格庄岩体岩性主要为花岗闪长岩、花岗岩(图3−c, 图3−k, 图3−l)。花

❶山东正元地质资源勘查有限责任公司. 山东省烟台市莱山区杏山北矿区铜钼矿详查报告[R]. 济南: 山东黄金集团有限公司, 2010.

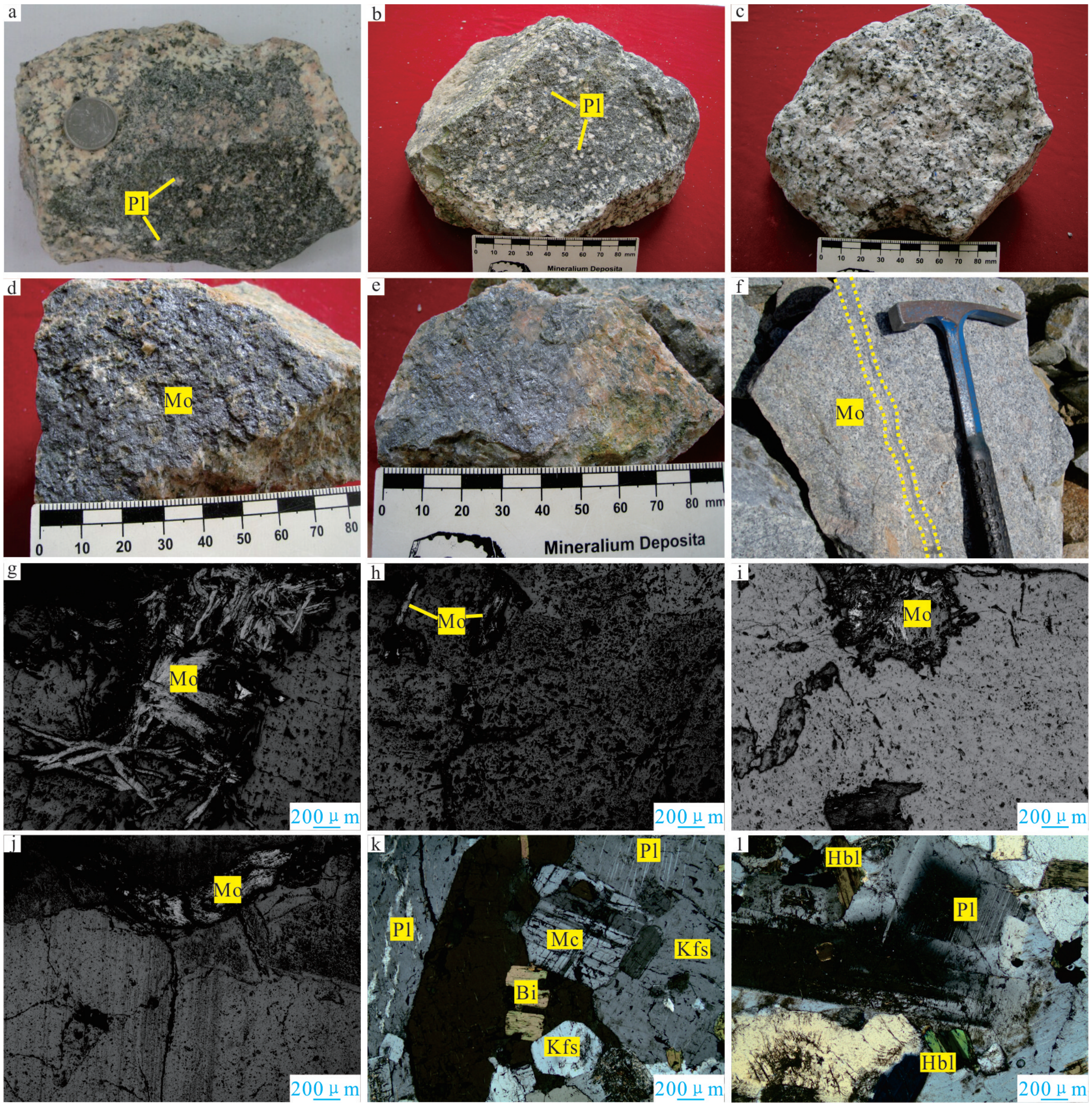

图3 院格庄岩体露头、手标本和显微照片

a, b—暗色微粒包体; c—花岗闪长岩; d—薄膜状辉钼矿; e—浸染状辉钼矿; f—细脉状辉钼矿; g, h—薄膜状辉钼矿(黑白照片); i—浸染状辉钼矿(黑白照片); j—细脉状辉钼矿(黑白照片); k—花岗闪长岩(正交偏光); l—花岗岩(正交偏光)Bi—黑云母; Mc—微斜长石; Mo—辉钼矿; Pl—斜长石; Hbl—普通角闪石; Kfs—钾长石

