

郭志军, 李进文, 黄光杰, 等. 内蒙古红花尔基白钨矿矿床赋矿花岗岩Sr-Nd-Pb-Hf同位素特征[J]. 中国地质, 2014, 41(4): 1226-1241.
Guo Zhijun, Li Jinwen, Huang Guangjie, et al. Sr-Nd-Pb-Hf isotopic characteristics of ore-bearing granites in the Honghuaerji scheelite deposit, Inner Mongolia[J]. Geology in China, 2014, 41(4): 1226-1241(in Chinese with English abstract).

内蒙古红花尔基白钨矿矿床赋矿 花岗岩Sr-Nd-Pb-Hf同位素特征

郭志军^{1,2} 李进文¹ 黄光杰³ 关继东⁴
董旭舟⁵ 田京^{1,5} 杨郟城¹ 余宏全¹ 向安平¹ 康永建¹

(1. 中国地质科学院矿产资源研究所 国土资源部成矿作用与资源评价重点实验室, 北京 100037; 2. 北京矿冶研究总院 矿物加工科学与技术国家重点实验室, 北京 100160; 3. 内蒙古地质勘查有限公司, 内蒙古 呼和浩特 010020; 4. 内蒙古自治区第六地质矿产勘查开发院, 内蒙古 海拉尔 021008; 5. 中国地质大学(北京) 地球科学与资源学院, 北京 100083)

摘要:对内蒙古红花尔基白钨矿矿床的赋矿花岗岩进行了全岩Sr、Nd同位素、钾长石Pb同位素以及LA-MC-ICP-MS锆石Hf同位素特征研究。结果表明,从肉红色二长花岗岩、灰白色二长花岗岩到石英二长岩,它们的(⁸⁷Sr/⁸⁶Sr)_t值依次降低,均值分别为0.70525、0.70517和0.70482,ε_{Nd}(t)值则依次增加,均值分别为+2.2、+2.3和+3.1。2种二长花岗岩的钾长石Pb同位素值较均一,其中²⁰⁶Pb/²⁰⁴Pb为18.258~18.276, ²⁰⁷Pb/²⁰⁴Pb为15.507~15.512; ²⁰⁸Pb/²⁰⁴Pb为37.994~38.018。3种花岗岩的锆石Hf同位素特征显示ε_{Hf}(t)值分别为+5.2~+10.4(均值+8.1)、+3.1~+9.8(均值+7.5)、+5.8~+14.4(均值+9.2)。赋矿花岗岩的Sr-Nd-Pb-Hf同位素特征指示其源岩物质很可能是以新元古代起源于亏损地幔的下地壳物质为主,石英二长岩可能是岩浆混合了少量地幔物质形成的包体。区域构造分析表明,红花尔基白钨矿矿床赋矿花岗岩岩浆源区的形成可能与新元古代古亚洲洋演化过程中俯冲大洋板块与上地幔的相互作用有关;早侏罗世,蒙古-鄂霍次克洋盆在本区闭合后,板块碰撞隆起的挤压环境触发了源岩物质的部分熔融,从而形成了赋矿花岗岩。

关键词:红花尔基;白钨矿矿床;花岗岩;锆石Hf同位素;Sr-Nd-Pb同位素;古亚洲洋;蒙古-鄂霍次克洋;上地幔
中图分类号:P597.1 **文献标志码:**A **文章编号:**1000-3657(2014)04-1226-16

大兴安岭中北段地区位于兴蒙造山带东段,其构造背景十分复杂,相继经历了前中生代古亚洲洋构造体系演化、中生代蒙古-鄂霍次克构造体系以及环太平洋构造体系的叠加作用^[1,2],形成了本区巨大的北东向和北北东向岩浆岩带,同时也形成了区域广泛分布的内生金属成矿带。近年来,随着找矿投入的增加,本区找矿工作取得重要进展,在呼伦贝尔市红花

尔基镇以北2 km处发现了红花尔基白钨矿矿床。该矿床为区域上发现的首例钨矿床,对其进行研究对区域未来可能发现的钨矿床具有示范意义。研究表明,燕山早期早侏罗世赋矿花岗岩体(I型花岗岩类)是矿床形成的重要热源和物质供给源,为成矿母岩,但是对于赋矿花岗岩体的来源问题的研究却涉及较少。同位素是判断地质体物质来源的重要手段之一,对赋

收稿日期:2014-05-19; 改回日期:2014-06-19

基金项目:科技部973项目(2013CB428805)及中国地质调查局地质调查项目(1212011085260、科[2013]01-042-003)联合资助。

作者简介:郭志军,男,1988年生,硕士,矿物学、岩石学、矿床学专业,主要从事矿床学及工艺矿物学研究;E-mail: GHN_07@163.com。

通讯作者:李进文,男,1964年生,研究员,矿产普查与勘探专业,主要从事矿床学及矿产勘查学研究;E-mail: lijinwen958@sohu.com。

矿花岗岩体的同位素组成特征研究可以揭示花岗岩体的成岩物质来源、构造环境特征等。赋矿花岗岩的锆石U-Pb年龄测定表明,肉红色二长花岗岩、灰白色二长花岗岩和石英二长岩分别形成于(179.2±0.5) Ma、(179.0±0.6) Ma和(178.6±0.7) Ma(笔者另文发表)。本文在已取得花岗岩年龄的基础上,对赋矿花岗岩体进行了详细的全岩Sr、Nd同位素、钾长石Pb同位素以及锆石Hf同位素特征研究,来探讨花岗岩的来源、演化等相关问题。

1 区域地质与矿床地质

区域前中生代属于西伯利亚古板块大陆边缘向南增生的环境,中生代则主要受蒙古-鄂霍茨克洋盆向南俯冲以及太平洋板块向西俯冲作用影响,构造-岩浆作用复杂^[3]。区域地层主要出露有下元古界兴华渡口群,奥陶系下一中统多宝山组、中一上统裸河组,泥盆系下一中统泥鳅河组、中一上统大民山组,石炭系下统红水泉组、莫尔根河组,侏罗系上统满克头鄂博组、玛尼吐组和白音高老组,白垩系下统梅勒图组以及第四系。区域构造发育,断裂构造走向以北东向为主,次为北西向,与大兴安岭地区的整体构造线方向基本一致^[4],褶皱走向以北西向为主。区域早古生代岩浆作用以海相喷发活动为主,晚古生代则以岩浆侵入活动为主,形成中酸性侵入岩体;中生代岩浆活动非常频繁,早一中侏罗世以花岗岩侵入岩为主,中一晚侏罗世一早白垩世则以陆相火山-次火山活动为主。

矿区出露地层为奥陶系裸河组(O₂₋₃lh)变质粉砂岩和第四系风成砂(图1-b)。断裂构造主要是北东向和北西向两组,侵入岩主要是二长花岗岩和石英二长岩。赋矿围岩主要为二长花岗岩,侵入奥陶系裸河组地层中。花岗岩体从下至上岩性略有变化:下部为肉红色二长花岗岩,其上为灰白色二长花岗岩,石英二长岩在上述两种花岗岩中以椭圆状或不规则状包体形式存在(图1-c,图中石英二长岩分布位置和大小仅为示意图),界线截然。石英二长岩包体大小不一,小的直径约几cm,大者直径可达50cm左右,大多集中在10~20cm。

2 样品采集及其岩相学特征

本次研究选取了肉红色二长花岗岩3件、灰白

色二长花岗岩2件以及石英二长岩2件样品进行Sr、Nd全岩同位素分析;从2件肉红色二长花岗岩和3件灰白色二长花岗岩中选取钾长石进行Pb同位素测试;同时选取3种花岗岩各1件进行LA-MC-ICP-MS锆石Hf同位素测试(采样位置见图1-b和表1)。

肉红色二长花岗岩,似斑状、中-粗粒花岗结构,块状构造,主要矿物为石英(25%~35%,1~4mm)、钾长石(25%~35%,1~5mm)、条纹长石(5%~18%)和斜长石(20%~25%,1~5mm)等,次要矿物为黑云母(4%~6%,0.1~0.6mm),副矿物为磷灰石、榍石和锆石等。斜长石晶体可见环带构造,主要发育绢云母化、碳酸盐化,且环带中心部位蚀变较强,而边缘蚀变相对较弱。灰白色二长花岗岩,似斑状、中-细粒花岗结构,块状构造,主要矿物为石英(25%~30%,0.4~1.2mm)、钾长石(20%~30%,0.5~1.5mm)、条纹长石(5%~15%)、斜长石(25%~30%,0.2~1.6mm)等,次要矿物为黑云母(4%~5%,0.1~0.4mm),副矿物为磷灰石、榍石、锆石等。石英二长岩具二长结构,块状构造,主要矿物有石英(15%~25%,0.4~3mm)、钾长石(20%~25%,0.3~2mm)和斜长石(35%~40%,0.1~1mm)等,次要矿物为黑云母(4%~7%,0.05~0.1mm),副矿物为磷灰石和锆石等。石英二长岩最大的特点是长石和黑云母均具长宽比较大(约8:1~20:1)的长板状,甚至呈针状,呈一定半定向特征包裹在石英或钾长石中或切穿二者的颗粒边缘。石英二长岩较前两者可见较多的磷灰石等副矿物。

从3种赋矿花岗岩的岩石学特征可以看出:①肉红色二长花岗岩和灰白色二长花岗岩除颜色明显不同外,其他岩石学特征差别较小;②与肉红色和灰白色二长花岗岩相比,石英二长岩含较多针状磷灰石副矿物,且长板状或针状的长石类矿物和黑云母被包裹在石英和长石巨晶中或将其切穿(图2)。

3 分析测试方法

全岩Rb-Sr、Sm-Nd同位素测试在国土资源部天津地质矿产研究所同位素实验室的TRITON热电离质谱仪上完成,设备型号为08-100016sb,检测环境温度18℃,湿度20%。含量测定和同位素比值测定均由Triton热电离质谱承担,用平行双灯丝构件

