



黑龙江省多宝山 Cu-Mo 矿床成矿斑岩锆石 U-Pb 年龄及地球化学特征*

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摘 要 多宝山矿床位于大兴安岭北部, 是中国东北地区规模最大的斑岩型 Cu-Mo 矿床。文章对该矿床中与成矿关系密切的花岗闪长斑岩进行了详细的 LA-ICP-MS 锆石 U-Pb 定年、主量元素、微量元素及 Hf 同位素研究。结果表明, 花岗闪长斑岩的 LA-ICP-MS 锆石 U-Pb 年龄为 (474.9 ± 1.8) Ma, 其 $w(\text{SiO}_2)$ 为 70.73% ~ 73.45%, $w(\text{K}_2\text{O})$ 和 $w(\text{Na}_2\text{O})$ 分别为 2.99% ~ 3.88%、3.86% ~ 4.38%, 属高钾钙碱性系列。岩石富集轻稀土元素, $(\text{La}/\text{Yb})_{\text{N}} = 6.32 \sim 12.76$, 显示出 Ba、K、La、Sr、Zr、Hf、Sm 等元素富集, Th、Ta、Nb、Ce、P、Ti 等元素亏损的特征。锆石 $\epsilon_{\text{Hf}}(t)$ 值介于 10.3 ~ 14.6。详尽的元素和同位素地球化学特征表明多宝山花岗闪长斑岩可能形成于大陆边缘弧环境, 来源于加厚陆壳条件下亏损地幔新增生的年轻地壳物质的部分熔融过程。

关键词 地球化学 锆石 U-Pb 定年 Hf 同位素 花岗闪长斑岩 多宝山矿床

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Zircon U-Pb dating, geochemistry of ore-bearing porphyry in Duobaoshan Cu-Mo deposit, Heilongjiang Province, China

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Abstract

The Duobaoshan deposit, located in northern Da Hinggan Mountains, is the largest porphyry Cu-Mo deposit in Northeast China. In this study, the authors report LA-ICP-MS zircon U-Pb age, major, trace elements, and Hf isotopic compositions of the ore-related granodiorite porphyry in the Duobaoshan deposit. LA-ICP-MS zircon U-Pb dating yielded crystallization age of (474.9 ± 1.8) Ma for the granodiorite porphyry. Geochemical results indicate that the $w(\text{SiO}_2)$ values are in the range of 70.73% ~ 73.45%, whereas $w(\text{K}_2\text{O})$ and $w(\text{Na}_2\text{O})$ range from 2.99% to 3.88% and from 3.86% to 4.38%, respectively, suggesting that the rocks belong to high-K calc-alkaline series. The trace elements are characterized by enrichment of Ba, K, La, Sr, Zr, Hf, Sm, and depletion of Th, Ta, Nb, Ce, P, Ti. The REE characteristics are LREE enrichment with $(\text{La}/\text{Yb})_{\text{N}}$ ratios of 6.32 ~ 12.76. The zircon Hf isotope analysis shows $\epsilon_{\text{Hf}}(t)$ values vary from 10.3 to 14.6. The geochemical results indicate that the Duobaoshan granodiorite porphyry was probably formed in a continental marginal arc

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setting, and originated from partial melting of juvenile lower crust materials that were derived from the depleted mantle under the thickened crust condition.

Key words: geochemistry, zircon U-Pb dating, Hf isotope, granodiorite porphyry, Duobaoshan deposit

多宝山斑岩型 Cu-Mo 矿田位于大兴安岭北段,主要由多宝山大型斑岩铜(钼)矿床、铜山大型斑岩铜(钼)矿床、三矿沟小型矽卡岩铁铜矿床、关鸟河小型矽卡岩白钨矿矿床及小多宝山、跃进、育宝山铁铜矿点等组成,是中亚造山带东段最重要的斑岩型铜矿床聚集区(杜琦等,1988;韩振新等,2004;武广等,2009;刘军等,2009;Liu et al., 2012;2017)。近年来,区域上又陆续发现了小泥鳅河金矿、三道湾子金碲矿、争光金矿、铜山金矿、上马厂金矿等一批热液脉型金银钼锑矿床或矿化点(谭成印等,2010),使得多宝山地区成为大兴安岭地区又一重要的金矿集中区。多宝山矿床拥有多宝山矿田绝大部分铜(钼)储量,前人对该矿床地质特征、成岩成矿年龄、成矿流体性质及物质源区等方面开展了较多的研究工作(杜琦等,1988;刘弛等,1995;赵一鸣等,1997a;葛文春等,2007;王喜臣等,2007;刘军等,2010;Liu et al., 2012;向安平等,2012;Zeng et al., 2014;Wu et al., 2015),多数学者认为该矿床的形成与早古生代中酸性浅成侵入岩关系密切,然而多宝山矿床成矿斑岩的岩石成因及构造背景方面的研究仍较薄弱。多宝山矿床产出的大地构造背景争议较大,主要有 3 种观点:一些学者认为矿床形成于典型的岛弧环境(杜琦等,1988;Wu et al., 2011;向安平等,2012;Zeng et al., 2014);另一些学者认为属于陆陆碰撞造山环境(赵一鸣等,1997b;陈衍景等,2009);近年的研究表明,多宝山矿床可能形成于陆缘弧环境(武广等,2009;Liu et al., 2017)。为此,本文以多宝山矿床内与成矿关系密切的花岗闪长斑岩体为研究对象,通过系统的锆石 U-Pb 定年、岩石主量元素和微量、稀土元素及 Hf 同位素地球化学研究,探讨了多宝山成矿斑岩的成因及其地球动力学背景。

1 区域地质

多宝山 Cu-Mo 矿田位于中亚造山带北东段,地处北兴安造山带(亦称兴安地块)东北缘,贺根山-黑河缝合带北西侧(图 1a)。矿田内出露地层主要为奥陶系铜山组和多宝山组,其次为志留系、泥盆系和白

垩系(图 1b)。铜山组以沉积岩为主夹少量火山碎屑岩,岩性为凝灰砂岩、粉砂岩、砂砾岩、凝灰岩及结晶灰岩;多宝山组是一套滨海-浅海相的火山熔岩、火山碎屑岩和碎屑火山沉积岩组合,其中遍布矿区的主体岩石为中性到中-基性的安山岩、玄武岩和苦橄岩类;志留系岩性为砂岩、粉砂岩、砂砾岩、板岩,局部夹中基性火山岩;泥盆系岩性为砂岩、粉砂岩、泥质板岩、板岩夹灰岩透镜体、安山岩、英安岩及凝灰熔岩和细碧岩等;白垩系为一套陆相含煤建造(杜琦等,1988;韩振新等,2004;刘军等,2010)。

区内发育多期岩浆岩,包括早古生代、晚古生代和中生代花岗岩类(图 1b)。其中,早古生代侵入岩包括英云闪长岩、花岗闪长岩、花岗闪长斑岩和花岗斑岩。葛文春等(2007)、崔根等(2008)、向安平等(2012)、Zeng 等(2014)、Wu 等(2015)分别获得多宝山矿床内花岗闪长岩体的 SHRIMP 或 LA-ICP-MS 锆石 U-Pb 年龄为 (485 ± 8) Ma、 (480 ± 5) Ma、 (478 ± 4) Ma、 (482 ± 4) Ma、 (479 ± 2) Ma。向安平等(2012)和 Zeng 等(2014)分别报道了多宝山矿床内花岗闪长斑岩体的 LA-ICP-MS 锆石 U-Pb 年龄为 (475 ± 5) Ma、 (477 ± 4) Ma。Liu 等(2017)获得了铜山矿床内英云闪长岩体的 LA-ICP-MS 锆石 U-Pb 年龄为 (471.5 ± 1.3) Ma。车合伟等(2015)报道了争光金矿 3 件英安斑岩样品的 LA-ICP-MS 锆石 U-Pb 年龄分别为 (482 ± 3) Ma、 (481 ± 3) Ma、 (478 ± 3) Ma。晚古生代花岗岩类包括花岗闪长岩、花岗闪长斑岩、石英闪长岩和斜长花岗岩,其全岩 Rb-Sr 等时线年龄为 292 Ma 和 283 Ma(杜琦等,1988)。花岗闪长岩的角闪石、黑云母和全岩同位素年龄(K-Ar 法、Rb-Sr 等时线法)为 226 ~ 310 Ma(赵一鸣等,1997b)。中生代花岗岩类包括角闪花岗闪长岩、花岗闪长岩、钾长花岗岩和细晶闪长岩,其中,花岗闪长岩的 LA-ICP-MS 锆石 U-Pb 年龄为 (177 ± 3) Ma 和 (176 ± 3) Ma(葛文春等,2007)。

多宝山矿田受北西西向的三矿沟-多宝山-裸河构造带控制,该构造带由北西向南东呈反“S”型弯曲,由一系列的褶皱和断裂组成,长约 25 km(韩振新等,2004;李之彤等,2008;刘军等,2010)。