Fig.3 Field, hand specimen and microscopic photos of rocks from the Yuangezhuang pluton

a, b−MME; c−Granodiorite; d−Pellicular molybdenite; e−Disseminated molybdenite; f−Veinlet molybdenite; g, h−Pellicular molybdenite (black and white photo); i−Disseminated molybdenite (black and white photo); j−Veinlet molybdenite (black and white photo); k−Granodiorite (CPL); l−Granite (CPL)

Bi−Biotite, Mc− Microcline, Mo−Molybdenite, Pl−Plagioclase, Hbl−Hornblende, Kfs−Potassium feldspar

岗闪长岩为花岗结构, 块状构造, 主要矿物: 斜长石, 含量约为55%, 聚片双晶发育; 钾长石, 含量约为15%, 卡斯巴双晶发育(微斜长石, 格子状双晶发育); 石英, 含量约为25%, 少量黑云母、角闪石, 含量约为5%。花岗岩为花岗结构, 块状构造, 主要矿物: 斜长石, 含量约为10%, 聚片双晶发育, 环带状构造; 钾长石, 含量约为55%, 卡斯巴双晶发育; 石英, 含量约为25%, 黑云母、角闪石含量为10%。

4 样品采集与实验方法

此次新发现的辉钼矿矿化发育在院格庄花岗岩体内部, 共采集到含辉钼矿矿化的新鲜花岗岩样

品11件，具体地理坐标：37°19′11.05″N，121°20′46.01″E；37°19′06.93″N，121°19′46.06″E；37°18′02.29″N，121°19′54.63″E(图2)。辉钼矿多呈浸染状、薄膜状分布于花岗岩中，偶见其呈细脉状发育于石英脉内部(图3)。

经单矿物挑纯后，送6件辉钼矿样品在中国地质科学院国家地质实验测试中心进行Re−Os同位素年龄测试工作，采用电感耦合等离子质谱仪TJA X−series ICP−MS进行测量。实验全流程空白Re为(0.0035±0.0002) ng，普Os为(0.00010±0.00002) ng，^{187}Os为(0.00021±0.00006) ng。Re−Os化学分离和质谱测定分为4个步骤：分解样品、直接蒸馏分离Os、萃取分离Re和质谱测定，具体测试步骤见文献[31−34]。实验过程采用国家标准物质GBW04436 (JDC)作为标准样品，监控化学流程和分析数据的可靠性。普Os是根据量子表[35]和同位素丰度表[36]，通过测量$^{192}Os/^{190}Os$比值计算得出[35, 36]。Re、Os含量的不确定度包括样品和稀释剂的称量误差、稀释剂的标定误差、质谱测量的分馏校正误差、待分析样品同位素比值测量误差，置信水平95%。由于采用混合稀释剂，模式年龄的不确定度不包括稀释剂和样品的称量误差，但还包括衰变常数的不确定度(1.02%)，模式年龄置信水平95%。模式年龄t按下式计算：$t=1/\lambda[\ln(1+{}^{187}Os/{}^{187}Re)]$，式中$^{187}Re$衰变常数$\lambda=1.666\times10^{-11}a^{-1}(\pm1.02\%)$[37]。

此次还对该区的8件新鲜花岗岩样品进行了主量元素、微量元素和稀土元素分析测试，在澳实分析检测(广州)有限公司澳实矿物实验室完成。主量元素分析使用硼酸锂/偏硼酸锂熔融，X荧光光谱分析，报13种构岩元素及烧失量(LOI)和硼酸锂—硝酸锂熔融，X荧光光谱分析，精密控制硅铁铝镁等；酸消解、重铬酸钾滴定测量FeO，基于已测定的全铁和亚铁的数据计算出Fe^{3+}的含量。微量元素、稀土元素分析采用硼酸锂熔融、等离子质谱定量和四酸消解，质谱/光谱仪分析。