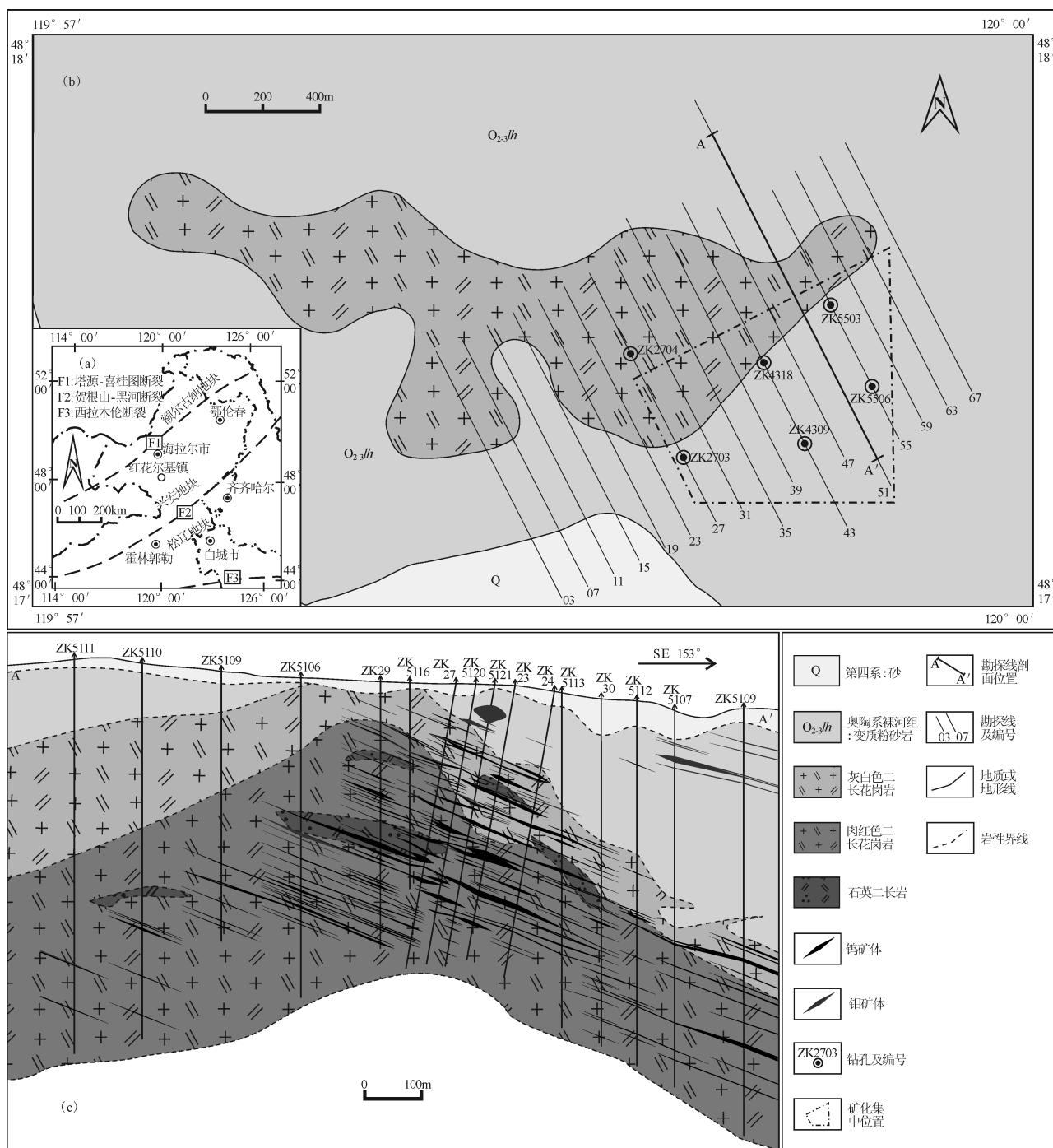


图1 红花尔基白钨矿矿床大地构造位置图(a)^[3]、基岩地质简图(b)和勘探线剖面A—A'图(c)

(图b、c据资料①修改)

Fig.1 Tectonic position (a), schematic geological map (b) and NW-SE cross section (c) of the Honghuaerji scheelite deposit (Fig. a after [3]; Fig.b and c after reference①)

① 内蒙古第六地质矿产勘查开发有限责任公司. 内蒙古自治区鄂温克自治旗红花尔基矿区钨矿详查报告. 2013.

表1 红花尔基白钨矿矿床Sr-Nd-Pb-Hf同位素测试采样位置
Table 1 Sampling positions for Sr-Nd-Pb-Hf isotope test in the Honghuaerji sheelite deposit

样号	岩性	测试项目	采样位置
HH4309-157	肉红色二长花岗岩	Sr-Nd-Pb-Hf 同位素	ZK4309 的 820~1168 m 之间的 1070 m 处
HH4309-158		Sr-Nd 同位素	ZK4309 的 970 m 处
HH5503-32		Sr-Nd 同位素	ZK5503 的 440 m 处
HH4309-144		Pb 同位素	ZK4309 的 620 m 处
HH2704-12	灰白色二长花岗岩	Sr-Nd-Pb-Hf 同位素	ZK2704 的 63~163 m 之间和 99 m 处
HH4318-01		Sr-Nd 同位素	ZK4318 的 96 m 处
HH5506-50		Pb 同位素	ZK5506 的 387 m 处
HH4318-03		Pb 同位素	ZK4318 的 182 m 处
HH5503-01	石英二长岩	Sr-Nd-Hf 同位素	ZK5503 的 64~333 m 之间和 112 m 处
HH4309-146		Sr-Nd 同位素	ZK4309 的 662 m 处

的离子源测 Sm、Nd。Sr 的质谱标准样 NBS987 Sr 的结果为 $^{87}\text{Sr}/^{86}\text{Sr} = 0.710253 \pm 6$; J.M.CNd 质谱标准样的结果为 $^{143}\text{Nd}/^{144}\text{Nd} = 0.511132 \pm 5$ 。 $^{87}\text{Sr}/^{86}\text{Sr}$ 用 $^{88}\text{Sr}/^{86}\text{Sr} = 8.37521$ 、 $^{143}\text{Nd}/^{144}\text{Nd}$ 用 $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ 标准化。详细分析流程和方法见文献[5]。

锆石 Lu-Hf 同位素测试同样在国土资源部天津地质矿产研究所同位素实验室完成,采用配有 193 nm 的 LA-MC-ICP-MS 仪器进行分析,分析时采用 8~10 Hz 的激光频率、100 mJ 的激光强度和 50 μm 的激光束斑直径。激光剥蚀物质以氦为载气送入 Neptune,采用 GJ-1 作为监控标样,具体测试过程见文献[6]。为使 Hf 同位素分析与锆石 U-Pb 年龄分析相对应,锆石 Hf 同位素的分析点与锆石 U-Pb 年龄分析点位于同一颗锆石晶体内部。可以认为所分析的 Hf 同位素和 U-Pb 年龄是基本对应的。所以在计算 Hf 同位素的相关参数时,采用的是同一颗粒锆石所测得的 U-Pb 年龄。计算 ^{176}Lu 的衰变常数采用 $1.867 \times 10^{-11}/\text{a}$ [7]。球粒陨石的 $^{176}\text{Lu}/^{177}\text{Hf}$ 和 $^{176}\text{Hf}/^{177}\text{Hf}$ 的比值分别为 0.0332 和 0.282772^[8],亏损地幔的 $^{176}\text{Lu}/^{177}\text{Hf}$ 和 $^{176}\text{Hf}/^{177}\text{Hf}$ 的比值分别为 0.0384 和 0.28325^[9], $^{176}\text{Lu}/^{177}\text{Hf}$ 平均地壳为 0.015^[10]。

钾长石 Pb 同位素测试在核工业北京地质研究所完成,测试仪器型号为 ISOPROBE-T 热电离质谱仪,测试方法和依据参照 GB/T 17672-1999《岩石中铅、铋、钷同位素测定方法》,实验过程中温度为 20℃,相对湿度 50%,同位素比值误差以 2σ 计。

3 分析结果

3.1 Rb-Sr、Sm-Nd 同位素特征

从 3 种花岗岩全岩 Rb-Sr、Sm-Nd 同位素测试结果及特征值(表 2)可以看出:肉红色二长花岗岩、灰白色二长花岗岩、石英二长岩的($^{87}\text{Sr}/^{86}\text{Sr}$)_t 值依次降低,均值分别为 0.70525、0.70517 和 0.70482,接近现代大洋玄武岩(0.702~0.706)而小于大陆地壳(0.706~0.718)^[11,12]。三者的 $\epsilon_{\text{Nd}}(t)$ 值则依次增加,均值分别为 +2.2、+2.3 和 +3.1;对应的两阶段亏损地幔 Nd 同位素模式年龄 T_{DM} 介于 715~818 Ma(均值为 765 Ma),与中亚造山带内花岗岩类的 Nd 模式年龄(集中于 600~800 Ma)^[13,14] 相一致。在 ($^{87}\text{Sr}/^{86}\text{Sr}$)_t - $\epsilon_{\text{Nd}}(t)$ 图解(图 3-a)中,3 种花岗岩样品点均靠近亏损地幔端元,明显远离华北板块下地壳和年轻的上地壳^[15]。红花尔基花岗岩样品的 $f_{\text{Sm/Nd}}$ 值均为负值,介于 -0.46~-0.31,均值为 -0.38,说明花岗岩源区的 Sm、Nd 分馏不明显,符合计算模式年龄的条件^[16,17]。通常 $\epsilon_{\text{Nd}}(t)$ 值以 0 为界,正值代表岩浆来源于亏损地幔,负值代表来自地壳或富集地幔^[12]。3 种花岗岩的 $\epsilon_{\text{Nd}}(t)$ 均大于 0,说明源岩物质可能来自亏损地幔。

3.2 Pb 同位素特征

花岗岩中钾长石的铅同位素能代表岩体的初始铅同位素组成^[11,18],因此本文选择红花尔基矿区二长花岗岩中的钾长石作为测定铅同位素的对象。Pb 同位素组成及其特征值见表 3,可以看出铅同位