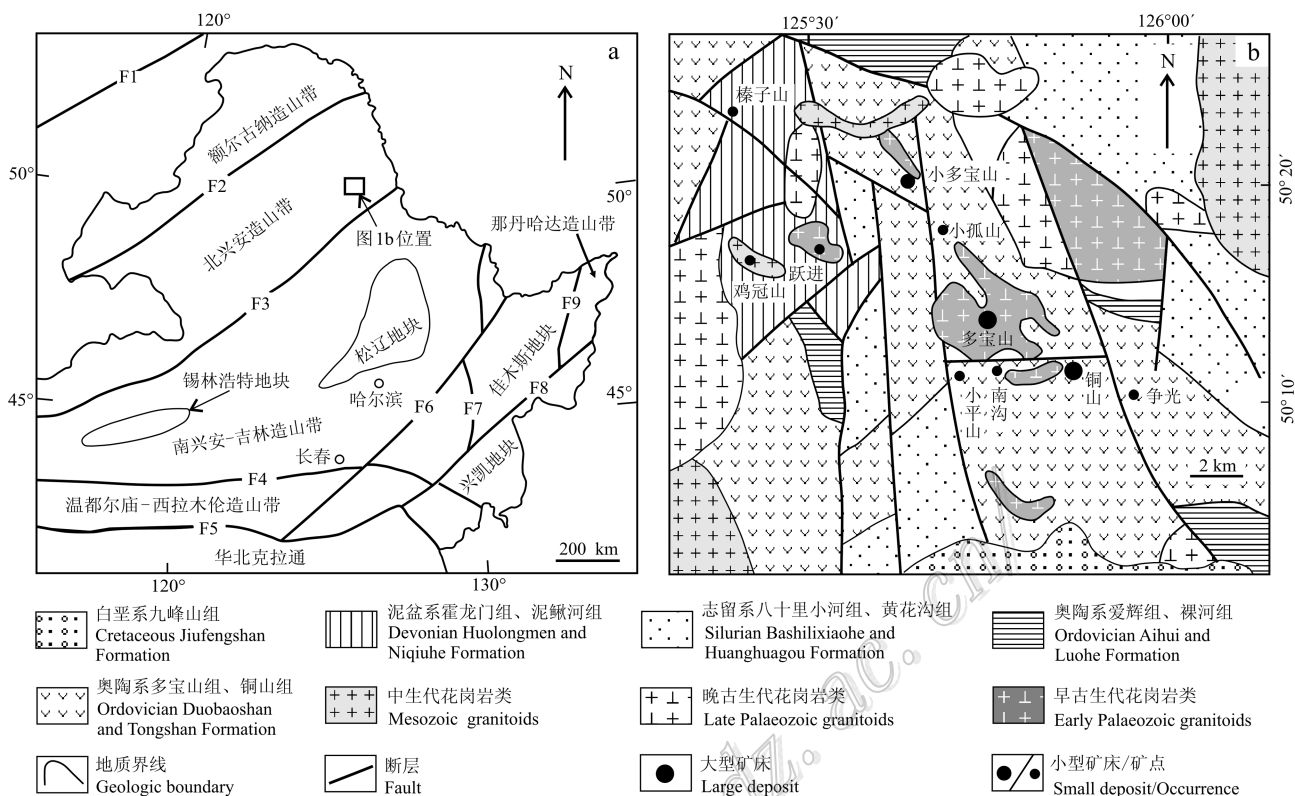


图 1 多宝山矿田大地构造位置(a, 据葛文春等, 2007 改编)和区域地质简图(b, 据韩振新等, 2004 修改)

F1—蒙古-鄂霍茨克缝合带; F2—得尔布干断裂; F3—贺根山-黑河缝合带; F4—索伦山-延吉缝合带; F5—化德-赤峰-开原断裂;
F6—依兰-伊通断裂; F7—牡丹江断裂; F8—敦化-密山断裂; F9—同江-迎春断裂

Fig. 1 Tectonic location map (a, modified after Ge et al., 2007) and regional geological map (b, modified after Han et al., 2004) of the Duobanshan orefield

F1—Mongolia-Okhotsk suture zone; F2—Deerbugan fault; F3—Hegenshan-Heihe suture zone; F4—Suolunshan-Yanji suture zone;

F5—Huade-Chifeng-Kaiyuan fault; F6—Yilan-Yitong fault; F7—Mudanjiang fault; F8—Dunhua-Mishan fault; F9—Tongjiang-Yingchun fault

2 矿床地质

多宝山斑岩 Cu-Mo 矿床位于黑龙江省嫩江县境内。矿床发现于 1958 年,70 年代起进行了详细的地质勘探工作,铜储量 242.5 万吨,平均品位为 0.47%,钼金属量 11 万吨,平均品位 0.016%,伴生金、银、硒、铼和铂族元素。向安平等(2012)和 Zeng 等(2014)分别获得多宝山矿床辉钼矿 Re-Os 年龄为 $(475.1 \pm 5.1) \text{ Ma}$ 、 $(475.9 \pm 7.9) \text{ Ma}$ 。

矿区主要出露铜山组和多宝山组。矿区内出露 3 个时期的侵入岩,它们构成了一个面积约 9 km² 的复式岩体(图 2a、b)。花岗闪长岩体沿区域北西向和北东向断裂交汇部位侵入,略作北西-南东向延长,断续延长约 6 km,宽约 3 km,岩体向南西倾伏,倾角 60°,向下有膨大的趋势。岩体与多宝山组接触带呈

犬牙交错状,且岩体中部有一北西向多宝山组顶垂体带。花岗闪长岩体的主体为花岗闪长岩相,岩体边缘为斜长花岗岩相。花岗闪长岩多为半自形粒状结构,部分为似斑状花岗结构,以斜长石(55%~65%)为主,其次是石英(15%~20%)、钾长石(5%~15%)、角闪石(5%~10%)和黑云母(1%~5%)。花岗闪长斑岩体沿北西向断裂侵入于花岗闪长岩体中部,侵入接触界面复杂,形成犬牙交错的接触带。其地表面积(地表分为两支)分别为 0.08 km² 和 0.09 km²,倾向南西,倾角 75°~80°,向北西侧伏,向下有明显膨大的趋势,斑岩体主要为花岗闪长斑岩相,边缘为斜长花岗斑岩相。花岗闪长斑岩呈块状构造,斑状结构,基质为显微花岗结构。斑晶含量变化大,在 20%~80% 之间。斑晶以斜长石(30%~65%)和石英(10%~20%)为主,其次为钾长石(10%~15%)和黑云母(5%~10%)(图3a、b)。多

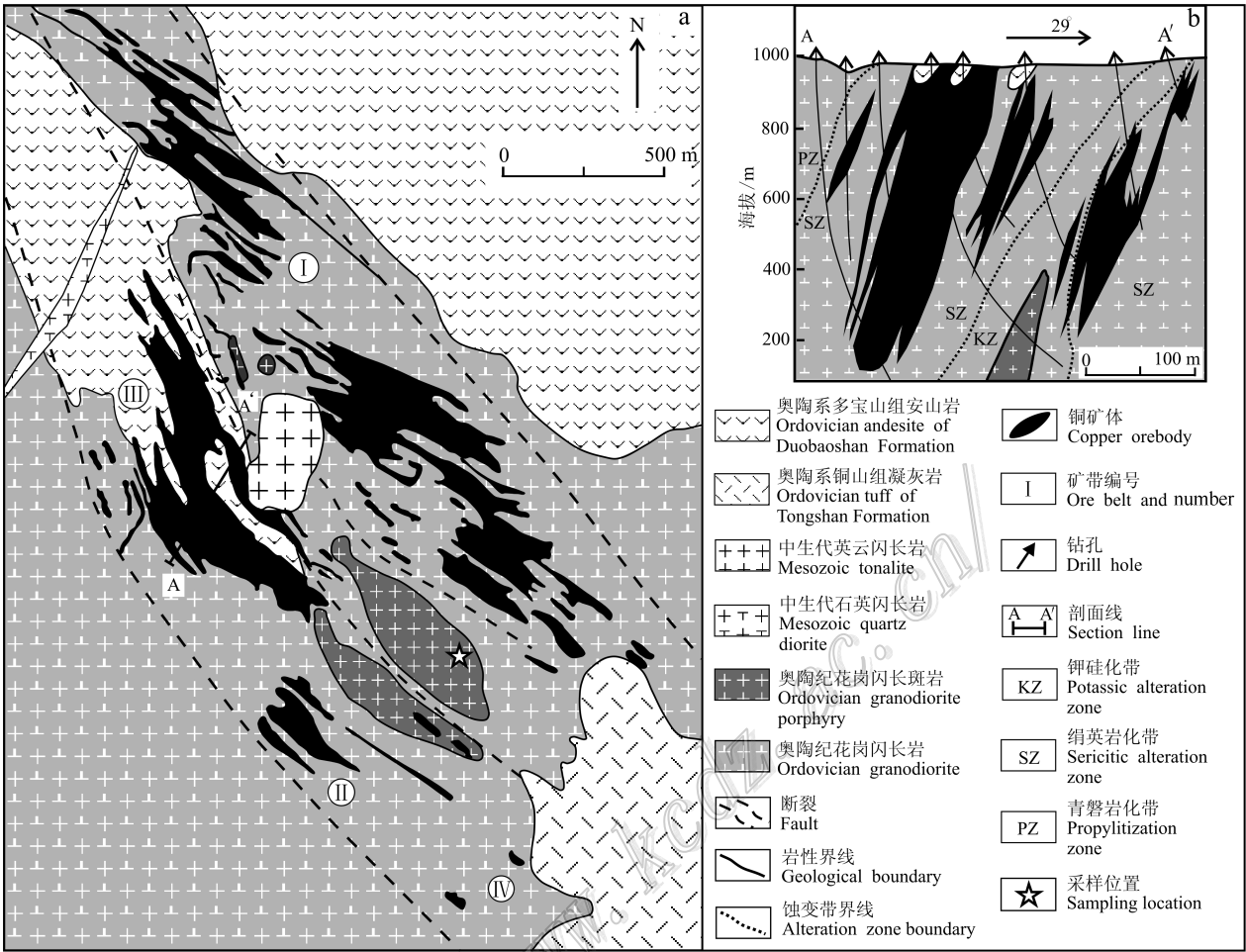


图 2 多宝山斑岩 Cu-Mo 矿床地质简图(a)及Ⅲ号矿带剖面图(b, 据杜琦等, 1988; 赵一鸣等, 1997b 修改)