5 结果分析

5.1 主量元素特征

从样品分析结果(表1)中可以看出，SiO_2含量介于67.90%~70.80%，平均为69.51%，富硅；Al_2O_3变化于13.42%~15.26%，平均14.60%，高铝；K_2O、Na_2O含量变化范围分别为3.78%~4.92%和3.28%~3.99%，高钾高碱；CaO含量为1.54%~2.69%，钙含量较低；MgO为0.42%~1.56%，贫镁；TiO_2为0.19%~0.36%，低钛。全碱K_2O+Na_2O含量为7.72%~8.49%之间，平均为8.01%；分异指数DI为80.34~88.94，分异演化程度较高；固结指数SI为4.15~12.73，酸性程度较高；碱度率AR为2.67~3.43，碱性较强；里特曼指数δ为2.13~2.56<3.3，属钙碱性岩。从TAS图解(图4)可以看出，样品分布在石英二长岩、花岗闪长岩和花岗岩范围内；SiO_2-K_2O图解(图5)显示属高钾钙碱性系列，只有2件落在范围外，可能是样品花岗岩发生钾化造成；在A/CNK−A/NK图解(图6)中，显示准铝质−过铝质特征。

表1 院格庄岩体主量元素分析结果(%)

Table 1 Major element (%) analyses of rocks from the Yuangezhuang pluton

分析项目	11−YGZ−2	11−YGZ−5	11−YGZ−7	11−YGZ−8	13−YGZ−1	13−YGZ−18	13−YGZ−30	13−YGZ−33
SiO_2	68.87	69.01	67.90	70.68	70.00	70.40	70.80	68.40
Al_2O_3	15.26	14.68	14.57	13.42	15.05	14.50	14.65	14.70
Fe_2O_3	0.93	0.63	0.67	0.54	0.73	0.79	0.73	1.36
FeO	0.96	1.28	1.28	0.96	1.03	1.22	1.19	1.33
CaO	1.97	2.23	2.33	1.54	2.03	2.19	2.32	2.69
MgO	0.92	0.84	0.80	0.42	0.79	0.93	0.89	1.56
Na_2O	3.97	3.96	3.99	3.28	3.60	3.76	3.87	3.61
K_2O	4.17	3.78	4.09	4.92	4.89	3.96	3.85	4.41
TiO_2	0.26	0.25	0.26	0.19	0.25	0.30	0.28	0.36
MnO	0.03	0.03	0.04	0.04	0.03	0.04	0.04	0.05
P_2O_5	0.09	0.09	0.09	0.10	0.08	0.10	0.09	0.13
LOI	1.26	1.09	1.80	2.50	0.53	1.05	0.53	0.70
Total	98.69	97.87	97.82	98.59	99.01	99.24	99.24	99.30
DI	84.52	83.60	83.98	88.94	85.27	83.77	83.54	80.34
SI	8.41	8.01	7.39	4.15	7.16	8.72	8.45	12.73
AR	2.79	2.69	2.83	3.43	2.98	2.72	2.67	2.71
δ	2.52	2.26	2.56	2.38	2.65	2.15	2.13	2.51

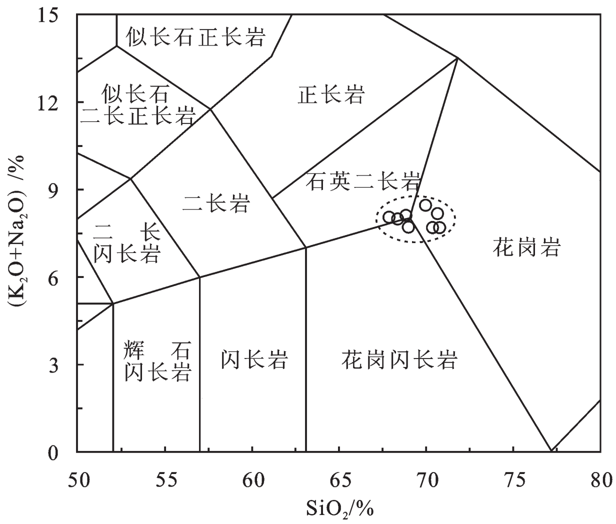

图4 院格庄岩体TAS图解(底图据文献[38])
Fig.4 TAS diagram of the Yuangezhuang pluton (base map after reference [38])