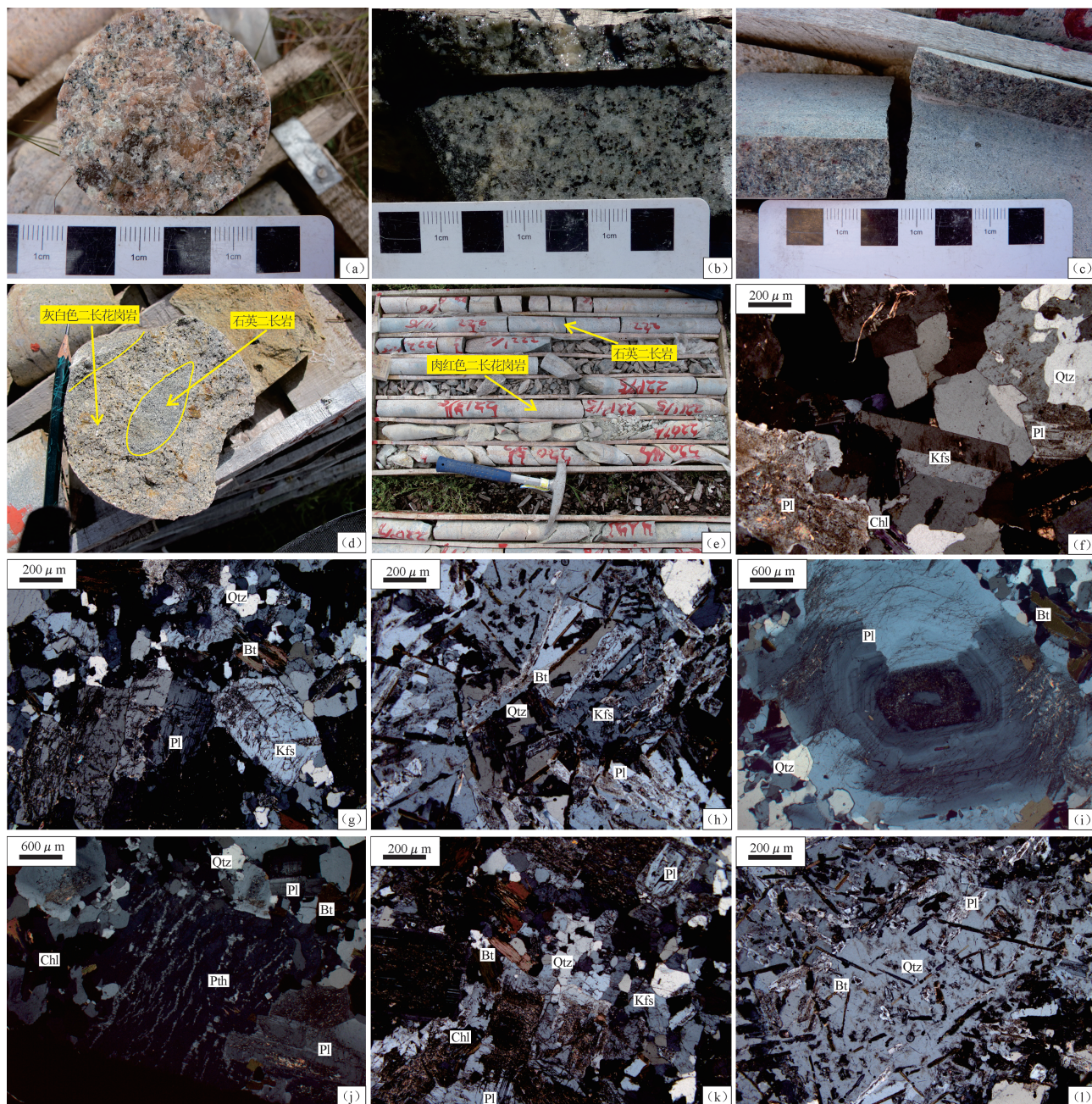


图2 红花尔基白钨矿矿床赋矿花岗岩手标本及镜下显微照片

a—肉红色二长花岗岩;b—灰白色二长花岗岩;c—石英二长岩;d—灰白色二长花岗岩中的石英二长岩包体;e—石英二长岩与肉红色二长花岗岩接触界线;f—肉红色二长花岗岩;g—灰白色二长花岗岩;h—石英二长岩;i—肉红色二长花岗岩中斜长石的环带结构;j—肉红色二长花岗岩中的钾-钠正条纹长石;k—灰白色二长花岗岩中斜长石的绢云母化;l—石英二长岩中的石英包裹有长石和黑云母;Qtz—石英;Bt—黑云母;Pl—斜长石;Pth—条纹长石;Kfs—钾长石;Chl—绿泥石

Fig.2 Photographs and photomicrographs of the three ore-bearing granites in the Honghuaerji scheelite deposit
a—Pink monzogranite; b—Gray monzogranite; c—Quartz monzonite; d—Inclusions in gray monzogranite; e—Inclusions in pink monzogranite; f—Pink monzogranite; g—Gray monzogranite; h—Quartz monzonite; i—Zoning texture of plagioclase in pink monzogranite; j—Perthite in pink monzogranite; k—Sericitization of plagioclase in gray monzogranite; l—Feldspars and biotites as inclusions in quartz from quartz monzonite; Qtz—Quartz; Bt—Biotite; Pl—Plagioclase; Pth—Perthite; Kfs—K-feldspar; Chl—Chlorite

表2 红花尔基白钨矿矿床赋矿花岗岩Rb-Sr、Sm-Nd同位素数据及特征值
Table 2 Rb-Sr and Sm-Nd isotopic data and some major parameters of ore-bearing granites in the Honghuaerji scheelite deposit

分析项目	肉红色二长花岗岩			灰白色二长花岗岩		石英二长岩	
	HH4309-157	HH4309-158	HH5503-32	HH2704-12	HH4318-01	HH5503-01	HH4309-146
Rb / 10 ⁻⁶	104	102	123	131	88	102	113
Sr / 10 ⁻⁶	224	254	153	118	206	420	367
Sm / 10 ⁻⁶	5.83	5.32	4.30	5.10	4.07	5.34	5.17
Nd / 10 ⁻⁶	29.2	27.6	19.3	23.9	18.2	29.3	29.4
⁸⁷ Rb/ ⁸⁶ Sr	1.3437	1.1657	2.3305	3.2056	1.2336	0.7029	0.8920
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.1205	0.1167	0.1349	0.1290	0.1352	0.1104	0.1064
⁸⁷ Sr/ ⁸⁶ Sr	0.708659	0.708217	0.711177	0.7133	0.708327	0.706549	0.707140
±2σ (mean)	0.000007	0.000006	0.000003	0.000003	0.000005	0.000003	0.000007
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512659	0.512648	0.512692	0.512651	0.512703	0.512694	0.512684
±2σ (mean)	0.000002	0.000003	0.000002	0.000005	0.000002	0.000004	0.000003
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.70524	0.70525	0.70525	0.70514	0.70519	0.70476	0.70487
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.51252	0.51251	0.51253	0.51250	0.51254	0.51256	0.51256
f _{Sm/Nd}	-0.39	-0.41	-0.31	-0.34	-0.31	-0.44	-0.46
ε _{Nd} (0)	+0.4	+0.2	+1.1	+0.3	+1.3	+1.1	+0.9
ε _{Nd} (t)	+2.2	+2.0	+2.5	+1.8	+2.7	+3.1	+3.0
T _{DM} /Ma	806	792	889	901	871	676	665
T _{2DM} /Ma	790	800	764	818	747	715	723

注: (⁸⁷Sr/⁸⁶Sr)_{CHUR}⁰=0.7045, (⁸⁷Rb/⁸⁶Sr)_{CHUR}⁰=0.0827, (¹⁴⁷Sm/¹⁴⁴Nd)_{CHUR}⁰=0.1967, (¹⁴³Nd/¹⁴⁴Nd)_{CHUR}⁰=0.512638;
λ_{Rb}=1.42×10⁻¹¹/a, λ_{Sm}=6.5×10⁻¹²/a, t=179 Ma。

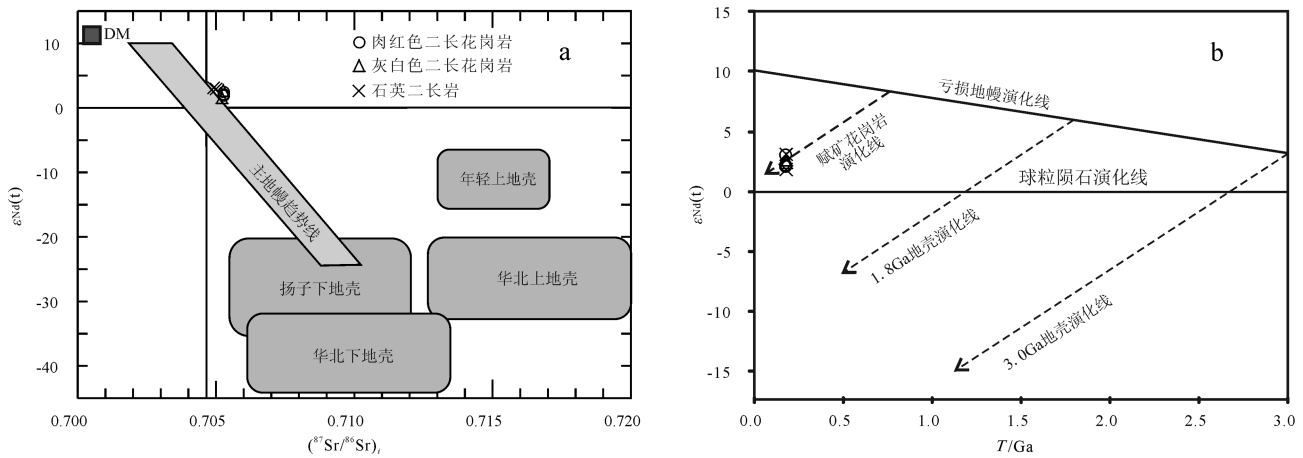


图3 红花尔基白钨矿矿床赋矿花岗岩(⁸⁷Sr/⁸⁶Sr)_i - ε_{Nd}(t)图解(a)和 ε_{Nd}(t) - T图解(b)
Fig. 3 (⁸⁷Sr/⁸⁶Sr)_i - ε_{Nd}(t) (a) and ε_{Nd}(t) - T(b) diagrams of ore-bearing granites in the Honghuaerji scheelite deposit

素值较均一,其²⁰⁶Pb/²⁰⁴Pb值变化于18.258~18.276;²⁰⁷Pb/²⁰⁴Pb值介于15.507~15.512;²⁰⁸Pb/²⁰⁴Pb值主要在37.994~38.018;μ值变化范围在9.30~9.31,ω值变化范围为34.66~34.75。在铅构造模式图(图4)上,所有样品点集中落在造山带与地幔演化线之间,并靠近地幔演化线,说明源岩物质与地幔关系密切。

3.3 Lu-Hf 同位素特征

锆石Hf同位素分析结果(表4)显示,绝大多数锆石的(¹⁷⁶Lu/¹⁷⁷Hf)_m小于0.002,表明锆石在形成以后具有较低的放射成因Hf的积累,所测样品的(¹⁷⁶Lu/¹⁷⁷Hf)_m基本可以代表其形成时体系的Hf同位素组成^[19-21]。由于锆石U-Pb定年与Hf同位素测试是在同一颗锆石上进行的,因此在Hf同位素计算过程中,一般采用单个锆石的测试年龄值,对于年龄偏离谐和线较远的

点采用该样品的加权平均年龄值。肉红色二长花岗岩(HH4309-157)样品24个分析点的(¹⁷⁶Hf/¹⁷⁷Hf)_i比值分布于0.282809~0.282953,ε_{Hf(t)}值为+5.2~+10.4,平均为+8.1,比较均一(图5-a);单阶段Hf模式年龄(T_{DM1})变化范围为626~424 Ma,两阶段Hf模式年龄(T_{DM2})变化范围也为889~562 Ma(图5-b);灰白色二长花岗岩(HH2704-12)样品24个分析点的(¹⁷⁶Hf/¹⁷⁷Hf)_i比值为0.282748~0.282937,ε_{Hf(t)}值为+3.1~+9.8,平均为+7.5,同样比较均一(图5-c),单阶段Hf模式年龄(T_{DM1})变化范围为723~453 Ma,两阶段Hf模式年龄(T_{DM2})变化范围为1028~599 Ma(图5-d);石英二长岩(HH5503-01)样品21个分析点的(¹⁷⁶Hf/¹⁷⁷Hf)_i比值为0.282823~0.283067,ε_{Hf(t)}值为+5.8~+14.4,平均为+9.2,总体分布比较分散(图

表3 红花尔基白钨矿矿床二长花岗岩中钾长石Pb同位素数据及特征值
Table 3 Pb isotopic data and some major parameters of K-feldspars selected from monzogranites in Honghuaerji scheelite deposit

