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祁连南缘柴达木山复式花岗岩体中部 二长花岗岩锆石 U-Pb 定年及其地质意义

朱小辉¹ 王洪亮¹ 杨 猛²

(1. 国土资源部岩浆作用成矿与找矿重点实验室, 中国地质调查局西安地质调查中心, 陕西 西安 710054;

2. 西北有色地质勘查局, 陕西 西安 710054)

摘要: 文章对祁连地块南缘柴达木山复式岩体中部的似斑状二长花岗岩以及二长花岗岩进行了详细的岩石学、地球化学及锆石 U-Pb 年代学研究, 结果表明似斑状二长花岗岩为富钾弱过铝质 S 型花岗岩, 是杂砂岩在温度约 820°C, 压力 0.8~0.9 Gpa 的条件下, 经黑云母脱水引发部分熔融形成, 形成于同碰撞环境, 时代为(456.2±3) Ma; 二长花岗岩为富钾准铝质 S 型花岗岩, 是砂泥质沉积岩在温度约 750°C, 压力 < 0.8 Gpa 的条件下, 经白云母脱水引发部分熔融形成, 形成于伸展背景下, 时代为(437.2±1.5) Ma。结合前人的研究成果, 认为柴达木山复式岩体是一个挤压到伸展等多种构造体制下形成的岩体。

关键词: 祁连地块; 柴北缘; 柴达木山; 锆石 U-Pb 定年

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Zircon U-Pb age of the monzogranite from the middle segment of the Qaidam Mountain composite granite on the south margin of the Qilian Mountain

ZHU Xiao-hui¹, WANG Hong-liang¹, YANG Meng²

(1. Key Laboratory for the Study of Focused Magmatism and Giant Ore Deposits, Xi'an Center of Geological Survey, CGS, Xi'an, Shaanxi, China 710054; 2. Northwest Mining and Geology Group Co., Ltd., for Nonferrous Metals (NWME), Shaanxi, China, 710054)

Abstract: Based on integrated studies of petrography, geochemical and geochronology of the porphyritic monzogranite and monzogranite from the middle segment of the Qaidam Mountain composite granite, the authors hold that the porphyritic monzogranite is a K-rich peraluminous S-type granite formed by the biotite partial melting of greywacke under the condition of higher pressure (0.8-0.9 Gpa) and temperature (about 820°C), and resulted from continent-continent collision in (456.2±3) Ma; The monzogranite is a K-rich metaluminous S-type granite, which was formed by the muscovite partial melting of meta-politic-arenaceous sedimentary rocks under the condition of lower pressure (< 0.8 Gpa) and temperature (about 750°C), and was formed in

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作者简介: 朱小辉, 男, 1986 年生, 工程师, 岩石学专业; E-mail: zhuxiaohui_012@163.com。

an extension geological setting in (437.2 ± 1.5) Ma. Combined with the results of previous studies, the authors consider that the Qaidam Mountain composite granite was formed in a complex plate tectonic system which transformed from contraction to extension.

Key words: Qilian massif; North Qaidam; Qaidam Mountain; LA-ICP-MS U-Pb dating

About the first author: ZHU Xiao-hui, male, born in 1986, engineer; E-mail: zhuxiaohui_012@163.com.

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柴北缘构造带位于祁连地块南缘,是一条在早古生代经历过陆壳深俯冲形成的高压-超高压变质岩带,人们已经发现了多种类型的高压-超高压变质岩石^[1-9],这引起了人们对本地区早古生代构造背景的广泛关注。沿祁连地块南缘以及柴北缘高压-超高压变质带分布有大量的古生代花岗岩,为了揭示陆壳深俯冲过程中的岩浆响应事件及柴北缘构造带的形成与演化,人们已对这些花岗岩开展了大量的年代学、地球化学和成因等方面的研究工作^[10-22]。柴达木山复式岩体是分布在祁连地块南缘规模最大的岩体之一,有人认为该岩体形成于陆-陆碰撞环境,时代为436~446 Ma^[11,21],有人则认为该岩体应形成在后碰撞或后造山环境,时代为440 Ma^[18-19]。为准确限定该岩体的成因、源区性质、形成时代和构造环境,本文在前人研究的基础上,对柴达木山复式岩体开展了进一步的岩石学、地球化学和锆石LA-ICP-MS U-Pb年代学研究,以期探讨柴达木山复式岩体的成因及形成环境,并为进一步探讨区内构造演化历史提供重要约束。