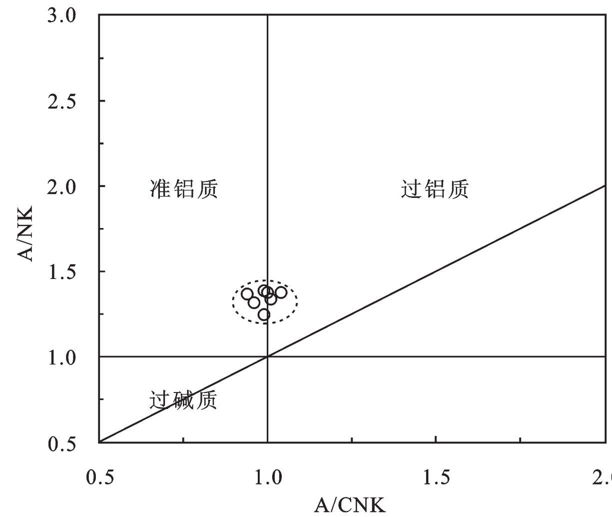

图6 院格庄岩体A/CNK−A/NK图解(底图据文献[41])
Fig.6 A/CNK−A/NK diagram of the Yuangezhuang pluton (base map after reference [41])

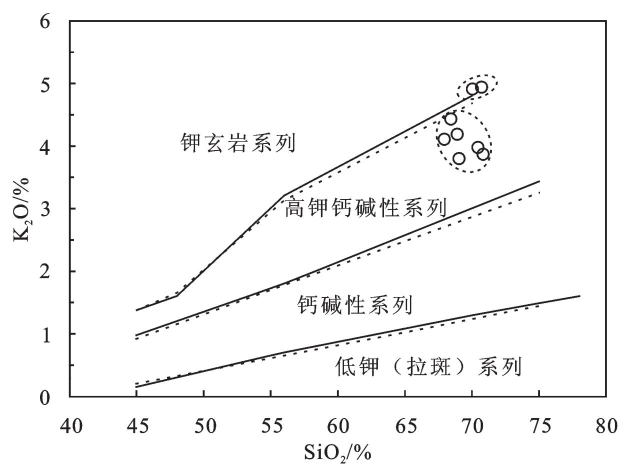

图5 院格庄岩体SiO_2−K_2O图解(底图据文献[39, 40])
Fig.5 SiO_2−K_2O diagram of the Yuangezhuang pluton (base map after reference [39, 40])

5.2 微量元素特征

从样品分析结果(表2)中可以看出, Ba含量599.00×10^{-6}~1795.00×10^{-6}, Sr含量254.00×10^{-6}~716.00×10^{-6}, Nb含量6.50×10^{-6}~18.40×10^{-6}, Ta含量0.60×10^{-6}~1.70×10^{-6}, Hf含量3.10×10^{-6}~4.70×10^{-6}, 整体Ba、K和Sr(LILE)相对富集, Ta、Nb和Hf (HFSE)相对亏损。在微量元素原始地幔标准化蛛网图(图7)上, Pb、Sr、Nd有明显的正异常, Hf和Y有正异常, 而Nb、La、P有显著的负异常。从(Y+Nb)−Rb图解(图8)上可以看出, 样品分布在火山弧花岗岩范围内。

5.3 稀土元素特征

从样品分析结果(表2)中可以看出, 稀土元素总量∑REE变化较大, 为89.30×10^{-6}~203.78×10^{-6}, 平均为132.94×10^{-6}。LREE介于85.27×10^{-6}~193.75×10^{-6}, HREE变化于4.03×10^{-6}~10.03×10^{-6}, LREE/HREE为19.32~23.62, 平均值为21.60, 轻重稀土元素分异明显, 岩浆分异程度较高。$(La/Sm)_N$介于5.94~8.23, LREE比较富集, $(Gd/Yb)_N$介于1.74~2.37, LREE分馏程度比HREE分馏程度高。δEu介于0.56~1.21, 平均为0.90, Eu异常不明显。在稀土元素球粒陨石标准化配分图(图9)上, 呈右倾斜近平滑曲线, 无明显的"V"字形分布。

5.4 辉钼矿Re−Os年龄

院格庄岩体辉钼矿Re−Os同位素测定结果(表3)表明, ^{187}Re含量介于5.573×10^{-6}~7.301×10^{-6}, ^{187}Os含量变化于10.99×10^{-9}~14.42×10^{-9}, 得到模式年龄变化范围在(117.7±1.7) Ma~(118.9±1.9) Ma，所获得的Re−Os同位素数据结果利用Isoplot软件[44]对其进行等时线年龄和加权平均年龄计算, 得到等时线年龄为(117.8±5.7) Ma(MSWD=0.44, 图10), 与加权平均年龄(118.27±0.70) Ma(MSWD=0.20, 图11)基本一致。初始^{187}Os含量为(0.05±0.60) $\times10^{-9}$, 接近于0, 表明辉钼矿形成时含有^{187}Os的量是很低的, 辉钼矿