样号	岩石名称	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	²⁰⁶ Pb/ ²⁰⁷ Pb	μ	ω	Th/U
HH4309-157	肉红色二长花岗岩	18.263	15.512	38.004	1.18	9.31	34.73	3.61
HH4309-144		18.276	15.507	38.015	1.18	9.30	34.66	3.61
HH2704-12	灰白色二长花岗岩	18.258	15.508	37.994	1.18	9.30	34.68	3.61
HH5506-50		18.274	15.512	38.017	1.18	9.31	34.73	3.61
HH4318-03		18.265	15.509	38.018	1.18	9.30	34.75	3.62

注: μ为现代测定的²³⁸U/²⁰⁴Pb; ω为现代测定的²³²Th/²⁰⁴Pb。

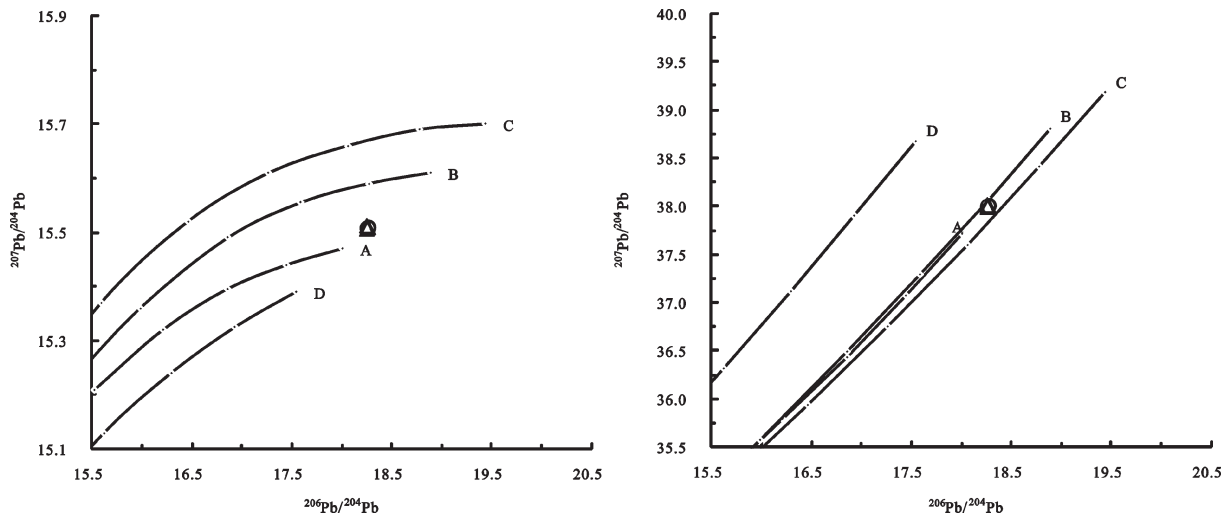


图4 红花尔基白钨矿矿床二长花岗岩钾长石Pb同位素组成图解^[19](图例同图3)

A—地幔; B—造山带; C—上地壳; D—下地壳

Fig. 4 Pb isotopic diagrams of selected K-feldspar from monzogranites in the Honghuaerji scheelite deposit (symbols as for Fig. 3)

A—Mantle; B—Orogenic; C—Upper Crust; D—Lower Crust

表4红花尔基白钨矿矿床赋矿花岗岩锆石Lu-Hf同位素数据及参数

Table 4 Lu-Hf isotopic data and some major parameters of zircons from ore-bearing granites in the Honghuaerji scheelite deposit

测点号	t/Ma	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	$(^{176}\text{Hf}/^{177}\text{Hf})_i$	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	T_{DM1}	T_{DM2}	$f_{\text{Lu-Hf}}$
HH4309-157, 肉红色二长花岗岩											
HH4309-157-1	179.66	0.052408	0.001361	0.282896	0.000013	0.282891	4.4	8.2	509	702	-0.96
HH4309-157-2	178.78	0.039437	0.001058	0.282868	0.000014	0.282864	3.4	7.2	545	763	-0.97
HH4309-157-3	179.46	0.064328	0.001658	0.282912	0.000013	0.282906	5.0	8.7	490	668	-0.95
HH4309-157-4	179.18	0.079820	0.002062	0.282948	0.000016	0.282941	6.2	9.9	443	589	-0.94
HH4309-157-5	179.56	0.067523	0.001757	0.282959	0.000015	0.282953	6.6	10.4	424	562	-0.95
HH4309-157-6	180.56	0.056515	0.001374	0.282844	0.000017	0.282839	2.5	6.3	584	819	-0.96
HH4309-157-7	179.18	0.049724	0.001238	0.282906	0.000016	0.282902	4.7	8.5	494	678	-0.96
HH4309-157-8	178.96	0.101719	0.002596	0.282946	0.000020	0.282937	6.2	9.8	453	598	-0.92
HH4309-157-9	179.89	0.055840	0.001390	0.282860	0.000013	0.282855	3.1	6.9	561	783	-0.96
HH4309-157-10	179.51	0.056137	0.001397	0.282815	0.000018	0.282810	1.5	5.3	626	886	-0.96
HH4309-157-11	178.64	0.052593	0.001356	0.282936	0.000016	0.282931	5.8	9.6	452	612	-0.96
HH4309-157-12	178.18	0.057389	0.001496	0.282918	0.000014	0.282913	5.2	8.9	480	654	-0.95
HH4309-157-13	179.18	0.074204	0.001999	0.282915	0.000017	0.282908	5.1	8.8	491	664	-0.94
HH4309-157-14	176.75	0.046448	0.001270	0.282821	0.000015	0.282817	1.7	5.5	615	873	-0.96
HH4309-157-15	179.22	0.061576	0.001795	0.282863	0.000014	0.282857	3.2	6.9	563	780	-0.95
HH4309-157-16	180.64	0.075344	0.002053	0.282838	0.000033	0.282831	2.3	6.1	604	838	-0.94
HH4309-157-17	180.41	0.067616	0.001817	0.282951	0.000013	0.282945	6.3	10.1	436	580	-0.95
HH4309-157-18	180.79	0.062192	0.001682	0.282912	0.000014	0.282906	5.0	8.7	491	667	-0.95
HH4309-157-19	180.94	0.069127	0.001750	0.282909	0.000014	0.282903	4.8	8.6	496	674	-0.95
HH4309-157-20	177.80	0.041347	0.001106	0.282813	0.000014	0.282809	1.4	5.2	624	889	-0.97
HH4309-157-22	179.18	0.080038	0.002047	0.282888	0.000017	0.282881	4.1	7.8	531	725	-0.94
HH4309-157-23	179.97	0.055669	0.001422	0.282919	0.000016	0.282914	5.2	9.0	477	650	-0.96
HH4309-157-24	180.33	0.053974	0.001410	0.282931	0.000014	0.282926	5.6	9.4	460	622	-0.96
HH4309-157-25	178.40	0.051287	0.001346	0.282898	0.000013	0.282894	4.5	8.2	506	698	-0.96
HH2704-12, 灰白色二长花岗岩											
HH2704-12-1	178.85	0.062700	0.001705	0.282875	0.000016	0.282869	3.6	7.4	545	752	-0.95
HH2704-12-2	178.31	0.051077	0.001269	0.282857	0.000014	0.282853	3.0	6.8	564	790	-0.96
HH2704-12-3	178.55	0.067843	0.001674	0.282884	0.000018	0.282878	4.0	7.7	531	732	-0.95
HH2704-12-4	179.12	0.061396	0.001571	0.282868	0.000019	0.282863	3.4	7.1	553	767	-0.95
HH2704-12-5	178.65	0.115322	0.003733	0.282854	0.000114	0.282842	2.9	6.4	608	815	-0.89
HH2704-12-6	178.21	0.059042	0.001575	0.282869	0.000018	0.282864	3.4	7.2	551	765	-0.95
HH2704-12-7	180.05	0.060226	0.001518	0.282905	0.000016	0.282900	4.7	8.5	499	682	-0.95
HH2704-12-8	178.86	0.068165	0.001773	0.282821	0.000016	0.282815	1.7	5.5	624	875	-0.95
HH2704-12-9	178.46	0.072448	0.001885	0.282754	0.000016	0.282748	-0.6	3.1	723	1028	-0.94
HH2704-12-10	177.83	0.060479	0.001588	0.282863	0.000016	0.282858	3.2	6.9	560	779	-0.95
HH2704-12-11	177.78	0.070901	0.001904	0.282895	0.000017	0.282889	4.3	8.0	518	709	-0.94
HH2704-12-12	178.20	0.041958	0.001185	0.282866	0.000013	0.282862	3.3	7.1	550	769	-0.96
HH2704-12-13	179.08	0.120049	0.003365	0.282908	0.000019	0.282897	4.8	8.3	520	690	-0.90
HH2704-12-15	180.57	0.067295	0.001774	0.282900	0.000015	0.282894	4.5	8.3	509	695	-0.95
HH2704-12-16	177.57	0.121908	0.003158	0.282926	0.000016	0.282916	5.4	9.0	490	648	-0.90
HH2704-12-17	179.34	0.055690	0.001446	0.282889	0.000014	0.282884	4.1	7.9	521	718	-0.96
HH2704-12-18	180.36	0.064798	0.001586	0.282882	0.000013	0.282877	3.9	7.7	533	735	-0.95
HH2704-12-19	176.47	0.037022	0.000932	0.282904	0.000013	0.282901	4.7	8.4	492	682	-0.97
HH2704-12-20	178.52	0.056750	0.001362	0.282886	0.000015	0.282881	4.0	7.8	524	725	-0.96
HH2704-12-21	180.01	0.103559	0.002486	0.282945	0.000020	0.282937	6.1	9.8	453	599	-0.93
HH2704-12-22	178.57	0.059698	0.001443	0.282887	0.000013	0.282882	4.1	7.8	524	723	-0.96
HH2704-12-23	178.82	0.056897	0.001405	0.282934	0.000014	0.282929	5.7	9.5	456	616	-0.96
HH2704-12-24	179.10	0.066887	0.001639	0.282884	0.000012	0.282879	4.0	7.7	531	731	-0.95
HH2704-12-25	181.77	0.065383	0.001657	0.282853	0.000014	0.282847	2.9	6.7	576	800	-0.95