1 地质背景和岩石学特征

祁连地块位于青藏高原东北部,其南北分别以宗务隆-青海南山断裂及野牛台-托莱河南侧-门源-白银断裂为界与柴北缘构造带及北祁连俯冲-增生杂岩带相邻。该地块具有三重结构,其中早前寒武纪结晶基底由西段的北大河岩群、托赖岩群,中段的湟源群以及东段的马衔山群组成,岩石类型主要为角闪岩相的副片麻岩和花岗质片麻岩,中、上部则由中元古界变质火山岩-沉积岩组成的变质基底以及新元古界碎屑岩-碳酸盐岩组成的沉积盖层构成。柴北缘构造带以乌兰-鱼卡断裂为界可划分为南北两部分,北带发育有完整的基底和沉积盖层双层结构,陆松年等^[23]称之为“欧龙布鲁克微板块”。其基底主要由德令哈杂岩和达肯大坂群组成,沉积盖层由中元古代万洞沟群和新元古代全

吉群共同构成^[24-25]。南带位于柴北缘构造带靠近柴达木盆地一侧,为早古生代形成的俯冲碰撞杂岩带,主要由岛弧火山岩、岛弧深成岩和经历了高压-超高压变质作用的深俯冲板片组成。

柴达木山复式岩体位于祁连地块南缘,柴北缘构造带的北侧(图1,图2),岩体规模很大,面积可达2000 km²,其北部、东部均被新生代沉积物覆盖,西南部及东南部则有较强韧性剪切带通过,为祁连地块南部边界的一部分。该岩体南部主要为一套浅灰白色-肉红色粗粒-巨粒环斑花岗岩,周边被中粗粒正长花岗岩、似斑状正长花岗岩和粗粒二长花岗岩等围绕;中部主要由中-细粒二长花岗岩、二长花岗斑岩、正长花岗岩等组成;北部则以中粗粒正长花岗岩、似斑状正长花岗岩和粗粒二长花岗岩为主^[18-19]。本文主要对分布于柴达木山岩体中部的似斑状二长花岗岩以及中-细粒二长花岗岩进行了研究。其中似斑状二长花岗岩(图3-a)呈灰白色,(似)斑状结构,块状构造。斑晶(约25%)主要由长石和石英组成,其中斜长石呈半自形板状,含量约40%;钾长石呈半自形板状、粒状,含量约35%;石英呈半自形-他形粒状,含量约25%。基质(约75%)主要由细粒半自形-他形长英质矿物及少量黑云母等副矿物组成。中-细粒二长花岗岩(图3-b)呈灰白色,中-细粒花岗结构,块状构造。主要由钾长石(约45%)、斜长石(约20%)、石英(约30%)以及黑云母(约4%)组成,其中钾长石和斜长石呈半自形板状,斜长石可见弱绿帘石化、绢云母化;石英呈半自形-他形粒状;黑云母主要呈片状集合体产出,具弱的绿帘石化。

2 分析方法

本文涉及的所有分析测试皆在西北大学大陆动力学国家重点实验室完成。主量元素分析在荧光光谱仪(XRF)上测定,元素分析误差<5%。微量元素和稀土元素测定在电感耦合等离子质谱仪