Fig. 2 Simplified geological map (a) and schematic geological cross section of ore belt Ⅲ (b) of the Duobaoshan porphyry Cu-Mo deposit (modified after Du et al., 1988; Zhao et al., 1997b)

宝山矿床以花岗闪长斑岩体为核心,发育一套典型的斑岩型条带状蚀变及铜钼矿化。英云闪长岩小岩株侵入花岗闪长岩体中,该岩株向深部切穿花岗闪长斑岩体及Ⅲ号矿带。区内断裂构造以北西向为主,至少有 3 条北西向压扭性断裂,它们由强片理化的破碎带构成,控制了矿体的形成,使矿体群呈雁行斜列产出。

多宝山矿床已圈定 215 个 Cu-Mo 矿体,矿体呈条带状或透镜状,走向 $310^{\circ}\sim 330^{\circ}$,倾角 $70^{\circ}\sim 80^{\circ}$,构成沿北西向弧形构造分布的矿带。花岗闪长斑岩体下盘的矿体构成 I 号矿带,上盘矿体由西北向东南依次构成 II、III、IV 号矿带。矿体一般厚几米到几十米,延伸一般 100~500 m。其中,Ⅲ号矿带 10 号矿体规模最大,长 1.4 km,宽 23~340 m,延深 300~

1000 m,铜金属储量占全矿床储量一半以上。矿体全部分布于花岗闪长斑岩体两侧,且主要赋存于绢英岩化花岗闪长岩和安山岩中(图 2)。矿石类型以铜矿石为主,钼矿石少量。金属矿物总量在 3% 左右,主要为黄铜矿、黄铁矿、斑铜矿、辉钼矿,偶见方铅矿、闪锌矿、黝铜矿、辉铜矿(图 3c~f)。脉石矿物以石英、绢云母、绿泥石和碳酸盐为主,其次为绿帘石、黑云母、钾长石等。矿石构造以浸染状、细脉状为主,可见块状、条带状和角砾状构造。矿石结构复杂,主要有半自形-他形粒状结构、交代残余结构、斑状变晶结构和压碎结构,矿石中伴生有益组分金、银、硒、铯、钼、铋、铀等(杜琦等,1988)。矿区发育了多期热液蚀变作用,中心是强钾硅化的花岗闪长斑岩、往两侧依次是钾硅化带、绢英岩化带、青磐岩化带(图 2b)。

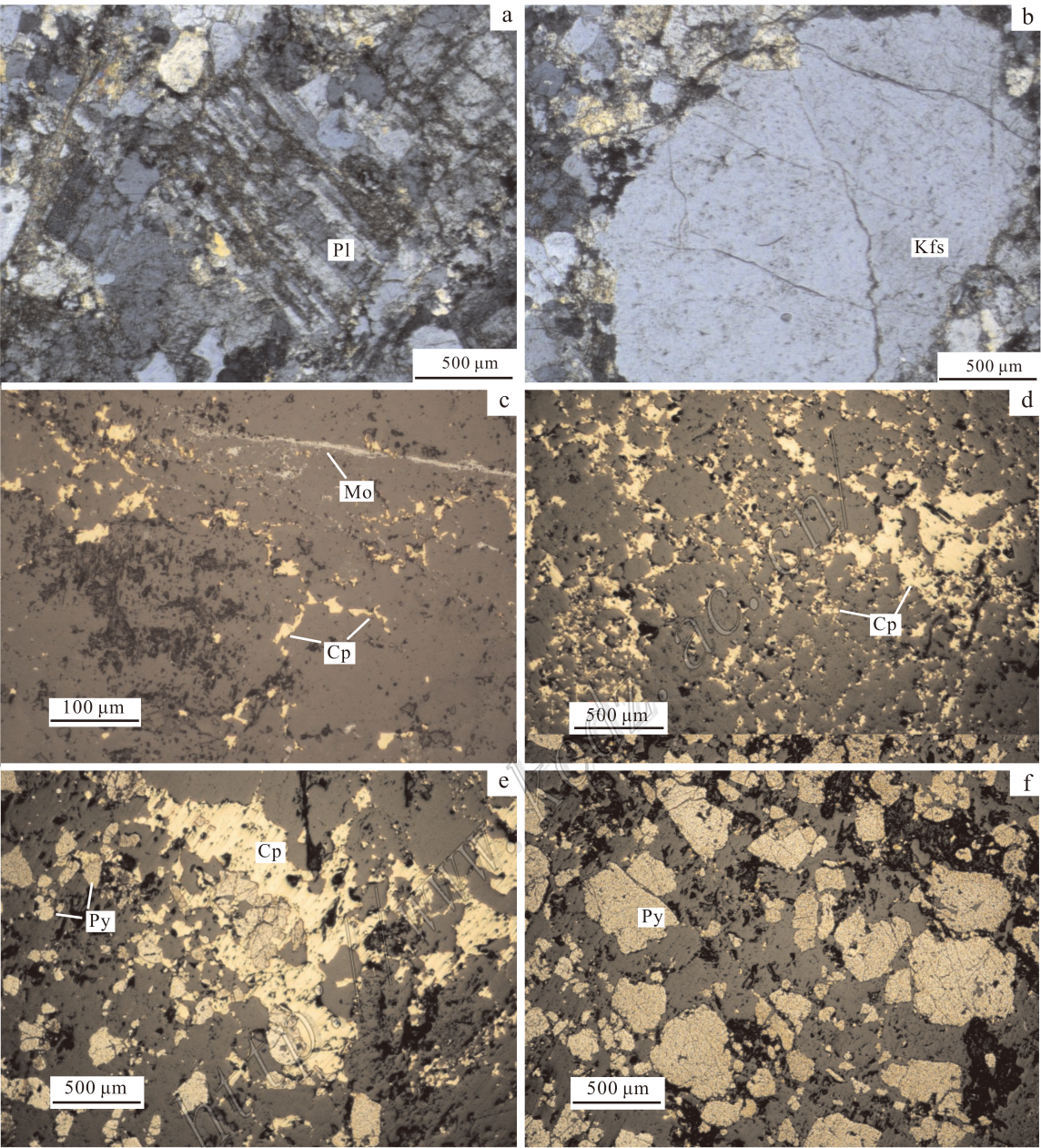


图 3 多宝山矿床典型岩/矿石显微照片

a. 花岗闪长斑岩; b. 花岗闪长斑岩; c. 他形粒状黄铜矿、薄膜状辉钼矿; d. 他形粒状黄铜矿; e. 他形粒状黄铜矿交代早期黄铁矿;
f. 半自形-他形粒状黄铁矿

Kfs—钾长石; Pl—斜长石; Cp—黄铜矿; Mo—辉钼矿; Py—黄铁矿

Fig. 3 Microscope photographs of rock/ores from the Duobaoshan deposit

a. Granodiorite porphyry; b. Granodiorite porphyry; c. Anhedral granular chalcopyrite and film molybdenite; d. Anhedral granular chalcopyrite; e. Anhedral granular chalcopyrite replacing pyrite; f. Subhedral-anhedral granular pyrite

Kfs—K-feldspar; Pl—Plagioclase; Cp—Chalcopyrite; Mo—Molybdenite; Py—Pyrite

3 样品特征及测试方法

3.1 样品特征

花岗闪长斑岩样品采自Ⅲ号矿带采坑东南 500

m 的地表探槽中(图 2a)。采样时,尽量选择新鲜未蚀变的岩石,但部分样品仍可见轻微的硅化和钾化蚀变。岩石呈块状构造,斑状结构。斑晶含量 25%~40%,主要斑晶矿物有斜长石(40%~65%)、石英(15%~20%)、钾长石(10%~15%)及黑云母(5%

~10%),大小在 0.5~4 mm 左右。其中,斜长石呈半自形板状,聚片双晶发育,可见绢云母化;石英呈他形粒状,波状消光;钾长石为半自形板状或他形粒状,具条纹结构,表面发育高岭石化。基质含量 60%~75%,呈显微花岗结构,由细粒状斜长石、钾长石及石英等组成,粒径一般<0.2 mm。副矿物为锆石、磷灰石和榍石等。