续表4

测点号	t/Ma	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	$(^{176}\text{Hf}/^{177}\text{Hf})_i$	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	T_{DM1}	T_{DM2}	$f_{\text{Lu-Hf}}$
HH5503-01, 石英二长岩											
HH5503-01-1	179.44	0.118821	0.003027	0.283048	0.000021	0.283038	9.8	13.3	305	369	-0.91
HH5503-01-2	179.87	0.077423	0.002247	0.282962	0.000023	0.282954	6.7	10.4	425	559	-0.93
HH5503-01-3	180.06	0.318041	0.007625	0.282985	0.000029	0.282959	7.5	10.6	459	547	-0.77
HH5503-01-4	180.05	0.035396	0.000953	0.282920	0.000015	0.282917	5.2	9.1	470	644	-0.97
HH5503-01-5	181.56	0.055083	0.001418	0.282934	0.000014	0.282929	5.7	9.5	456	615	-0.96
HH5503-01-6	179.95	0.099799	0.002751	0.282919	0.000017	0.282910	5.2	8.8	495	660	-0.92
HH5503-01-7	179.05	0.146625	0.004540	0.283041	0.000023	0.283026	9.5	12.9	330	397	-0.86
HH5503-01-8	177.90	0.060062	0.001421	0.282835	0.000013	0.282830	2.2	6.0	598	841	-0.96
HH5503-01-9	179.30	0.080757	0.002040	0.282910	0.000013	0.282903	4.9	8.6	499	675	-0.94
HH5503-01-11	178.33	0.098121	0.002975	0.282884	0.000020	0.282874	4.0	7.5	551	742	-0.91
HH5503-01-12	180.02	0.059929	0.001612	0.282829	0.000015	0.282824	2.0	5.8	609	855	-0.95
HH5503-01-14	180.11	0.306203	0.008714	0.283096	0.000035	0.283067	11.5	14.4	277	303	-0.74
HH5503-01-16	178.49	0.073582	0.001921	0.282886	0.000014	0.282880	4.0	7.7	532	729	-0.94
HH5503-01-17	178.75	0.340581	0.009096	0.282885	0.000024	0.282855	4.0	6.8	663	785	-0.73
HH5503-01-18	178.61	0.073266	0.001928	0.282861	0.000012	0.282855	3.1	6.8	568	786	-0.94
HH5503-01-19	179.61	0.071830	0.001886	0.282946	0.000011	0.282940	6.2	9.9	444	592	-0.94
HH5503-01-21	176.03	0.236795	0.006442	0.282913	0.000026	0.282892	5.0	8.1	562	703	-0.81
HH5503-01-22	179.68	0.168440	0.004430	0.283028	0.000021	0.283013	9.1	12.5	349	425	-0.87
HH5503-01-23	181.37	0.128204	0.003478	0.282876	0.000018	0.282864	3.7	7.2	571	762	-0.90
HH5503-01-24	180.11	0.153407	0.004110	0.282837	0.000019	0.282823	2.3	5.8	641	856	-0.88
HH5503-01-25	180.27	0.176674	0.004878	0.283021	0.000021	0.283005	8.8	12.2	365	444	-0.85

5-e);单阶段 Hf 模式年龄 (T_{DM1}) 变化范围为 663~277 Ma, 两阶段 Hf 模式年龄 (T_{DM2}) 变化范围为 856~303 Ma (图 5-f)。考虑到锆石的 $f_{\text{Lu-Hf}}$ 明显小于镁铁质地壳的 $f_{\text{Lu-Hf}}$ (-0.34)^[22] 和硅铝质地壳的 $f_{\text{Lu-Hf}}$ (-0.72)^[23], 故 T_{DM2} 更能反映其源区物质在地壳的存留年龄, 由此暗示本区新元古代时期发生了一次重要的地壳增生事件^[24-29]。在 $t-\varepsilon_{\text{Hf}}(t)$ 图解 (图 6) 中, 绝大多数样品点落在球粒陨石演化线和亏损地幔之间, 也显示红花尔基花岗岩体的源岩物质可能主要来源于亏损地幔。

4 讨 论

4.1 岩浆源区

花岗岩岩浆来源研究一直是备受学术界关注的问题之一, 因为源区提供了花岗岩成岩的绝大部分物质。花岗岩成因最流行的模式是地壳物质的部分熔融, 根据源岩性质的不同可分为 I 型和 S 型花岗岩^[30]。笔者另文详细论述了红花尔基赋矿花岗岩的成因类型应属 I 型花岗岩。一般来说, I 型花岗岩的源岩主要是由地幔派生的下部地壳^[31,32]。从 Sr-

Nd-Pb-Hf 同位素数据资料可以看出, 红花尔基白钨矿矿床赋矿花岗岩岩浆源区应以新元古代起源于亏损地幔^[33] 的地壳物质为主。同时, 3 种花岗岩的 Sr-Nd-Hf 同位素特征具有一定的差别, 尤其是二长花岗岩和石英二长岩之间的同位素特征差别较明显。首先, 与 2 种二长花岗岩相比, 石英二长岩的初始 Sr 值明显较低, 且其 $\varepsilon_{\text{Nd}}(t)$ 值相对较高。在 $\varepsilon_{\text{Nd}}(t)-(^{87}\text{Sr}/^{86}\text{Sr})_i$ 图解 (图 3-a) 中, 石英二长岩更接近亏损地幔, 且 3 种花岗岩大致沿主地幔趋势线分布, 说明在花岗岩浆演化过程中可能有少量幔源物质的加入^[34]。锆石极强的稳定性使其 Hf 同位素组成较少受到后期地质事件的影响, 而极低的 Lu 含量可以使我们能够获得它形成时准确的 Hf 同位素组成。这些特性使得锆石成为目前探讨地壳演化和示踪岩石源区的重要工具^[10,20,22,35]。与 2 种二长花岗岩相比, 石英二长岩的 $\varepsilon_{\text{Hf}}(t)$ 值组成较分散, 其分布范围下限与前两者一致, 而其分布范围上限却明显大于前两者 (图 5-a、c、e)。这一点也从一定程度上说明石英二长岩可能是岩浆混合了少量地幔物质形成的。不仅如此, 笔者另文根据岩体的岩相

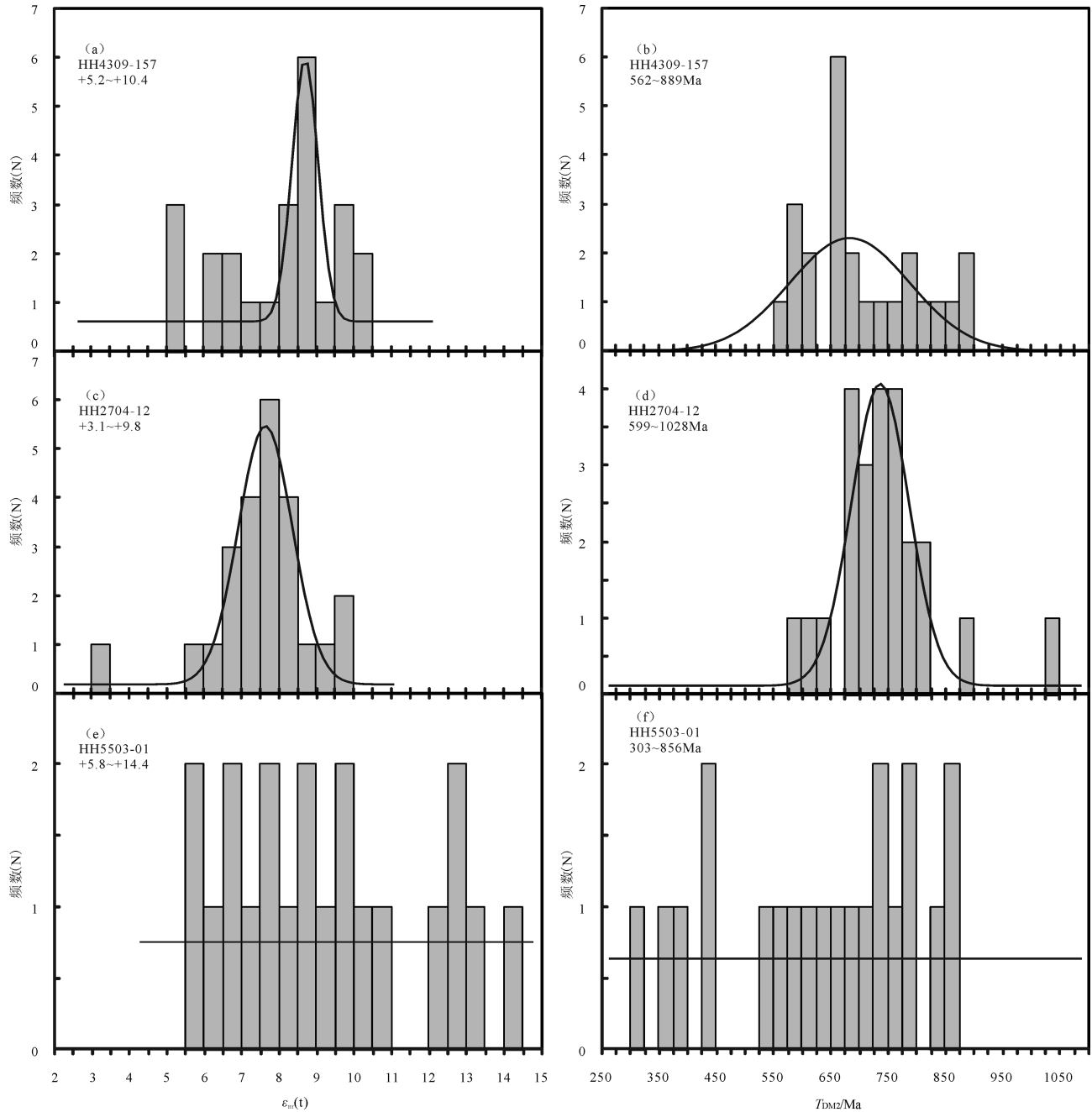


图5 红花尔基白钨矿矿床赋矿花岗岩 $\epsilon_{Hf}(t)$ 值和地壳两阶段Hf模式年龄(T_{DM2})统计直方图
Fig.5 Histograms of $\epsilon_{Hf}(t)$ values and T_{DM2} for ore-bearing granites in the Honghuaerji scheelite deposit

学和元素地球化学特征推断石英二长岩可能为岩浆混合了偏中(基)性物质形成的包体,本文的同位素地球化学研究支持了这一认识。从以上讨论可以得出,红花尔基白钨矿矿床赋矿花岗岩的源岩物质来自亏损地幔,其在新元古代加入下地壳。早侏罗世,岩浆在演化成岩过程中混合加入了少量的上

地幔偏中(基)性物质。

4.2 地质意义

兴蒙造山带及其邻区在前中生代经历了中小块体之间板块的俯冲、碰撞和拼贴过程^[36,37],也就是所谓的“多岛洋”演化^[38-44]。其中前寒武纪的微陆块主要有额尔古纳地块、兴安地块、松辽地块和佳木

斯地块^[45]。本区具体的表现形式就是在古亚洲洋闭合期间,板块通过俯冲、碰撞不断形成由幔源物质组成的新地壳^[25,46]。晚古生代或早中生代,古亚洲洋演化基本结束,陆块之间的拼贴、碰撞活动也随之基本完成,中亚造山带就此形成^[16,47-49]。中生代早期,古亚洲洋大部分闭合后,本区演化为存在于西伯利亚板块和拼合成的“联合板块”之间的鄂霍茨克洋盆^[36]。基于本区中生代花岗岩 Sr、Nd(Hf、Pb)同位素以及元素地球化学特征,前人研究已表明区域花岗岩的源岩物质可能是在新元古代从地幔加入地壳^[13,24-27],导致地壳的垂向增生^[24]。红花尔基白钨矿矿床赋矿花岗岩的正 $\epsilon_{Nd}(t)$ 值、正 $\epsilon_{Hf}(t)$ 值和年轻的两阶段 Nd 模式年龄、年轻的两阶段 Hf 模式年龄,同样显示其岩浆源区的形成可能与早期的板块俯冲有关^[25],在这种构造背景下,源岩物质在新元古代从亏损地幔加入下地壳。