表2 院格庄岩体微量元素、稀土元素分析结果(10^{-6})

Table 2 Analytical data and characteristic ratios (10^{-6}) of trace and rare earth elements from the Yuangezhuang pluton

分析项目	11-YGZ-2	11-YGZ-5	11-YGZ-7	11-YGZ-8	13-YGZ-1	13-YGZ-18	13-YGZ-30	13-YGZ-33
Rb	120.50	119.50	135.00	238.00	132.50	119.00	122.50	89.60
Ba	1575.00	913.00	961.00	599.00	1795.00	1160.00	950.00	1625.00
Th	10.25	12.20	12.05	34.00	8.72	12.50	12.40	18.25
U	2.21	4.42	5.34	6.95	2.51	4.41	3.83	2.51
Ta	0.60	0.80	0.70	1.70	0.70	0.80	0.90	0.90
Nb	6.50	8.70	8.10	18.40	7.90	9.70	8.80	11.10
La	24.40	31.50	30.10	56.70	28.50	30.90	32.70	44.80
Ce	39.70	51.40	48.60	91.60	52.50	60.60	63.90	83.30
Sr	716.00	539.00	429.00	254.00	489.00	456.00	444.00	623.00
Nd	14.10	18.00	16.60	30.50	17.70	21.30	20.90	25.90
Zr	113.00	124.00	127.00	164.00	101.00	121.00	110.00	146.00
Hf	3.10	3.50	3.50	4.70	2.80	3.50	3.30	4.10
Sm	2.13	2.65	2.36	4.72	2.85	3.46	2.97	3.83
Y	6.20	8.00	7.60	16.50	7.10	8.50	7.70	10.10
Yb	0.52	0.71	0.66	1.36	0.67	0.78	0.70	1.06
Lu	0.08	0.12	0.11	0.21	0.11	0.13	0.10	0.19
Pr	4.20	5.39	5.03	9.47	5.16	5.92	6.08	7.62
Eu	0.74	0.76	0.68	0.76	0.67	0.74	0.76	0.93
Gd	1.49	1.77	1.62	3.36	1.72	2.16	1.91	2.23
Tb	0.19	0.22	0.20	0.45	0.22	0.29	0.28	0.34
Dy	0.97	1.27	1.14	2.57	1.26	1.52	1.30	1.86
Ho	0.18	0.23	0.22	0.48	0.25	0.30	0.26	0.33
Er	0.52	0.70	0.64	1.40	0.59	0.85	0.74	0.93
Tm	0.08	0.10	0.09	0.20	0.10	0.13	0.10	0.16
Co	4.60	4.20	5.70	2.00	3.60	4.10	3.80	6.90
Ni	8.00	5.00	5.00	5.00	4.80	7.80	5.00	12.80
V	31.00	30.00	30.00	15.00	25.00	28.00	29.00	47.00
Cr	20.00	10.00	10.00	10.00	10.00	10.00	10.00	40.00
Ga	18.70	18.50	18.30	18.40	17.80	18.50	18.40	18.50
Tl	0.50	0.50	0.50	1.20	0.66	0.58	0.61	0.34
Sn	1.00	1.00	1.00	2.00	1.00	1.00	1.00	1.00
Pb	26.00	24.00	21.00	36.00	28.70	27.60	26.00	19.90
Zn	34.00	32.00	32.00	35.00	35.00	40.00	38.00	35.00
ΣREE	89.30	114.82	108.05	203.78	112.30	129.08	132.70	173.48
LREE	85.27	109.70	103.37	193.75	107.38	122.92	127.31	166.38
HREE	4.03	5.12	4.68	10.03	4.92	6.16	5.39	7.10
LREE/HREE	21.16	21.43	22.09	19.32	21.83	19.95	23.62	23.43
$(La/Yb)_N$	33.66	31.82	32.71	29.91	30.51	28.42	33.51	30.32
δEu	1.21	1.01	1.01	0.56	0.86	0.77	0.91	0.89
δCe	0.88	0.89	0.88	0.88	0.98	1.03	1.03	1.01