3.2 测试方法

将采集的花岗闪长斑岩样品破碎,按重力和磁选方法分选,最后在双目镜下根据锆石颜色、自形程度、形态等特征初步分类,挑选出具有代表性的锆石。将分选好的锆石用环氧树脂制靶、打磨和抛光。锆石的阴极发光(CL)图像在北京铅年领航科技有限公司完成,仪器为日本 JEOL 公司生产的 JSM6510 型扫描电子显微镜。LA-MC-ICP-MS 锆石 U-Pb 定年测试工作在国土资源部成矿作用与资源评价重点实验室完成,锆石定年分析所用仪器为 Finnigan Neptune 型 MC-ICP-MS 及与之配套的 Newwave UP 213 激光剥蚀系统。激光剥蚀所用束斑直径为 25 μm ,频率为 10 Hz,能量密度约为 2.5 J/cm²,以 He 为载气。信号较小的 ²⁰⁷Pb、²⁰⁶Pb、²⁰⁴Pb(+ ²⁰⁴Hg)、²⁰²Hg 用离子计数器(multi-ion-counters)接收,²⁰⁸Pb、²³²Th、²³⁸U 信号用法拉第杯接收,实现了所有目标同位素信号的同时接收,并且不同质量数的峰基本上都是平坦的,进而可以获得高精度的数据,均匀锆石颗粒 ²⁰⁷Pb/²⁰⁶Pb、²⁰⁶Pb/²³⁸U、²⁰⁷Pb/²³⁵U 的测试精度均为 2% 左右,对锆石标准的定年精度和准确度在 1% 左右。测试过程中在每测定 5~7 个样品前后重复测定 2 个锆石 GJ1 对样品进行校正,并测量 1 个锆石 Plesovice,观察仪器的状态以保证测试的精确

度。详细实验测试过程见侯可军等(2009)。

7 件花岗闪长斑岩样品的主量、微量元素测试工作在中国科学院地球化学研究所矿床地球化学国家重点实验室完成,其中,主量元素采用 Axios PW4400 型 X 射线荧光光谱仪(XRF)分析,分析误差小于 5%,微量、稀土元素分析采用 Finnigan MAT 公司 ELEMENT 型 ICP-MS 分析,分析精度优于 10%。

锆石完成 U-Pb 定年后,在原位用 LA-MC-ICP-MS 进行 Lu-Hf 同位素分析,测试工作在国土资源部成矿作用与资源评价重点实验室完成。实验过程中采用 He 作为剥蚀物质载气,剥蚀直径为 55 μm ,测定时使用锆石国际标样 GJ1 作为参考物质,分析点与 U-Pb 定年分析点为同一位置。分析过程中锆石标准 GJ1 的 ¹⁷⁶Hf/¹⁷⁷Hf 测试加权平均值为 0.282 008 $\pm$ 0.000 025(2 σ , n = 26)。相关仪器运行条件及详细分析流程见侯可军(2007)。

4 测试结果

4.1 锆石 U-Pb 定年

花岗闪长斑岩中锆石大多呈长柱状,少量为短柱状,粒径集中在 100~150 μm ,无色透明或黄褐色,显示清楚的生长韵律环带(图 4)。11 颗锆石的 Th/U 比值介于 0.5~1.2,大于 0.1; $w(\text{Th})$ 介于 $24.8 \times 10^{-6} \sim 218.8 \times 10^{-6}$,平均值 92.3×10^{-6} ; $w(\text{U})$ 介于 $50.1 \times 10^{-6} \sim 205.6 \times 10^{-6}$,平均值 118.8×10^{-6} (表 1),据此认为锆石为岩浆成因。11 颗锆石给出了 $(474.9 \pm 1.8)\text{Ma}$ 的加权平均年龄(MSWD = 1.8)(图 5),代表了花岗闪长斑岩体的结

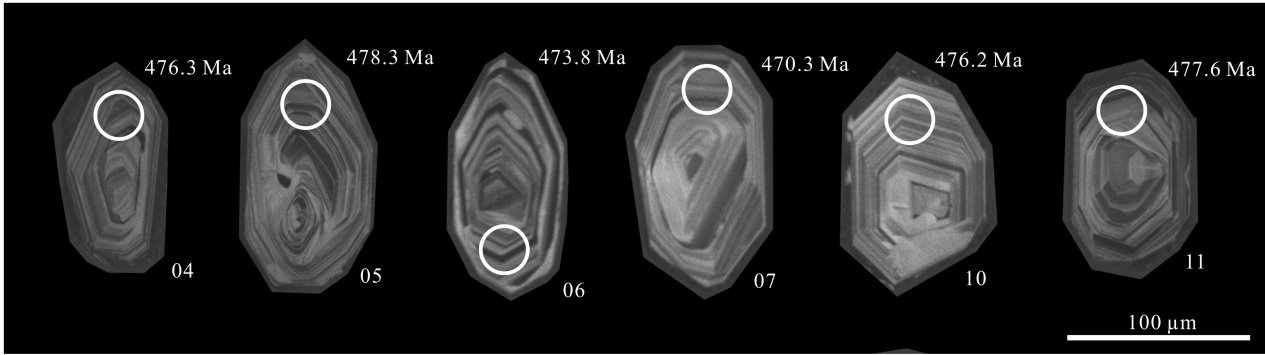


图 4 多宝山矿床花岗闪长斑岩锆石代表性 CL 图像

Fig. 4 Representative cathodoluminescence (CL) images of zircons from the granodiorite porphyry with analytical numbers of the Duobaoshan deposit

表 1 多宝山矿床花岗闪长斑岩 LA-ICP-MS 锆石 U-Pb 分析结果
Table 1 LA-ICP-MS zircon U-Pb data of the granodiorite porphyry from the Duobaoshan deposit

样品号	$\omega(^{232}\text{Th})/10^{-6}$	$\omega(^{238}\text{U})/10^{-6}$	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	Th/U	$^{206}\text{Pb}/^{238}\text{U}$ 年龄/Ma	1 σ /Ma	谐和度/%
HD3-16.1	103.1	122.9	0.0566	0.0002	0.5984	0.0084	0.0768	0.0011	0.8	476.9	6.3	99
HD3-16.2	44.1	76.0	0.0565	0.0002	0.5929	0.0045	0.0762	0.0005	0.6	473.2	3.2	99
HD3-16.3	97.9	127.6	0.0567	0.0002	0.6003	0.0062	0.0769	0.0007	0.8	477.3	4.5	99
HD3-16.4	218.8	189.8	0.0567	0.0001	0.5996	0.0041	0.0767	0.0005	1.2	476.3	2.9	99
HD3-16.5	70.4	102.6	0.0564	0.0003	0.5976	0.0071	0.0770	0.0009	0.7	478.3	5.5	99
HD3-16.6	41.9	76.6	0.0562	0.0002	0.5910	0.0043	0.0763	0.0005	0.5	473.8	3.0	99
HD3-16.7	186.5	205.6	0.0563	0.0001	0.5874	0.0023	0.0757	0.0002	0.9	470.3	1.3	99
HD3-16.8	49.2	75.5	0.0569	0.0002	0.5985	0.0033	0.0764	0.0003	0.7	474.4	2.1	99
HD3-16.9	24.8	50.1	0.0567	0.0003	0.5962	0.0039	0.0764	0.0004	0.5	474.4	2.4	99
HD3-16.10	62.8	106.9	0.0572	0.0002	0.6045	0.0024	0.0767	0.0002	0.6	476.2	1.1	99
HD3-16.11	115.5	172.7	0.0571	0.0002	0.6055	0.0023	0.0769	0.0002	0.7	477.6	1.4	99

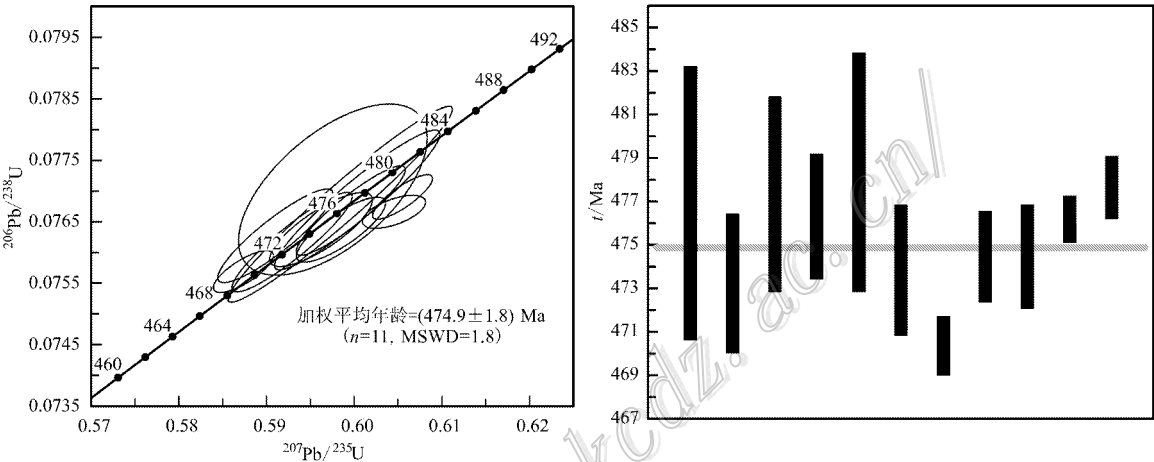


图 5 多宝山矿床花岗闪长斑岩锆石 U-Pb 年龄图解
Fig. 5 Zircon U-Pb ages of the granodiorite porphyry from the Duobaoshan deposit