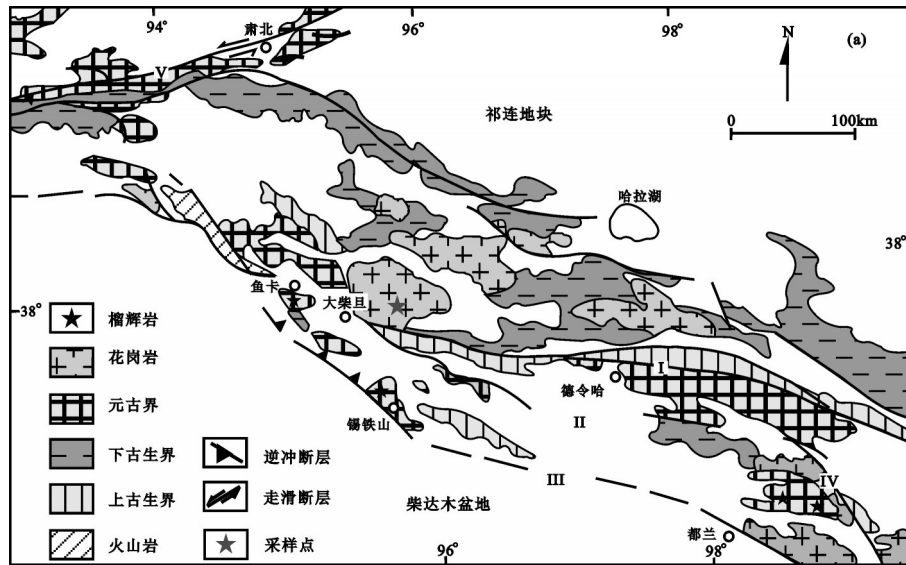


图1 柴北缘地质简图^[1]

I—宗务隆—青海南山断裂; II—乌兰—鱼卡断裂; III—柴北缘断裂; IV—哇洪山—温泉断裂; V—阿尔金走滑断裂

Fig.1 Simplified geological map of northern marginal Qaidam^[1]

I—Zongwulong—Qinghainanshan fault; II—Wulan—Yuka fault; III—North Qaidam fault; IV—Wahongshan—Wenquan fault; V—Altun strike-slip fault

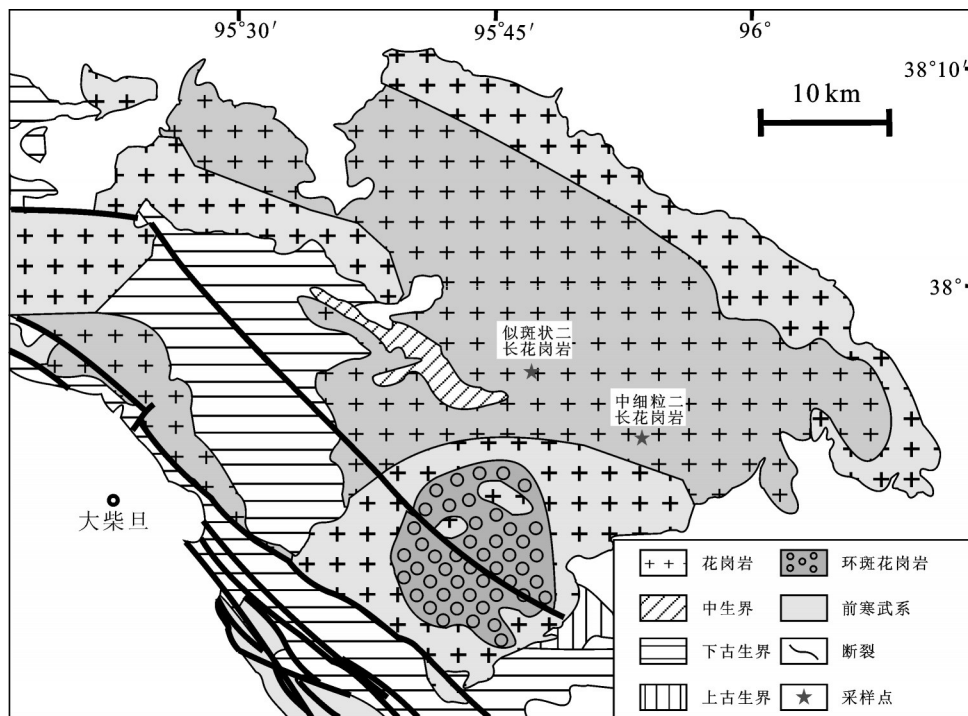


图2 柴达木山岩体地质简图^[19]

Fig.2 Geological map of the Qaidam Basin^[19]

(ICP-MS)上进行, Co、Ni、Zn、Ga、Rb、Y、Zr、Nb、Hf、Ta、REE(除Hf和Lu)等元素分析精度优于5%, 其他低浓度元素的分析精度为5%~10%。详细的分