本区广泛分布着的中生代花岗岩类岩石^[3]绝不是偶然地质事件导致的结果,是受区域中生代的构造背景所制约的。中生代早期,古亚洲洋大部分已闭合,存在于西伯利亚板块和中国东北的“联合板块”之间的鄂霍茨克洋盆向南的俯冲、碰撞作用使

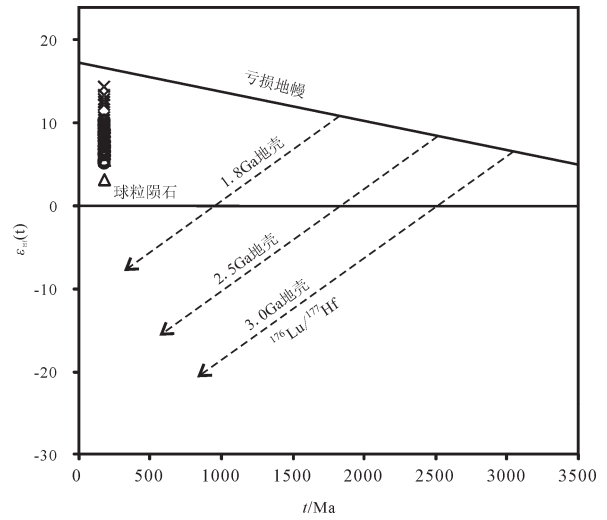


图6 红花尔基白钨矿矿床赋矿花岗岩的锆石 Hf 同位素特征^[24](图例同图 3)

Fig.6 Hf isotopic compositions of zircons from ore-bearing granites in the Honghuaerji scheelite deposit (symbols as for Fig. 3)

内蒙古大兴安岭中北段地区处在陆缘弧到碰撞隆起的构造环境^[50-52],这种环境下形成了本区三叠纪到早侏罗世的花岗岩。与之对应的是,区域此时期

表 5 大兴安岭中北段及邻区三叠纪到早侏罗世主要矿床成矿年龄

Table 5 Ore-forming ages of the main ore deposits in central-northern Da Hinggan Mountains in the period from Triassic to Early Jurassic

矿床类型	矿床名称	测试岩石(矿物)	测试方法	年龄/Ma	资料来源	
斑岩型铜钼矿床	八八一	花岗岩	LA-MC-ICP-MS 锆石 U-Pb	234.39±0.57	余宏全等, 未发表资料	
	八大关	花岗闪长斑岩	LA-MC-ICP-MS 锆石 U-Pb	230.6±1.8	康永建等, 未发表资料	
				230.5±4.4		
		辉钼矿	Re-Os 等时线	228.7±3.1		
	太平川	花岗闪长斑岩	LA-MC-ICP-MS 锆石 U-Pb	202.4±5.7	[51]	
	乌奴格吐山	二长花岗斑岩	单颗粒锆石 U-Pb	183.3±0.6	[58]	
			全岩 Rb-Sr 等时线	183.9±1.0		
		绢云母	K-Ar 法	183.5±1.7		
		辉钼矿	Re-Os 等时线	178±10		[59]
		二长花岗斑岩	LA-MC-ICP-MS 锆石 U-Pb	178.1±0.6		[60]
红花尔基	肉红色二长花岗岩	LA-MC-ICP-MS 锆石 U-Pb	179.2±0.5	郭志军等, 未发表资料		
			179.0±0.6			
	石英二长岩	178.6±0.7				
	辉钼矿	Re-Os 等时线	176.8±2.2		[61]	

的内生多金属矿床广泛发育,从三叠纪到早侏罗世分别发育有八八一、八大关、太平川以及乌奴格吐山斑岩型铜钼矿床,其成矿年龄见表5。已有研究资料证实,此类三叠纪到早侏罗世的斑岩铜钼矿床的形成与蒙古—鄂霍茨克洋从东到西的剪刀式闭合作用有关^[1,46,50,51,53]。从世界范围来看,钨矿床大多分布在靠近板块消亡带的内侧(仰冲板块一侧),与处于其外部靠近大洋一侧的斑岩铜(钼)矿带相接^[54]。因此,红花尔基白钨矿矿床与存在于其北部200 km左右的北东-南西向斑岩铜钼矿带的形成可能具有相同的成矿动力学背景。前人研究认为大兴安岭中北段地区在早侏罗世处在蒙古—鄂霍茨克洋碰撞晚造山阶段,此时洋盆的中段已经闭合^[46,50,55],而此时太平洋板块对本区的影响较小^[56,57]。同时大兴安岭中北段地区缺失早侏罗世地层沉积,说明当时该区很可能处在碰撞隆起的环境。因此,红花尔基白钨矿矿床形成时,区域可能已处在陆-陆碰撞隆起的构造环境。到中侏罗世晚期,本区大规模双峰式火山岩的出现说明区域进入了造山后伸展的构造环境^[46]。

总之,红花尔基白钨矿矿床赋矿花岗岩的形成是与区域构造演化历史密切相关的。新元古代,古亚洲洋演化期间板块的俯冲、拼贴为岩体提供了幔源的成岩物质;早侏罗世,蒙古—鄂霍茨克洋盆的闭合、板块的碰撞隆起诱发了源岩的部分熔融从而形成了与成矿密切相关的花岗岩体。

5 结 论

通过对红花尔基白钨矿矿床赋矿花岗岩的Sr-Nd-Pb-Hf同位素特征进行研究,可以得出以下结论:

(1)赋矿花岗岩的源岩为新元古代加入下地壳的亏损地幔物质,花岗岩浆在演化过程中混合加入了少量的上地幔偏中(基)性物质。

(2)古亚洲洋闭合期间,中一小陆块之间的俯冲、碰撞形成了由幔源物质组成的下地壳,其为赋矿花岗岩的形成提供了物质来源。

(3)早侏罗世,蒙古—鄂霍茨克洋盆在本区闭合后,板块碰撞隆起的挤压环境触发了源岩的部分熔融,形成了赋矿花岗岩体。

致谢:野外地质工作期间得到了内蒙古第六地质矿产勘查开发有限责任公司的全力支持和帮助,

天津地质矿产研究所同位素实验室的刘卉老师、核工业北京地质研究院刘牧老师、中国地质科学院矿产资源研究所郭春丽老师以及熊欣同学在论文实验中给予了大力帮助,特此谢忱。

参考文献(References):

- [1] 余宏全,李红红,李进文,等. 内蒙古大兴安岭中北段铜铅锌金银多金属矿床成矿规律与找矿方向[J]. 地质学报, 2009, 83(10): 1456-1472.
She Hongquan, Li Honghong, Li Jinwen, et al. The metallogenetical characteristics and prospecting direction of the copper-lead-zinc polymetal deposits in the Northern-Central Daxing'anling Mountain, Inner Mongolia [J]. Acta Geologica Sinica, 2009, 83(10): 1456-1472 (in Chinese with English abstract).
- [2] 周振华,欧阳荷根,武新丽,等. 内蒙古道伦达坝铜钨多金属矿黑云母花岗岩年代学、地球化学特征及其地质意义[J]. 岩石学报, 2014, 30(1): 79-94.
Zhou Zhenhua, Ouyang Hegen, Wu Xinli et al. Geochronology and geochemistry study of the biotite granite from the Daolundaba Cu-W polymetallic deposit in the Inner Mongolia and its geological significance [J]. Acta Petrologica Sinica, 2014, 30(1): 79-94 (in Chinese with English abstract).
- [3] 王东方,权恒. 大兴安岭中生代构造岩浆作用[J]. 地球科学—武汉地质学院学报, 1984, 26(3): 81-90.
Wang Dongfang, Quan Heng. Mesozoic tectonic-magmatism in Daxinganling, China [J]. Earth Science, 1984, 26(3): 81-90 (in Chinese with English abstract).
- [4] 刘建明,张锐,张庆洲. 大兴安岭地区的区域成矿特征[J]. 地学前沿, 2004, 11(1): 269-277.
Liu Jianming, Zhang Rui, Zhang Xingzhou. The regional metallogeny of Da Hinggan Ling, China [J]. Earth Science Frontiers, 2004, 11(1): 269-277 (in Chinese with English abstract).
- [5] 毛德宝,钟长汀,陈志宏,等. 承德北部高压基性麻粒岩的同位素年龄及其地质意义[J]. 岩石学报, 1999, 15(4): 524-531.
Mao Debao, Zhong Changting, Chen Zhihong, et al. The isotope ages and their geological implications of high-pressure basic granulites in north region to Chengde, Hebei Province, China [J]. Acta Petrologica Sinica, 1999, 15(4): 524-531 (in Chinese with English abstract).
- [6] 耿建珍,李怀坤,张健,等. 锆石Hf同位素组成的LA-MC-ICP-MS测定[J]. 地质通报, 2011, 30(10): 1508-1513.
Geng Jianzhen, Li Huaikun, Zhang Jian, et al. Zircon Hf isotope analysis by means of LA-MC-ICP-MS [J]. Geological Bulletin of China, 2011, 30(10): 1508-1513 (in Chinese with English abstract).
- [7] 吴福元,李献华,郑永飞,等. Lu-Hf同位素体系及其岩石学应用[J]. 岩石学报, 2007, 23(2): 185-220.
Wu Fuyuan, Li Xianhua, Zheng Yongfei, et al. Lu-Hf isotopic systematics and their applications in petrology [J]. Acta Petrologica