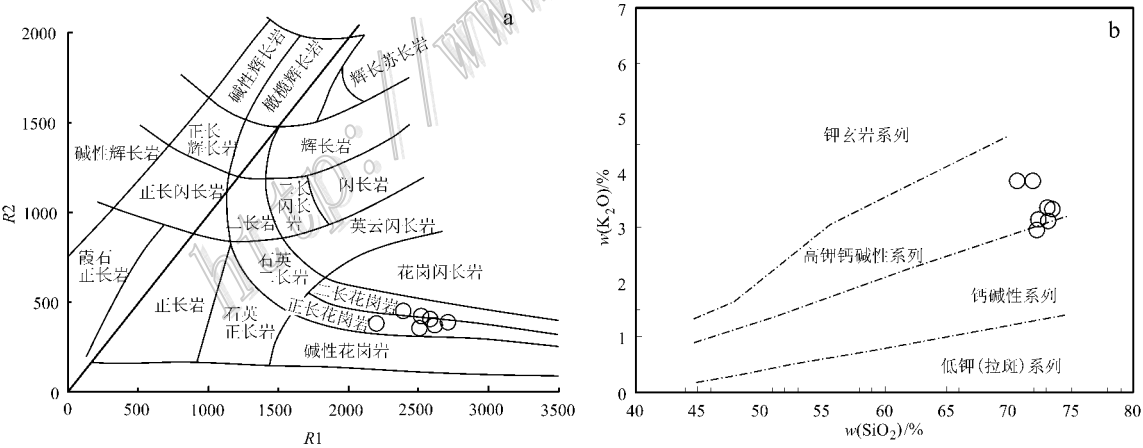


图 6 多宝山矿床花岗闪长斑岩 R1-R2 分类图解(a,底图据 De la Roche et al. , 1980)和 SiO₂-K₂O 图解(b,底图据 Peccerillo et al. , 1976)

Fig. 6 R1-R2 diagram (a, base map after De la Roche et al. , 1980) and SiO₂-K₂O diagram (b, base map after Peccerillo et al. , 1976) of the granodiorite porphyry from the Duobaoshan deposit

晶年龄,与多宝山矿床铜钼矿化年龄相吻合。

4.2 岩石主量、微量及稀土元素

花岗闪长斑岩的 $\omega(\text{SiO}_2)$ 和 $\omega(\text{Al}_2\text{O}_3)$ 分别为 70.73%~73.45%、13.20%~14.99%。 $\omega(\text{K}_2\text{O})$ 、 $\omega(\text{Na}_2\text{O})$ 及 $\omega(\text{K}_2\text{O}+\text{Na}_2\text{O})$ 分别为 2.99%~

3.88%、3.86%~4.38% 及 7.22%~8.26%。 $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 比值介于 0.70~0.93。 $\omega(\text{MgO})$ 、 $\omega(\text{CaO})$ 和 $\omega(\text{FeO}^T)$ 分别为 0.35%~0.53%、0.56%~1.33% 及 1.87%~2.93%。铝指数 A/CNK 为 1.01~1.26 (表2)。在花岗岩类 R1-R2 分类图解(图6a)中,投

表 2 多宝山矿床花岗闪长斑岩主量元素、微量及稀土元素分析结果

Table 2 Analyzed data of major elements, trace and rare earth elements of the granodiorite porphyry from the Duobaoshan deposit

组分	HD17-1	HD17-2	HD17-3	HD17-4	HD15-1	HD15-2	HD15-3
				$w(B)/\%$			
SiO ₂	73.12	73.45	73.06	72.37	70.73	71.87	72.26
Al ₂ O ₃	13.20	14.16	14.13	14.25	14.94	14.46	14.99
FeO ^T	2.50	2.12	2.20	2.93	2.90	1.87	1.93
CaO	1.28	0.75	0.67	0.56	0.56	1.33	0.85
MgO	0.41	0.53	0.49	0.35	0.53	0.45	0.35
K ₂ O	3.39	3.36	3.14	3.16	3.88	3.87	2.99
Na ₂ O	4.30	3.86	4.22	4.32	4.38	4.14	4.30
MnO	0.01	0.02	0.03	0.03	0.01	0.01	0.02
TiO ₂	0.26	0.26	0.24	0.25	0.25	0.27	0.25
P ₂ O ₅	0.08	0.09	0.09	0.09	0.11	0.11	0.10
LOI	1.34	1.50	1.79	1.47	1.46	1.38	1.67
总和	99.89	100.10	100.06	99.78	99.75	99.76	99.71
K ₂ O/Na ₂ O	0.79	0.87	0.74	0.73	0.89	0.93	0.70
K ₂ O+Na ₂ O	7.69	7.22	7.36	7.48	8.26	8.01	7.29
A/CNK	1.01	1.25	1.22	1.23	1.20	1.08	1.26
				$\tau_w(B)/10^{-6}$			
Li	2.64	4.96	5.06	3.04	5.82	3.45	3.85
Be	1.05	1.03	0.98	0.93	1.24	1.07	1.09
Sc	6.55	6.92	6.97	6.45	7.37	6.99	7.21
V	53.60	55.20	52.00	47.8	65.20	58.80	45.50
Cr	7.61	24.10	11.90	21.00	11.80	13.80	10.50
Co	2.58	3.01	3.00	2.99	2.80	2.76	2.42
Ni	4.09	12.50	7.27	10.30	6.29	7.40	5.81
Ga	14.60	15.90	15.30	14.50	18.10	15.60	15.30
Ge	1.01	0.98	0.94	1.04	1.04	1.05	0.99
As	1.05	5.62	4.10	1.75	1.96	4.07	2.02
Rb	40.40	44.80	40.20	35.50	47.70	43.00	34.70
Sr	232.00	210.00	205.00	224.00	241.00	228.00	268.00
Y	5.49	9.30	12.80	8.09	5.42	4.60	7.00
Zr	80.20	82.10	85.50	86.00	84.80	87.60	82.30
Nb	4.58	3.68	3.69	4.19	3.57	4.07	3.67
In	0.034	0.014	0.017	0.058	0.087	0.025	0.035
Sn	4.85	1.14	1.52	7.75	2.27	3.00	3.51
Sb	0.65	0.43	0.42	0.41	0.43	0.50	0.47
Cs	0.97	0.88	0.82	0.77	1.21	0.87	0.85
Ba	519.00	516.00	471.00	504.00	520.00	560.00	480.00
La	9.87	9.15	9.28	10.10	9.43	8.52	10.10
Ce	21.50	16.20	16.40	19.60	19.40	18.70	19.30
Pr	2.64	2.34	2.39	2.62	2.40	2.20	2.46
Nd	9.98	9.35	9.35	10.10	8.93	8.41	9.90
Sm	1.84	1.86	1.96	1.97	1.62	1.61	1.87
Eu	0.48	0.59	0.61	0.56	0.49	0.47	0.58
Gd	1.46	1.63	1.86	1.59	1.31	1.30	1.59
Tb	0.19	0.24	0.28	0.21	0.18	0.16	0.21
Dy	1.00	1.30	1.69	1.20	0.96	0.80	1.07
Ho	0.19	0.27	0.35	0.23	0.18	0.15	0.21
Er	0.56	0.83	1.08	0.68	0.57	0.45	0.64
Tm	0.08	0.12	0.16	0.10	0.07	0.06	0.10
Yb	0.54	0.78	0.99	0.71	0.53	0.45	0.63
Lu	0.08	0.12	0.15	0.12	0.08	0.08	0.10
Hf	2.15	2.18	2.28	2.30	2.09	2.18	2.23
Ta	0.38	0.29	0.31	0.34	0.27	0.31	0.30
W	1.49	1.98	1.86	2.13	1.59	1.68	1.32
Tl	0.13	0.14	0.13	0.11	0.17	0.13	0.12
Pb	8.53	3.83	4.18	5.08	6.74	7.47	5.97
Bi	0.33	0.43	0.441	0.40	0.96	0.66	0.60
Th	1.80	1.82	1.83	1.94	1.68	1.76	1.87
U	0.86	1.03	0.98	1.05	0.76	1.94	0.87
Cd	0.32	0.15	0.20	0.539	0.30	0.22	0.31
∑REE	50.41	44.78	46.55	49.79	46.15	43.36	48.76
δEu	0.87	1.01	0.96	0.94	1.00	0.96	1.00
La/Yb	18.28	11.73	9.37	14.23	17.79	18.93	16.03
(La/Yb) _N	12.32	7.91	6.32	9.59	12.00	12.76	10.81