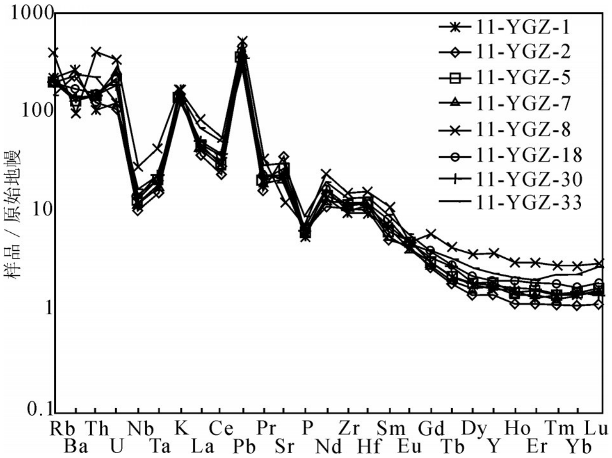

图7 院格庄岩体微量元素原始地幔标准化蛛网图
(底图据文献[42])
Fig.7 Preliminary mantle-normalized trace element patterns of the Yuangezhuang pluton (base map after reference [42])

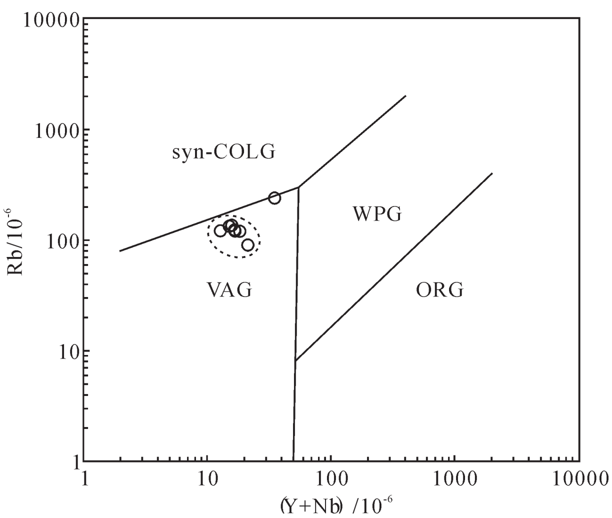

图8 院格庄岩体(Y+Nb)-Rb图解(底图据文献[43])
Fig.8 Y+Nb-Rb diagram of the Yuangezhuang pluton (base map after reference [43])

中的 ^{187}Os都是由 ^{187}Re衰变形成，符合Re-Os同位素体系模式年龄计算条件，也说明所获得模式年龄有效，等时线可代表辉钼矿的成矿年龄[45]。已有的研究发现，辉钼矿晶体或粗颗粒辉钼矿样品中的Re-Os同位素体系可能会出现失耦现象[46-48]，但对成矿时代较年轻、粒度<2 mm的辉钼矿而言，并不存在Re-Os同位素体系失耦作用[49, 50]，同时遵循"多采样，细磨碎"的原则，尽量采集细颗粒、完全均匀的

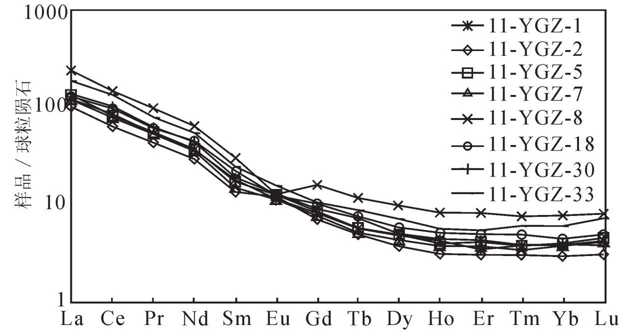

图9 院格庄岩体稀土元素球粒陨石标准化配分图
(底图据文献[42])
Fig.9 Chondrite-normalized REE patterns of the Yua

辉钼矿，准备1g左右的样品，可以有效减少失耦现象[51, 52]，但有时稳定的Re-Os体系也会受到后期构造和变质事件的影响。此次采集的样品粒度较细，相对均匀，未见明显的变形现象(图3)，6件样品具有相似的模式年龄。因此，等时线年龄(117.8±5.7) Ma可以准确代表院格庄岩体辉钼矿成矿年龄，即形成于燕山晚期。