- Sinica, 2007, 23(2): 185–220 (in Chinese with English abstract).
- [8] Blichert-Toft J, Albarede F. The Lu–Hf isotope geochemistry of chondrites and the evolution of the mantle–crust system [J]. *Earth Planetary Science Letters*, 1997, 148: 243–258.
- [9] Griffin W L, Pearson N J, Belousova E, et al. The Hf isotope composition of cratonic mantle: LA–MC–ICPMS analysis of zircon megacrysts in kimberlites [J]. *Geochim. Cosmochim. Acta*, 2000, 64: 133–147.
- [10] Griffin W L, Wang X, Jackson S E, et al. Zircon Chemistry and Magma Genesis, SE China: In-situ analysis of Hf isotopes, Tonglu and Pinglan Igneous Complexes [J]. *Lithos*, 2002, 61: 237–269.
- [11] 肖成东, 张忠良, 赵利青. 东蒙地区燕山期花岗岩Nd–Sr–Pb同位素及其岩石成因[J]. *中国地质*, 2004, 31(1): 57–63.
Xiao Chengdong, Zhang Zhongliang, Zhao Liqing. Nd, Sr and Pb isotope geochemistry of Yanshanian granitoids in eastern Inner Mongolia and their origins [J]. 2004, 31(1): 57–63 (in Chinese with English abstract).
- [12] 邵济安, 牟保磊, 朱慧忠, 等. 大兴安岭中南段中生代成矿物质的深部来源与背景[J]. *岩石学报*, 2010, 26(3): 649–656.
Shao Ji'an, Mu Baolei, Zhu Huizhong, et al. Material source and tectonic settings of the Mesozoic mineralization of the Da Hinggan Mountains [J]. *Acta Petrologica Sinica*, 2010, 26(3): 649–656 (in Chinese with English abstract).
- [13] 洪大卫, 王式洗, 谢锡林, 等. 兴蒙造山带正 $\epsilon_{\text{Nd}}(t)$ 值花岗岩的成因和大陆地壳生长[J]. *地学前缘*, 2000, 7(2): 441–455.
Hong Dawei, Wang Shiguang, Xie Xilin, et al. Genesis of positive $\epsilon_{\text{Nd}}(t)$ granitoids in the Da Hinggan Mountains [J]. *Earth Science Frontiers*, 2000, 7(2): 441–455 (in Chinese with English abstract).
- [14] 邵济安, 洪大卫, 张履桥. 内蒙古火成岩Sr–Nd同位素特征及成因[J]. *地质通报*, 2002, 21(12): 817–822.
Shao Ji'an, Hong Dawei, Zhang Lvqiao. Genesis of Sr–Nd isotopic characteristics of igneous rocks in Inner Mongolia [J]. *Geological Bulletin of China*, 2002, 21(12): 817–822 (in Chinese with English abstract).
- [15] Jahn Borming, Wu Fuyuan, Lo Chinghua, et al. Crust–mantle interaction induced by deep subduction of the continental crust: geochemical and Sr–Nd isotopic evidence from post-collisional mafic–ultramafic intrusions of the northern Dabie complex, central China [J]. *Chem. Geol.*, 1999, 157: 119–146.
- [16] 吴福元, 江博明, 林强. 中国北方造山带造山后花岗岩的同位素特点与地壳生长意义[J]. *科学通报*, 1997, 42(20): 2188–2192.
Wu Fuyuan, Jahn Bor-ming, Lin Qiang. The isotopic study on the post-orogeny granite and its significance to the crustal accretion [J]. *Chinese Science Bulletin*, 1997, 42(20): 2188–2192 (in Chinese).
- [17] Jahn Borming, Wu Fuyuan, Hong Dawei. Important crustal growth in the Phanerozoic: Isotopic evidence of granitoids from the east-central Aisa [J]. *Earth Planet. Sci.*, 2000, 109(1): 5–20.
- [18] Zartman R E, Doe B R. Plumbotectonics—the model [J]. *Tectonophysics*, 1981, 75: 135–162.
- [19] Patchett P J, Kouvo O, Hedge C E, et al. Evolution of continental crust and mantle heterogeneity: Evidence from Hf isotopes [J]. *Contributions to Mineralogy and Petrology*, 1981, 78(3): 279–97.
- [20] Amelin Y, Lee D C, Halliday A N, et al. Nature of the earth's earliest crust from hafnium isotopes in single detrital zircons [J]. *Nature*, 1999, 399(6733): 252–255.
- [21] Knudsen T L, Griffin W L, Hartz E H, et al. In-situ hafnium and lead isotope analyses of detrital zircon from the Devonian sedimentary basin of NE Greenland: A record of repeated crustal reworking [J]. *Contributions to Mineralogy and Petrology*, 2001, 141(1): 83–94.
- [22] Amelin Y, Lee D C, Halliday A N. Early–middle Archaean crustal evolution deduced from Lu–Hf and U–Pb isotopic studies of single zircon grains [J]. *Geochimica et Cosmochimica Acta*, 2000, 64 (24): 4205–4225.
- [23] Vervoort J D, Pachelt P J, Gehrels G E, et al. Constraints on early Earth differentiation from hafnium and neodymium isotopes [J]. *Nature*, 1996, 379: 624–627.
- [24] 吴福元, 孙德有, 林强. 东北地区显生宙花岗岩的成因与地壳增生[J]. *岩石学报*, 1999, 15(2): 181–189.
Wu Fuyuan, Sun Deyou, Lin Qiang. Petrogenesis of the Phanerozoic granites and crustal growth in Northeast China [J]. *Acta Petrologica Sinica*, 1999, 15(2): 181–189 (in Chinese with English abstract).
- [25] 林强, 葛文春, 吴福元, 等. 大兴安岭中生代花岗岩类的地球化学[J]. *岩石学报*, 2004, 20(3): 403–412.
Lin Qiang, Ge Wenchun, Wu Fuyuan, et al. Geochemistry of Mesozoic granites in Da Hinggan Ling ranges [J]. *Acta Petrologica Sinica*, 2004, 20(3): 403–412 (in Chinese with English abstract).
- [26] 隋振民, 徐学纯. 大兴安岭东北部侏罗纪花岗岩类Sr–Nd同位素特征及其地质意义[J]. *中国地质*, 2010, 37(1): 48–55.
Sui Zhenmin, Xu Xuechun. Sr–Nd isotopic characteristics of Jurassic granites in northeastern Da Hinggan Mountains and their geological implications [J]. *Geology in China*, 2010, 37(1): 48–55 (in Chinese with English abstract).
- [27] 郭志军, 周振华, 李贵涛, 等. 内蒙古敖尔盖铜矿中—酸性侵入岩体SHRIMP锆石U–Pb定年与岩石地球化学特征研究[J]. *中国地质*, 2012, 39(6): 1486–1500.
Guo Zhijun, Zhou Zhenhua, Li Guitao, et al. SHRIMP U–Pb zircon dating and petrogeochemical characteristics of the intermediate–acid intrusive rocks in the Aoergai copper deposit of Inner Mongolia [J]. *Geology in China*, 2012, 39(6): 1486–1500 (in Chinese with English abstract).
- [28] Wu Fuyuan, Jahn Bor-ming, Wilde SA, et al. Phanerozoic crustal growth: U–Pb and Sr–Nd isotopic evidence from the granites in northeastern China [J]. *Tectonophysics*, 2000, 328: 89–113.

- [29] Wu Fuyuan, Jahn Bor-ming, Wilde SA, et al. Highly fractionated I-type granites in NE China (II): isotopic geochemistry and implications for crustal growth in the Phanerozoic [J]. *Lithos*, 2003, 67: 191-204.
- [30] Chappell B W, White A J R. Two contrasting granite types [J]. *Pac. Geol.*, 1974, 8: 173-174.
- [31] 向鼎璞. 磁铁矿系列/钛铁矿系列花岗岩类和I型/S型花岗岩类对比的讨论[J]. *西北地质*, 1984, 3: 49-52.
Xiang Dingpu. The discussion of Magnetite-series / ilmenite-series granitoid and I-type / S-type granitoid [J]. *Northwestern Geology*, 1984, 3: 49-52 (in Chinese).
- [32] 陈建林, 郭原生, 付善明. 花岗岩研究进展—ISMA花岗岩类分类综述[J]. *甘肃地质学报*, 2004, 13(1): 67-73.
Chen Jianlin, Guo Yuansheng, Fu Shanming. The research headway to granitoid-classification review and synthesis of ISMA granitoid [J]. *Acta Geologica Guansu*, 2004, 13(1): 67-73 (in Chinese with English abstract).
- [33] 蔡剑辉, 阎国翰, 肖成东, 等. 太行山—大兴安岭构造岩浆带中生代侵入岩Nd、Sr、Pb同位素特征及物质来源探讨[J]. *岩石学报*, 2004, 20(5): 1225-1242.
Cai Jianhui, Yan Guohan, Xiao Chengdong, et al. Nd, Sr, Pb isotopic characteristics of the Mesozoic intrusive rocks in the Taihang-Da Hinggan Mountains Tectonomagmatic Belt and their source region [J]. *Acta Petrologica Sinica*, 2004, 20(5): 1225-1242 (in Chinese with English abstract).
- [34] 王婧, 张宏飞, 徐旺春, 等. 西秦岭党川地区花岗岩的成因及其构造意义[J]. *地球科学*, 2008, 33(4): 474-486.
Wang Jing, Zhang Hongfei, Xu Wangchun, et al. Petrogenesis of granites from Dangchuan area in West Qinling Orogenic Belt and its tectonic implication [J]. *Earth Science*, 2008, 33(4): 474-486 (in Chinese with English abstract).
- [35] 杨进辉, 吴福元, 柳小明, 等. 北京密云环斑花岗岩锆石U-Pb年龄和Hf同位素及其地质意义[J]. *岩石学报*, 2005, 21(6): 1633-1644.
Yang Jinhui, Wu Fuyuan, Liu Xiaoming, et al. Zircon U-Pb ages and Hf isotopes and their geological significance of the Miyun rapakivi granites from Beijing, China [J]. *Acta Petrologica Sinica*, 2005, 21(6): 1633-1644 (in Chinese with English abstract).
- [36] 李双林, 欧阳自远. 兴蒙造山带及邻区的构造格局与构造演化[J]. *海洋地质与第四纪地质*, 1998, 18(3): 45-54.
Li Shuanglin, Ouyang Ziyuan. Tectonic framework and evolution of Xing'anling-Mongolian Orogenic Belt (XMOB) and its adjacent region [J]. *Marine Geology & Quaternary Geology*, 1998, 18(3): 45-54 (in Chinese with English abstract).
- [37] Dolgoplova A, Seltmann R, Armstrong R, et al. Sr-Nd-Pb-Hf isotope systematics of the Hugo Dummett Cu-Au porphyry deposit (Oyu Tolgoi, Mongolia) [J]. *Lithos*, 2013, 164-167: 47-64.
- [38] Sengör A M C. Evolution of the Altaid tectonics collage and Palaeozoic crustal growth in Eurasia [J]. *Nature*, 1993, 364(22): 299-307.
- [39] Hsü K J, Yao Y Y, Hao J, et al. Origin of Chinese Tianshan by Arc-Arc collision [J]. *Eclogae Geol. Hell.*, 1994, 85/3: 1-61.
- [40] 刘本培, 冯庆来, Chonglakmani C, 等. 滇西古特提斯多岛洋的机构及其南北延伸[J]. *地质前缘*, 2002, 9(3): 161-171.
Liu Benpei, Feng Qinglai, Chonglakmani C, et al. Framework of Paleotethyan Archipelago Ocean of Western Yunnan and its elongation towards north and south [J]. *Earth Science Frontiers*, 2002, 9(3): 161-171 (in Chinese with English abstract).
- [41] 潘桂堂, 王立全, 尹福光, 等. 从多岛弧盆系研究实践看板块构造登陆的魅力[J]. *地质通报*, 2004, 23(9/10): 933-939.
Pan Guitang, Wang Liquan, Yin Fuguang, et al. Charm of landing of plate tectonics on the continent as viewed from the study of the archipelagic arc-basin system [J]. *Geological Bulletin of China*, 2004, 23(9/10): 933-939 (in Chinese with English abstract).
- [42] Xiao W J, Windley B F, Hao J, et al. Accretion leading to collision and the Permian Solonkersuture, Inner Mongolia, China: Termination of the central Asian orogenic belt [J]. *Tectonics*, 2003, 22(6): 1189-1217.
- [43] Xiao W J, Han C M, Yuan C, et al. Middle Cambrian to Permian subduction-related accretionary orogenesis of Northern Xinjiang, NW China: Implications for the tectonic evolution of central Asia [J]. *Journal of Asian Earth Sciences*, 2008, 32: 102-117.
- [44] 袁四化, 王立全, 汪新胜, 等. 多岛海(洋)及多岛弧盆系造山模式解析造山带演化的研究进展[J]. *地质科技情报*, 2009, 28(5): 1-11.
Yuan Sihua, Wang Liquan, Wang Xinsheng, et al. The retrospect and prospect on archipelago model and composite arc-basin system model of orogenesis [J]. *Geological Science and Technology Information*, 2009, 28(5): 1-11 (in Chinese with English abstract).
- [45] Shu Q H, Lai Y, Wang C, et al. Geochronology, geochemistry and Sr-Nd-Hf isotopes of the Haisugou porphyry Mo deposit, northeast China, and their geological significance [J]. *Journal of Asian Earth Sciences*, 2014, 79: 777-791.
- [46] 余宏全, 李进文, 向安平, 等. 大兴安岭中北段原岩锆石U-Pb测年及其与区域构造演化关系[J]. *岩石学报*, 2012, 28(2): 571-594.
She Hongquan, Li Jinwen, Xiang Anping, et al. U-Pb ages of the Zircons from primary rocks in middle-northern Daxinganling and its implications to geotectonic evolution [J]. *Acta Petrologica Sinica*, 2012, 28(2): 571-594 (in Chinese with English abstract).
- [47] Chen B, Jahn B M, Wilde S, et al. Two contrasting Paleozoic magmatic belts in northern Inner Mongolia, China: petrogenesis and tectonic implications [J]. *Tectonophysics*, 2000, 328: 157-182.
- [48] Heinhorst J, Lehmann B, Ermolov P, et al. Paleozoic crustal growth and metallogeny of Central Asia: evidence from