注：比值单位为 1。

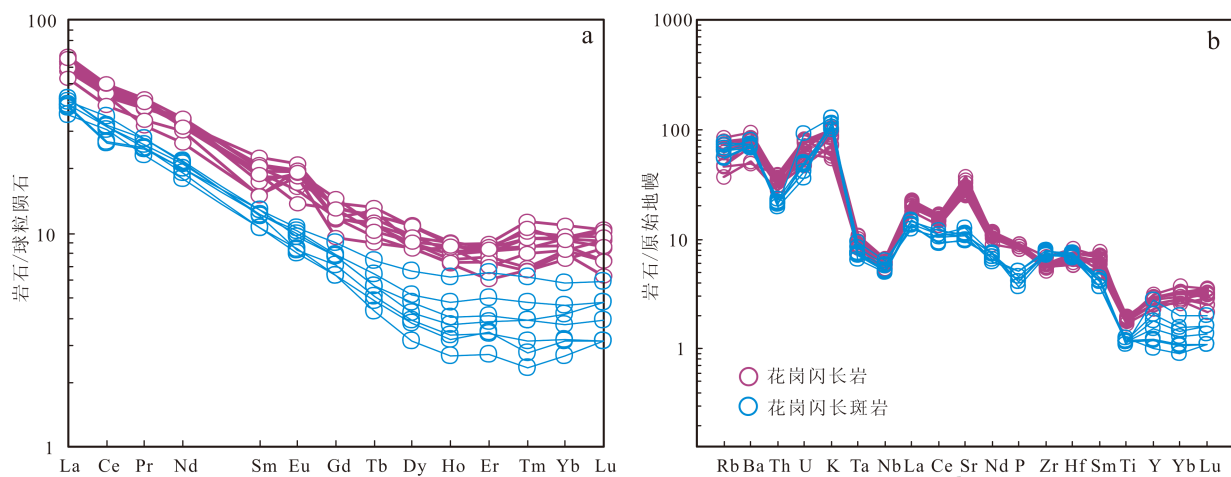


图7 多宝山矿床稀土元素配分曲线和微量元素蛛网图(标准化数值分别采用 Boynton, 1984; Taylor et al., 1985; 花岗闪长岩数据引自 Wu et al., 2015)

Fig. 7 Chondrite-normalized REE patterns and primitive mantle normalized trace elements spider diagram of the Duobaoshan deposit (normalization values after Boynton, 1984; Taylor et al., 1985; Data of granodiorite after Wu et al., 2015)

影点主要落入正长花岗岩和二长花岗岩区域。在 SiO_2 - K_2O 图解(图 6b)中,投影点主要落入高钾钙碱性系列区域。

稀土元素总量介于 $43.36 \times 10^{-6} \sim 50.41 \times 10^{-6}$, $(\text{La}/\text{Yb})_{\text{N}}$ 为 6.32~12.76, 呈现轻稀土元素富集的右倾特征, $(\text{Eu}$ 值为 0.87~1.01, 显示较弱的铕负异常(图 7a)。同时, 富集 Ba、K、La、Sr、Zr、Hf、Sm 等元素, 亏损 Th、Ta、Nb、Ce、P、Ti 等元素(图 7b)。

4.3 锆石 Lu-Hf 同位素

11 颗锆石的 $^{176}\text{Yb}/^{177}\text{Hf}$ 和 $^{176}\text{Lu}/^{177}\text{Hf}$ 比值分别为 0.013 99~0.035 823、0.000 554~0.001 327。 $^{176}\text{Lu}/^{177}\text{Hf}$ 比值小于 0.002, 表明这些锆石在形成后仅具有较少的放射成因 Hf 积累, 因此, 可以用初始 $^{176}\text{Hf}/^{177}\text{Hf}$ 比值代表锆石形成时的 $^{176}\text{Hf}/^{177}\text{Hf}$ 比值(吴福元等, 2007)。锆石的 $\epsilon_{\text{Hf}}(t)$ 值为 10.3~14.6, 平均值为 13.4。 $f_{\text{Lu}/\text{Hf}}$ 值介于 -0.98~-0.96, 明显小于镁铁质地壳的 $f_{\text{Lu}/\text{Hf}}$ (-0.34, Amelin et al., 2000) 和硅铝质地壳的 $f_{\text{Lu}/\text{Hf}}$ (-0.72, Vervoort et al., 1996), 故二阶段模式年龄更能反映其源区物质从亏损地幔被抽取的时间(第五春荣等, 2007), 锆石 Hf 同位素二阶段模式年龄 t_{DM2} 为 523~799 Ma, 平均值为 601 Ma(表 3)。

5 讨论

5.1 构造背景

古亚洲洋产生于罗迪尼亚大陆裂解时期, 长期存在于东欧-西伯利亚陆块与塔里木-华北陆块之间的一个东西向古大洋, 现今记录在西伯利亚板块南缘、东欧地台东南缘以及中亚造山带内(李三忠等, 2016)。古亚洲洋大约在 1000 Ma 前开始张开, 大规模扩张在 700~600 Ma, 在经历过若干微板块之间、微板块与南北大陆之间的碰撞之后, 直至二叠纪最终闭合(徐备等, 1997; Wu et al., 1998; 洪大卫等, 2003; 孙德友等, 2004; Li, 2006; 李锦轶等, 2007; Cao et al., 2013; Chen et al., 2016)。西伯利亚板块南缘近东西向展布的大型高压变质带中蓝片岩代表的洋盆于 650~520 Ma 开始俯冲(张兴洲等, 1992; 徐公愉, 1993; 李三忠等 2016)。石玉若等(2014)研究表明, 内蒙古中部地区(温都尔庙-西拉木伦、锡林浩特地区)不仅存在早奥陶世蛇绿岩, 而且存在该时期的俯冲消减事件, 反映奥陶纪古亚洲洋洋盆在这一区域仍较活跃, 存在双向俯冲作用。Ge 等(2005; 2007) 在大兴安岭北部发现了早古生代辉长岩(LA-ICP-MS 锆石 U-Pb 年龄为 480~494 Ma)和花岗

表 3 多宝山矿床花岗闪长斑岩锆石 Hf 同位素数据

Table 3 Zircon Hf isotopic compositions of the granodiorite porphyry from the Duobaoshan deposit

测点号	年龄/Ma	$^{176}\text{Yb}/^{177}\text{Hf}$	2σ	$^{176}\text{Lu}/^{177}\text{Hf}$	2σ	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	$(^{176}\text{Hf}/^{177}\text{Hf})_t$	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	t_{DM}/Ma	t_{DM2}/Ma	$f_{\text{Lu/Hf}}$
Hd3-16.1	476.9	0.028246	0.000944	0.001019	0.000032	0.282867	0.000013	0.282858	3.4	13.6	545	586	-0.97
Hd3-16.2	473.2	0.021183	0.000255	0.000790	0.000007	0.282892	0.000014	0.282885	4.3	14.5	507	527	-0.98
Hd3-16.3	477.3	0.035823	0.000313	0.001326	0.000009	0.282898	0.000013	0.282886	4.5	14.6	506	523	-0.96
Hd3-16.4	476.3	0.033123	0.000364	0.001197	0.000012	0.282882	0.000015	0.282871	3.9	14.1	527	557	-0.96
Hd3-16.5	478.3	0.035389	0.000920	0.001327	0.000038	0.282776	0.000016	0.282764	0.1	10.3	681	799	-0.96
Hd3-16.6	473.8	0.025940	0.000801	0.000988	0.000032	0.282843	0.000015	0.282835	2.5	12.7	579	642	-0.97
Hd3-16.7	470.3	0.013990	0.000059	0.000554	0.000004	0.282847	0.000015	0.282842	2.6	12.9	568	628	-0.98
Hd3-16.8	474.4	0.018262	0.000330	0.000693	0.000008	0.282863	0.000018	0.282857	3.2	13.5	547	592	-0.98
Hd3-16.9	474.4	0.019364	0.000265	0.000755	0.000008	0.282869	0.000017	0.282862	3.4	13.7	539	579	-0.98
Hd3-16.10	476.2	0.022431	0.000470	0.000866	0.000020	0.282867	0.000017	0.282859	3.3	13.6	544	586	-0.97
Hd3-16.11	477.6	0.023301	0.000280	0.000878	0.000007	0.282861	0.000015	0.282853	3.2	13.5	552	597	-0.97

注: $\epsilon_{\text{Hf}}(0) = 10000 \times [(^{176}\text{Hf}/^{177}\text{Hf})_s / (^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} - 1]$; $\epsilon_{\text{Hf}}(t) = 10000 \times [(^{176}\text{Hf}/^{177}\text{Hf})_s - (^{176}\text{Lu}/^{177}\text{Hf})_s \times (e^{\lambda t} - 1)] / [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} \times (e^{\lambda t} - 1)] - 1$; $t_{\text{DM}} = 1/\lambda \times \ln [1 + [(^{176}\text{Hf}/^{177}\text{Hf})_s - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}] / [(^{176}\text{Lu}/^{177}\text{Hf})_s - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}]]$; $t_{\text{DM2}} = t_{\text{DM}} - (t_{\text{DM}} - t) \times [(f_{\text{ce}} - f_s) / (f_{\text{ce}} - f_{\text{DM}})]$; $f_{\text{Lu/Hf}} = (^{176}\text{Lu}/^{177}\text{Hf})_s / ((^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} - 1)$; $(^{176}\text{Hf}/^{177}\text{Hf})_t = (^{176}\text{Hf}/^{177}\text{Hf})_s - (^{176}\text{Lu}/^{177}\text{Hf})_s \times (e^{\lambda t} - 1)$, 其中, $\lambda = 1.867 \times 10^{-11}/\text{a}$ (Soderlund et al., 2004); $(^{176}\text{Lu}/^{177}\text{Hf})_s$ 和 $(^{176}\text{Hf}/^{177}\text{Hf})_s$ 为样品测量值; $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} = 0.0332$, $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}} = 0.282772$; $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} = 0.0384$; $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}} = 0.28325$ (Blichert-Toft et al., 1997; Griffin et al., 2000); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{平均地壳}} = 0.015$; $f_{\text{ce}} = [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{平均地壳}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}] - 1$; t 为锆石结晶年龄。