6 讨　论

6.1 岩浆源区分析

院格庄岩体富集轻稀土和大离子亲石元素，亏损重稀土，表明源区内有角闪石、石榴石和辉石等残留[53]；亏损Nb、Ta、Ti等高场强元素，表明源区内有含角闪石或金红石等矿物残留[54]。Rb/Sr值为0.14~0.94，平均值为0.32，介于上地幔平均值(0.034)与地壳平均值(0.35)[55]之间；Nb/Ta值为9.78~12.33，平均值为11.20，介于地壳平均值(11~12)[56]与地幔平均值(17.4)[42]之间；Zr/Hf值为33.33~36.45，平均值为35.33，类似于平均陆壳值(35.7)[57]，又接近于原始地幔和球粒陨石值(34~36)[42, 58, 59]；Sr含量介于254.00×10⁻⁶~716.00×10⁻⁶，平均值为493.75×10⁻⁶，介于壳源花岗岩(Sr通常小于300×10⁻⁶)[60, 61]和幔源花岗岩(Sr大于1400×10⁻⁶)[62, 63]之间。因此，院格庄岩体属于壳幔混合来源花岗岩，同时暗色微粒包体的存在也能为此提供地质证据[64-66]。

胶东地区中生代花岗质岩石有3个显著不同的演化序列，即晚三叠世(205~255 Ma)幔源型花岗岩、晚侏罗世(150~160 Ma)地壳重熔型花岗岩和早白垩

表3 院格庄岩体辉钼矿Re−Os同位素分析结果

Table 3 Analytical results of Re−Os isotopes of molybdenites from the Yuangezhuang pluton

样号	样重/g	Re/10⁻⁶		普 Os/10⁻⁹		¹⁸⁷Re/10⁻⁶		¹⁸⁷Os/10⁻⁹		模式年龄/Ma	
		测定值	2σ	测定值	2σ	测定值	2σ	测定值	2σ	测定值	2σ
13−YGZ−7	0.04072	8.868	0.072	0.0387	0.0050	5.573	0.045	10.99	0.07	118.3	1.7
13−YGZ−8	0.04074	9.436	0.072	0.0002	0.1074	5.931	0.045	11.76	0.11	118.9	1.9
13−YGZ−11	0.04017	11.616	0.104	0.0143	0.0029	7.301	0.065	14.42	0.09	118.4	1.7
13−YGZ−12	0.04058	9.622	0.087	0.0241	0.0072	6.048	0.055	11.94	0.07	118.4	1.7
13−YGZ−15	0.04060	10.966	0.106	0.0215	0.0048	6.892	0.067	13.56	0.09	118.0	1.8
13−YGZ−19	0.04057	9.867	0.079	0.0225	0.0073	6.202	0.050	12.17	0.08	117.7	1.7

世(105~130 Ma)壳幔混合型花岗岩[25]。张岳桥和张田[25]对院格庄花岗岩体中的锆石测年, 得到锆石SHRIMP年龄为(113.4±2.5) Ma, 属于其中的典型花岗岩。

6.2 辉钼矿同位素年龄对胶东钼矿成因的指示意义

Re主要富集于地幔中, 并且地球化学行为与Mo相似, 在辉钼矿中能达到最大的富集程度, 因此辉钼矿中Re元素的含量可以在一定程度上反映相关矿床的物质来源[67]。随着研究成果的不断积累, 绝大多数研究者赞同这样的说法, 即Re−Os同位素体系不仅可以精确地确定硫化物矿床形成的时间, 同时可以示踪成矿物质来源以及指示成矿过程中不同来源物质混入的程度[47, 68−70]。毛景文等人在综合分析、对比了中国各种类型钼矿床中辉钼矿的Re含量后, 发现从地幔来源到壳幔混合来源再到地壳来源, 辉钼矿中Re的含量逐次呈数量级下降, 依次为$n\times10^{-4}$, $n\times10^{-5}$和$n\times10^{-6}$[68]。院格庄岩体Re含量介于8.868×10^{-6}~11.616×10^{-6}, 平均为10.062×10^{-6}, 表明钼可能为壳幔混合来源。

胶东地区的钼矿床不仅在空间上与中酸性花岗质侵入体具有密切的关系, 而且最新的高精度成岩成矿年代学研究表明, 在同一矿区的矽卡岩型或斑岩型矿化的成岩和成矿在时间上一致, 均形成于晚侏罗世—早白垩世(表4)。