- magmatic-hydrothermal ore systems of Central Kazakhstan [J]. *Tectonophysics*, 2000, 328:69-87.
- [49] 刘永江, 张兴洲, 金巍, 等. 东北地区晚古生代区域构造演化[J]. *中国地质*, 2010, 37(4): 943-951.
Liu Yongjiang, Zhang Xingzhou, Jin Wei, et al. Late Paleozoic tectonic evolution in Northeast China [J]. *Geology in China*, 2010, 37(4): 943-951(in Chinese with English abstract).
- [50] 陈志广, 张连昌, 万博, 内蒙古乌奴格吐山斑岩铜钼矿床低Sr-Yb型成矿斑岩地球化学特征及地质意义[J]. *岩石学报*, 2008, 24(1):115-128.
Chen Zhiguang, Zhang Lianchang, Wan Bo, et al. Geochemistry and geological significances of ore-forming porphyry with low Sr and Yb value in Wunugetushan copper-molybdenum deposit, Inner Mongolia [J]. *Acta Petrologica Sinica*, 2008, 24(1):115-128 (in Chinese with English abstract).
- [51] 陈志广, 张连昌, 卢百志, 等. 内蒙古太平川铜钼矿成矿斑岩时代、地球化学及地质意义[J]. *岩石学报*, 2010, 26(5):1437-1449.
Chen Zhiguang, Zhang Lianchang, Lu Baizhi, et al. Geochronology and geochemistry of the Taipingchuan copper-molybdenum deposit in Inner Mongolia, and its geological significances [J]. *Acta Petrologica Sinica*, 2010, 26(5):1437-1449 (in Chinese with English abstract).
- [52] 黄世武, 张连昌, 李克庆, 等. 得尔布干成矿带太平川铜钼矿床含CH₄流体包裹体研究[J]. *岩石学报*, 2010, 26(5): 1386-1396.
Huang Shiwu, Zhang Lianchang, Li Keqing, et al. CH₄-containing fluid inclusion study of the Taipingchuan porphyry Cu-Mo deposit, Inner Mongolia [J]. *Acta Petrologica Sinica*, 2010, 26(5): 1386-1396 (in Chinese with English abstract).
- [53] 徐志刚. 初论开合构造方式[J]. *地质通报*, 2004, 23(3): 238-245.
Xu Zhigang. On opening-closing patterns [J]. *Geological Bulletin of China*, 2004, 23(3): 238-245 (in Chinese with English abstract).
- [54] 康永孚. 钨的地球化学与矿床类型[J]. *地质地球化学*, 1981, 5(11): 1-7.
Kang Yongfu. Geochemistry and deposit types of tungsten [J]. *Geology-Geochemistry*, 1981, 5(11): 1-7 (in Chinese).
- [55] 毛景文, 谢桂青, 张作衡, 等. 中国北方中生代大规模成矿作用的期次及其地球动力学背景[J]. *岩石学报*, 2005, 21(1): 169-188.
Mao Jingwen, Xie Guiqing, Zhang Zuoheng, et al. Mesozoic large-scale metallogenic pulses in North China and corresponding geodynamic settings [J]. *Acta Petrologica Sinica*, 2005, 21(1): 169-188 (in Chinese with English abstract).
- [56] 贾盼盼, 魏俊浩, 巩庆伟, 等. 大兴安岭地区铜钼矿床成矿区带背景及找矿前景分析[J]. *地质与勘探*, 2011, 47(2): 151-162.
Jia Panpan, Wei Junhao, Gong Qingwei, et al. Analysis of geological background and ore-searching prospect for the copper-molybdenum deposits in the Da Hingan Ling area [J]. *Geology and Exploration*, 2011, 47(2): 151-162 (in Chinese with English abstract).
- [57] 许文良, 王枫, 裴福萍, 等. 中国东北中生代构造体制与区域成矿背景:来自中生代火山岩组合时空变化的制约[J]. *岩石学报*, 2013, 29(2): 339-353.
Xu Wenliang, Wang Feng, Pei Fuping, et al. Mesozoic tectonic regimes and regional ore-forming background in NE China: Constraints from spatial and temporal variations of Mesozoic volcanic rock associations [J]. *Acta Petrologica Sinica*, 2013, 29(2): 339-353 (in Chinese with English abstract).
- [58] 秦克章, 李惠民, 李伟实. 内蒙古乌奴格吐山斑岩铜钼矿床的成岩、成矿时代[J]. *地质论评*, 1999, 45(2): 180-185.
Qin Kezhang, Li Huimin, Li Weishi. Intrusion and mineralization ages of the Wunugetushan porphyry Cu-Mo deposit, Inner Mongolia, Northeastern China [J]. *Geological Review*, 1999, 45(2): 180-185 (in Chinese with English abstract).
- [59] 李诺, 孙亚莉, 李晶, 等. 内蒙古乌奴格吐山斑岩铜钼矿床辉钼矿铼钨等时线年龄及其成矿地球动力学背景[J]. *岩石学报*, 2007, 23(11): 2881-2888.
Li Nuo, Sun Yali, Li Jing, et al. Molybdenite Re/Os isochron age of the Wunugetu Shan Porphyry Cu/Mo deposit, Inner Mongolia and its implication for metallogenic geodynamics [J]. *Acta Petrologica Sinica*, 2007, 23(11): 2881-2888 (in Chinese with English abstract).
- [60] 谭钢. 内蒙古乌奴格吐山斑岩铜钼矿床成矿作用研究[D]. 北京: 中国地质科学院, 2011: 1-81.
Tan Gang. The Ore-Forming Processes and Mineralization of Wunugetushan Porphyry Cu-Mo Deposit, Inner Mongolia [D]. Beijing: Chinese Academy of Geological Sciences, 2011: 1-81 (in Chinese with English abstract).
- [61] 向安平, 王亚君, 秦大军, 等. 内蒙古红花尔基钨多金属矿床成岩成矿年代学研究[J]. *矿床地质*, 2014, 33(2): 428-439.
Xiang Anping, Wang Yajun, Qin Dajun, et al. Metallogenic and diagenetic age of Honghuaerji tungsten polymetallic deposit in Inner Mongolia [J]. *Mineral Deposits*, 2014, 33(2): 428-439 (in Chinese with English abstract).

Sr-Nd-Pb-Hf isotopic characteristics of ore-bearing granites in the Honghuaerji scheelite deposit, Inner Mongolia

GUO Zhi-jun^{1,2}, LI Jin-wen¹, HUANG Guang-jie³, GUAN Ji-dong⁴, DONG Xu-zhou⁵,
TIAN Jing^{1,5}, YANG Yun-cheng¹, SHE Hong-quan¹, XIANG An-ping¹, KANG Yong-Jian¹

(1. MLR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China; 2. State Key Laboratory of Mineral Processing Science and Technology, Beijing General Research Institute of Mining and Metallurgy, Beijing 100160, China; 3. Inner Mongolia Geological Prospecting Co., Ltd., Hohhot 010020, Inner Mongolia, China; 4. Inner Mongolia Sixth Geological and Mineral Exploration Institute, Hailar 010020, Inner Mongolia, China; 5. School of Earth Science and Mineral Resources, China University of Geosciences, Beijing 100083, China)

Abstract: A study of whole-rock Sr-Nd isotopes, Pb isotopes of K-feldspar and Hf isotopic compositions of zircons from the ore-bearing granites in the Honghuaerji scheelite deposit was carried out in this paper. The results show that the average ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios of pink monzogranite, gray monzogranite and quartz monzonite are 0.70525, 0.70517 and 0.70482 respectively, displaying a decreasing trend; however, the average $\epsilon_{\text{Nd}}(t)$ values are +2.2, +2.3 and +3.1 respectively, exhibiting an increasing trend. The Pb isotopic compositions of K-feldspar samples selected from pink and gray monzogranites are relatively uniform, with the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios ranging from 18.258 to 18.276, $^{207}\text{Pb}/^{204}\text{Pb}$ ranging from 15.507 to 15.512 and $^{208}\text{Pb}/^{204}\text{Pb}$ ranging from 37.994 to 38.018. The $\epsilon_{\text{Hf}}(t)$ values of zircons from the three samples are +5.2–+10.4, +3.1–+9.8, +5.8–+14.4 respectively. The Sr-Nd-Pb-Hf isotopic compositions show that the granites-forming materials might have been derived from a depleted mantle during Neoproterozoic. The quartz monzonite was likely the inclusion which was a product of magma mingling. The regional tectonic analysis indicates that the magma resources were probably related to the interaction between the ocean plate and the upper mantle during the closure of Paleo-Asian Ocean before Mesozoic Era; and after the disappearance of Mongolia–Okhotsk marine trough, the compression tectonic setting that had resulted from the collision of plates triggered the partial melting of the resources in early Jurassic epoch.

Key words: Honghuaerji; scheelite deposit; granites; zircon Hf isotope; Sr-Nd-Pb isotope; Paleo-Asian Ocean; Mongolia–Okhotsk Ocean; upper mantle

About the first author: GUO Zhi-jun, male, born in 1988, master, mainly engages in the study of mineral deposits and technological mineralogy; E-mail: GHN_07@163.com.

About the corresponding author: LI Jin-wen, doctor, senior researcher, mainly engages in the study of mineral deposits and mineral exploration; E-mail: lijinwen958@sohu.com.