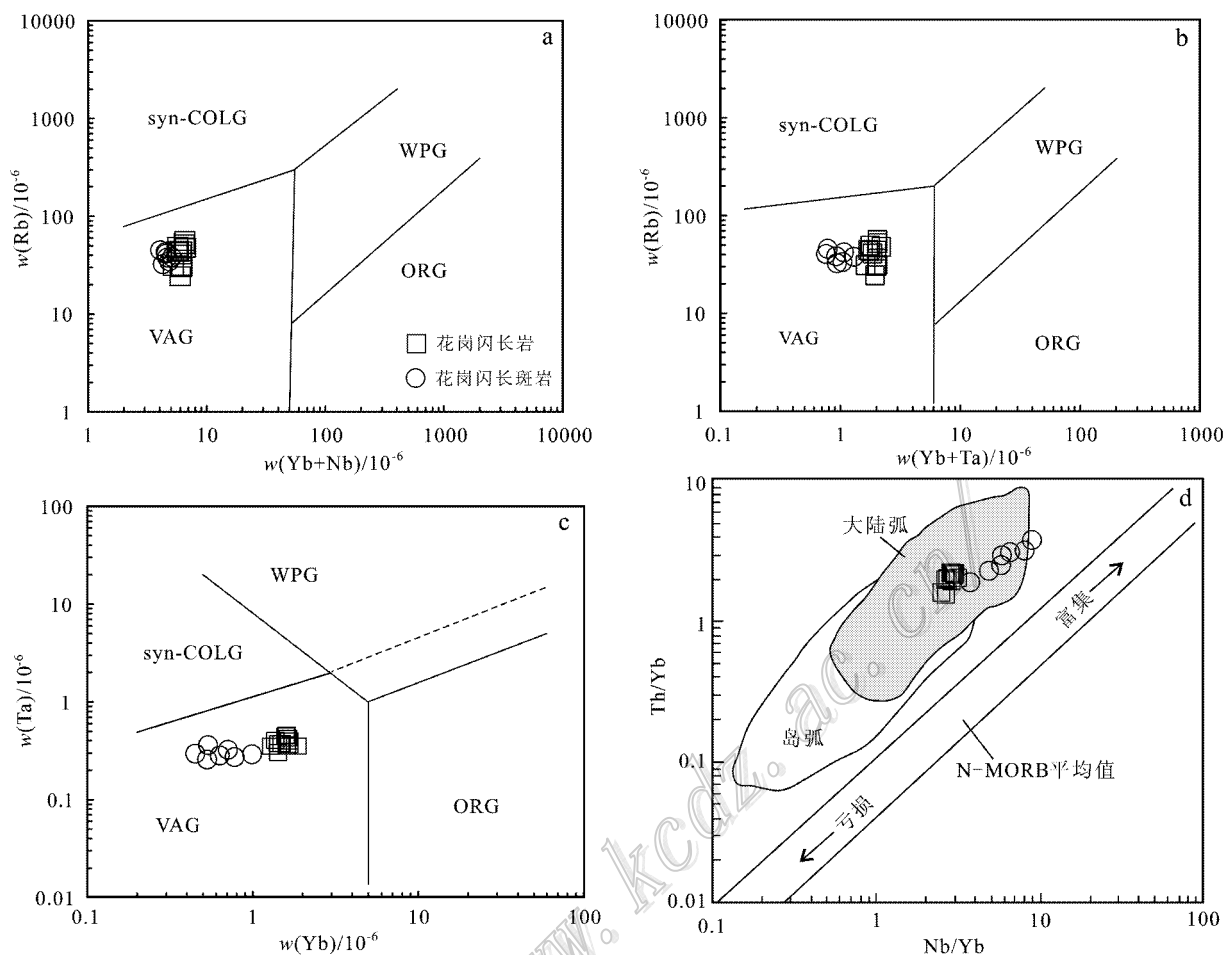


图 8 多宝山矿床构造环境判别图解(花岗闪长岩数据引自 Wu et al., 2015)

a. (Yb+Nb)-Rb 关系图(底图据 Pearce et al., 1984); b. (Yb+Ta)-Rb 关系图(底图据 Pearce et al., 1984); c. Yb-Ta 关系图(底图据 Pearce et al., 1984); d. Nb/Yb-Th/Yb 关系图(底图据 Pearce et al., 1995)

VAG—火山弧花岗岩; syn-COLG—同碰撞花岗岩; ORG—洋脊花岗岩; WPG—板内花岗岩

Fig. 8 Tectonic discrimination diagrams of the Duobaoshan deposit (Data of granodiorite after Wu et al., 2015)

a. (Yb+Nb)-Rb diagram (after Pearce et al., 1984); b. (Yb+Ta)-Rb diagram (after Pearce et al., 1984); c. Yb-Ta diagram (after Pearce et al., 1984); d. Nb/Yb-Th/Yb diagram (after Pearce and Peate, 1995)

VAG—Volcanic arc granites; syn-COLG—Syn-collisional granites; ORG—Oceanic ridge granites; WPG—Within plate granites

闪长岩(SHRIMP 锆石 U-Pb 年龄为 (485 ± 8) Ma), 认为古生代区域上发生了从俯冲消减到碰撞后阶段的演化过程, 而施光海等(2003)、Pei 等(2007)和 Miao 等(2007)在一些深变质杂岩中也发现了早古生代岩浆锆石。余宏全等(2012)对大兴安岭中北段岩浆岩的锆石 U-Pb 年龄进行了统计, 认为该地区在古生代期间经历了古陆块间的俯冲、拉张、拼贴碰撞的构造演化历史。综上所述, 晚寒武世—奥陶纪期间, 古亚洲洋在中亚造山带东段地区存在强烈的与俯冲作用有关的岩浆活动。

多宝山花岗闪长斑岩体位于中亚造山带东段, 结晶年龄为 474.9 Ma, 岩石富集大离子亲石元素(如 Rb、K、Ba 和 Sr), 稀土元素呈现右倾斜式模型,

相对亏损高场强元素(如 Ti、Nb 和 Ta), 显示出较高的 La/Nb ($2.09 \sim 2.75$)、 Ba/Nb ($113.32 \sim 145.66$)、 Ba/La ($47.52 \sim 65.73$)、 Ba/Th ($256.68 \sim 318.18$)、 Zr/Nb ($17.51 \sim 23.75$) 比值和低的 Th/Yb ($1.85 \sim 3.91$) 比值、低的 $w(TiO_2)$ ($< 1\%$), 具有俯冲环境下岩浆岩的地球化学特征 (Kelemen et al., 1990; Hawkesworth et al., 1991; Woodhead et al., 1993; Pearce et al., 1999; Stern, 2002; Zhou et al., 2004), Ti、Nb、Ta 的负异常及 HREE 亏损暗示着岩浆源区有钛铁矿、金红石、榍石、石榴子石等矿物的残留 (Green et al., 1986)。在 (Yb+Nb)-Rb、(Yb+Ta)-Rb 和 Yb-Ta 图解(图 8a~c) 中, 多宝山花岗闪长岩和花岗闪长斑岩样品均落入火山弧花岗岩区