矽卡岩型钼矿化与晚侏罗世—早白垩世的似斑状花岗闪长岩、似斑状二长花岗岩等关系密切, 常产于中酸性岩体与大理岩地层的接触带及外接触带部位, 该类矿床通常金属成矿元素多且组合复杂, 可能主要与被交代的地层围岩岩性有关。斑岩型矿化常产于含斑中细粒花岗闪长岩、斑状中粒花岗闪长岩及绢英岩化花岗闪长质碎裂岩中。综合以上分析, 晚侏罗世—早白垩世可能是胶东地区成矿强度较大、较具有经济意义的钼金属成矿期。此次测得的院格庄岩体中辉钼矿Re−Os同位素等时线年龄为(117.8±5.7) Ma, 可以准确代表辉钼矿的成矿年龄。杏山北矿床辉钼矿Re−Os同位素等时线年龄为122.986 Ma❶, 孔辛头矿床辉钼矿年龄也与此一致(另文待发表), 表明院格庄岩体可能为其成矿母岩, 具有一定的找矿潜力, 可为本区接触交代铜钼矿的勘查工作提供一定的指示意义。

表4 胶东地区钼矿成矿年龄统计

Table 4 The formation age of molybdenite in the Jiaodong region

矿床/矿化点	测试矿物	测试方法	年龄/Ma	资料来源
邢家山钨钼矿	辉钼矿	Re−Os	157.6±3.9	[14]
尚家庄钼矿	辉钼矿	Re−Os	116.4±1.6	[23]
冷家钼矿	辉钼矿	Re−Os	113.5±1.6	[71]
南宿钼矿化	辉钼矿	Re−Os	(111.8±0.3)~(128.9±0.3)	[22]
三山岛钼矿化	辉钼矿	Re−Os	149.7±1.5	[72]

7 结 论

(1)院格庄花岗岩体SiO_2、Al_2O_3、Na_2O和K_2O含量较高, 属高钾富碱的钙碱性岩系列, 并且为准铝质−过铝质, 是壳幔混合来源的花岗岩。

(2)院格庄花岗岩体中辉钼矿Re−Os同位素测年结果显示, 模式年龄变化在(117.7±1.7) Ma~(118.9±1.9) Ma, 等时线年龄为(117.8±5.7) Ma, 形成

❶山东正元地质资源勘查有限责任公司. 山东省烟台市莱山区杏山北矿区铜钼矿详查报告[R]. 济南: 山东黄金集团有限公司, 2010.

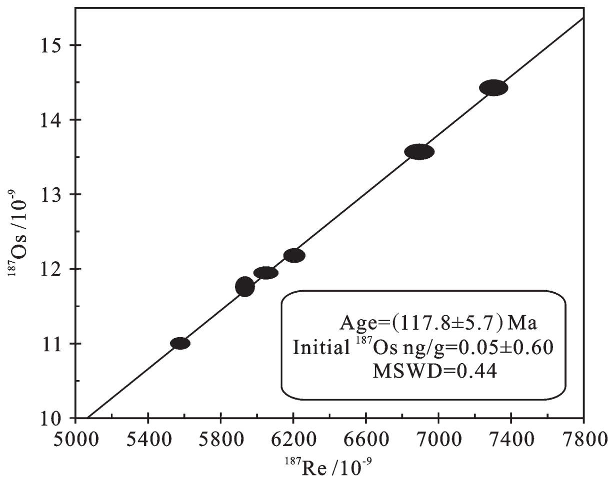

图10 院格庄岩体辉钼矿Re-Os等时线年龄
Fig.10 Re-Os isochron age of molybdenites from the Yuangezhuang pluton

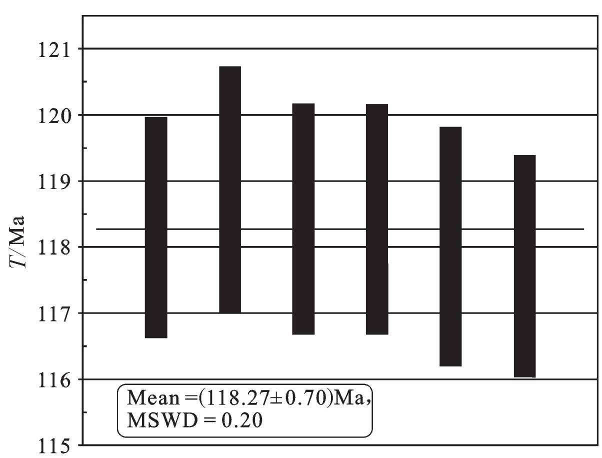

图11 院格庄岩体辉钼矿Re-Os模式年龄加权平均值
Fig.11 Weighted average of Re-Os model age of molybdenites from the Yuangezhuang pluton

于燕山晚期,并且与成岩年龄一致。

(3)院格庄花岗岩体及矿化辉钼矿形成时代与胶东已知多个燕山晚期铜钼矿赋矿岩体特征及成矿时代一致,表明该区可能具有良好的钼多金属成矿前景。

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