域,在 Nb/Yb-Th/Yb 图解(图 8d)中,样品落入大陆弧区域。综合区域构造-岩浆演化资料,多宝山花岗闪长斑岩可能形成于大陆边缘弧环境。

5.2 岩石成因及源区

埃达克岩是 Defant 等(1990)研究阿留申群岛新生代俯冲洋壳熔融产生的火山岩时提出来的术语,用于概括具有特定地球化学性质的一套中酸性火山岩和侵入岩组合,包括安山岩、英安岩、安粗岩、石英闪长岩、花岗闪长岩、石英二长岩、英云闪长岩和斜长花岗岩等,其地球化学标志是 $w(\text{SiO}_2) \geq 56\%$, $w(\text{Al}_2\text{O}_3) \geq 15\%$, $w(\text{MgO}) < 3\%$, $w(\text{Na}_2\text{O})/w(\text{K}_2\text{O}) > 2.4$, $w(\text{Y})$ 和重稀土元素(HREE)含量低($w(\text{Yb}) \leq 1.9 \times 10^{-6}$, $w(\text{Y}) \leq 18 \times 10^{-6}$),高 $w(\text{Sr})$ (多大于 400×10^{-6}),一般具有正铕异常(少数具有极弱负铕异常)。然而,具有上述地球化学特征、与俯冲洋壳熔融无关的岩石通常被称为“埃达克质(adakitic)岩”(Castillo, 2006; 2012)。多宝山花岗闪长岩体具有高 $w(\text{SiO}_2)$ (62.54% ~ 65.24%)、 $w(\text{Al}_2\text{O}_3)$ (16.22% ~ 17.43%) 和 $w(\text{Sr})$ (542×10^{-6} ~ 807×10^{-6})、低 $w(\text{Yb})$ (1.29×10^{-6} ~ 1.86×10^{-6}) 和 $w(\text{Y})$ (10.6×10^{-6} ~ 14.4×10^{-6}) 含量、正铕异常或弱负铕异常,显示出埃达克质岩石的特征(Wu et al., 2015)。Wu 等(2015)对多宝山花岗闪长岩体开展了详细的主微量元素及 Sr-Nd-Hf 同位素地球化学研究,认为花岗闪长岩体形成于增厚下地壳的部分熔融过程,来源于亏损地幔新增生的年轻地壳物质。一般认为由地幔熔融产生高 SiO_2 含量的花岗质岩浆是十分困难和有限的,具有正 $\epsilon_{\text{Hf}}(t)$ 值的花岗质岩石一般来自亏损地幔或从亏损地幔中新增生的年轻地壳物质的部分熔融(孙德有等, 2005; 隋振民等, 2007)。多宝山花岗闪长斑岩体具有较高的 Hf 同位素组成($\epsilon_{\text{Hf}}(t) = 10.3 \sim 14.6$),锆石 Hf 同位素二阶段模式年龄 t_{DM2} 为 523 ~ 799 Ma (平均值 601 Ma),揭示其源区可能为新元古代期间从亏损地幔新增生的年轻下地壳(图 9)。多宝山花岗闪长斑岩体侵位于大规模分布的花岗闪长岩体内,虽然不显示埃达克质岩石的地球化学特征,但其与花岗闪长岩体侵位时间接近并拥有相似的微量、稀土元素配分模式和 Hf 同位素组成(图 7,图 9),而且它们的主量元素随着 SiO_2 含量的递增表现出明显的线性变化趋势(图 10),因此,笔者认为这两期岩体可能是同源岩浆不同演化阶段的产物。

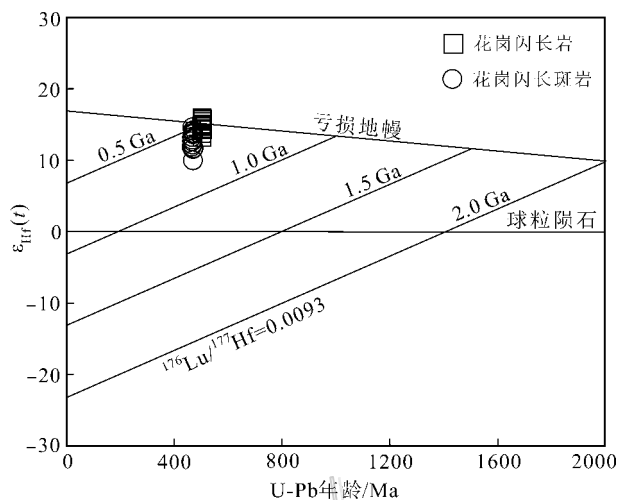


图 9 多宝山矿床花岗闪长斑岩锆石 $\epsilon_{\text{Hf}}(t)$ 与 U-Pb 年龄图解

花岗闪长岩数据引自 Wu et al., 2015

Fig. 9 Plot of $\epsilon_{\text{Hf}}(t)$ versus U-Pb ages for the granodiorite porphyry from the Duobaoshan deposit

Data of granodiorite after Wu et al., 2015

一种可能的成岩机制是“早奥陶世期间,古亚洲洋板块以缓倾角向西伯利亚大陆俯冲,这种缓俯冲消减过程会引起大规模地壳缩短加厚,使得脱水消减板片上的楔状地幔变冷而缺乏流动性,限制了地幔楔的部分熔融规模和流体溢出(Kay et al., 2001)。

从这种地幔产生的基性熔体底侵于加厚下地壳底部,必然使下地壳越来越富水并发生部分熔融作用,早阶段分异结晶出多宝山埃达克质花岗闪长岩体,晚阶段演化出多宝山花岗闪长斑岩体。这种在加厚陆壳条件下新生的水化基性下地壳的部分熔融机制,与秘鲁西北部高安第斯带著名的 Cordillera Blanca 花岗质岩基岩石成因相似(Atherton et al., 1993; Petford et al., 1992; 1996a; 1996b; 2001; 刘红涛等, 2004),同时,与 Kay 及其同事对智利中部新生代消减区埃达克岩浆的成因解释十分接近(Kay et al., 2001; 2002)。

6 结 论

多宝山矿床花岗闪长斑岩的 LA-ICP-MS 锆石 U-Pb 年龄为 $(474.9 \pm 1.8) \text{ Ma}$,形成于早奥陶世。岩石具有高 SiO_2 (70.73% ~ 73.45%) 和 Al_2O_3

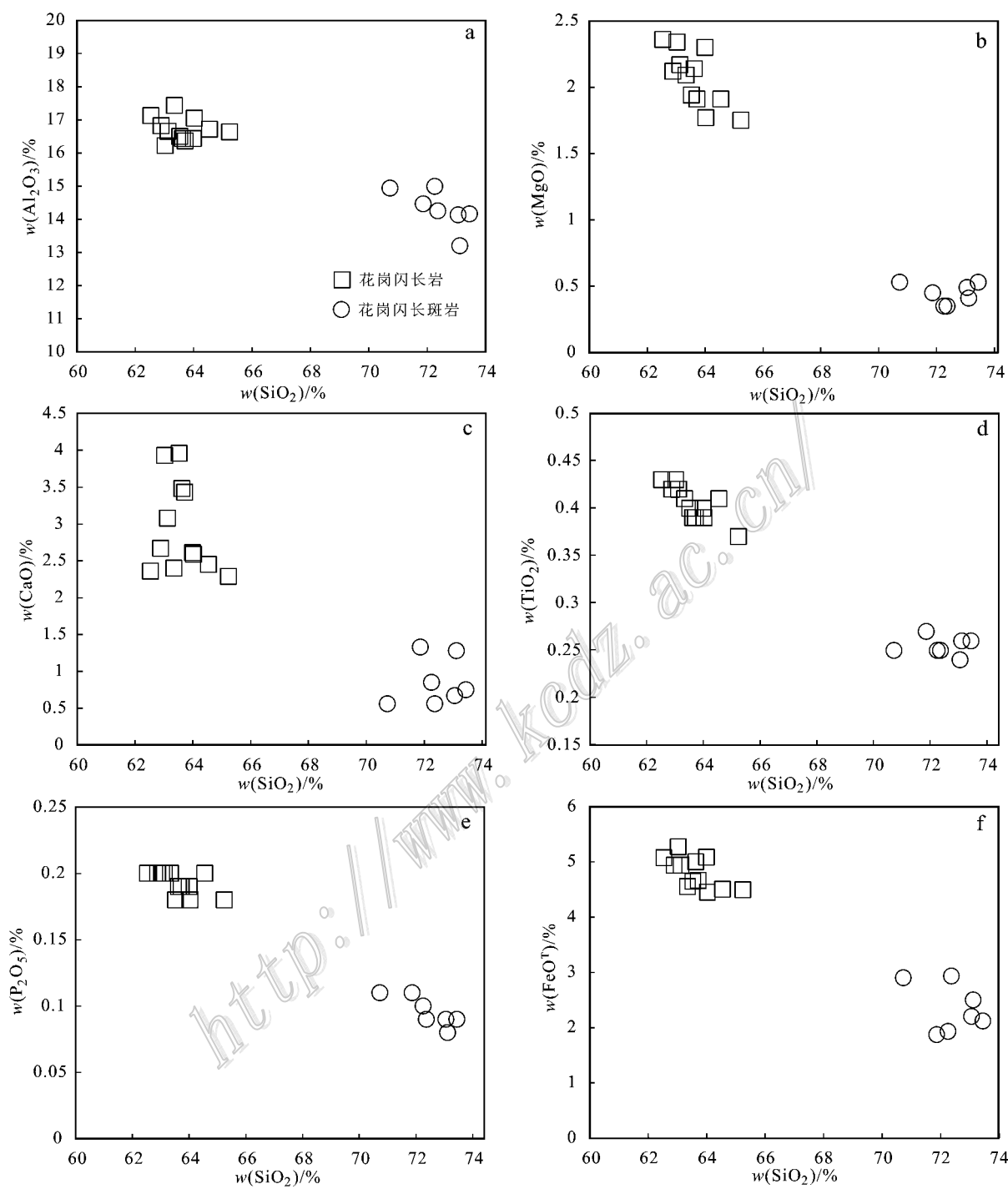


图 10 多宝山矿床 SiO_2 -氧化物变异图(花岗闪长岩数据引自 Wu et al. ,2015)

Fig. 10 Variation diagrams of SiO_2 -oxides of the Duobaoshan deposit (Data of granodiorite after Wu et al. ,2015)

(13.20%~14.99%)含量,轻稀土元素富集,重稀土元素亏损,具有较高的 La/Nb (2.09~2.75)、 Ba/Nb (113.32~145.66)、 Ba/La (47.52~65.73)、 Ba/Th (256.68~318.18)、 Zr/Nb (17.51~23.75)比值和低的 Th/Yb (1.85~3.91)比值、低的 TiO_2 ($<1\%$)含量,显示出俯冲环境下岩浆岩的地球化学特征。花岗闪长斑岩形成于大陆边缘弧环境,来源于加厚陆壳条件下亏损地幔新增生的年轻地壳物质的部分熔

融。

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