析方法见 Gao 等^[26]。

锆石的 CL 图像分析由加载英国 Gatan 公司的 Mono CL3+型阴极荧光探头的电子显微扫描电镜

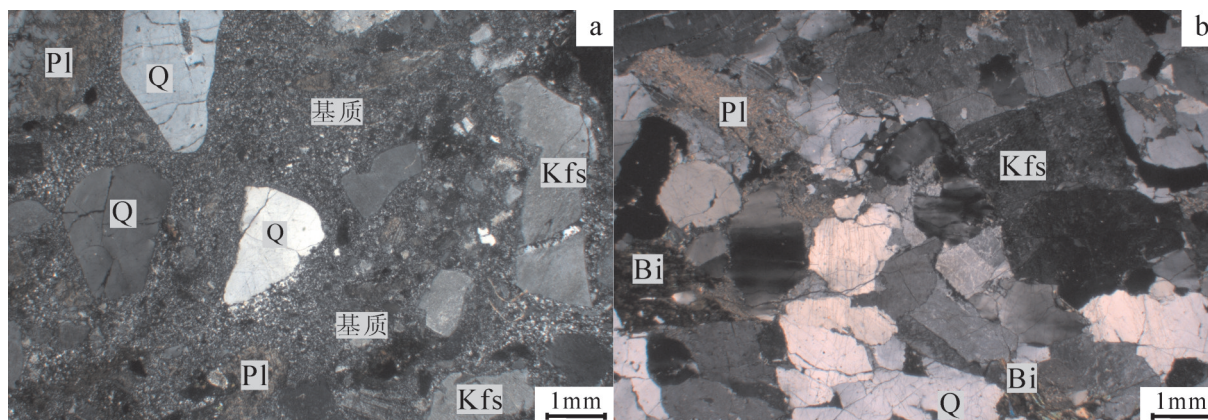


图3 柴达木山似斑状二长花岗岩(a)及二长花岗岩(b)显微岩石学照片

Kfs—钾长石; Pl—斜长石; Bi—黑云母; Q—石英

Fig.3 Microstructures of porphyritic monzogranite (a) and monzogranite (b) from Qaidam Basin

Kfs—K-feldspar; Pl—Plagioclase; Bi—Biotite; Q—Quartz

完成。LA-ICP-MS分析在Hewlett Packard公司的Agilent 7500a ICP-MS和德国Lambda Physik公司的ComPex102 Excimer激光器(工作物质ArF,波长193 nm)、MicroLas公司的GeoLas 200 M光学系统的联机上进行。实验中采用He作为剥蚀物质的载气,锆石年龄采用国际标准锆石91500作为外标标准物质,元素含量采用NIST SRM610作为外标,²⁹Si作为内标。详细试验步骤及数据处理方法见Yuan et al^[27]。

3 岩石地球化学

3.1 主量元素

本地区似斑状二长花岗岩及二长花岗岩的地球化学分析结果见表1。

似斑状二长花岗岩SiO₂含量变化于68.61%~70.11%, Al₂O₃含量为14.07%~14.09%, 铝饱和指数A/CNK=1.04~1.07, 在A/CNK-A/NK图解(图4-a)中, 样品点全部落在过铝质范围内, 属于弱过铝质花岗岩; 样品的Na₂O含量为2.56%~2.61%, K₂O含量为5.41%~5.68%, Na₂O+K₂O含量为8.02%~8.24%, K₂O/Na₂O为2.07~2.22, 里特曼指数为2.37~2.65, 在SiO₂-K₂O图上(图4-b), 样品点全部落在钾玄岩系列岩石范围内; 岩石的铁含量较高, Fe₂O₃^T为3.02%~3.14%, TiO₂含量为0.34%~0.37%, MgO含量为0.56%~0.90%, Mg[#]=30~40, 平均为35。上述特征表明柴达木山似斑状二长花岗岩具有富硅、铝、钾、铁、镁的特点, 总体显示了富钾弱过铝质花岗岩的特征。

二长花岗岩SiO₂含量变化于72.52%~75.34%, Al₂O₃含量为11.58%~12.93%, 铝饱和指数A/CNK=0.91~0.99, 属于准铝质花岗岩(图4-a); 样品Na₂O含量为2.44%~2.87%, K₂O含量为5.31%~6.42%, Na₂O+K₂O含量为8.16%~9.06%, K₂O/Na₂O为1.86~2.50, 里特曼指数为2.08~2.78, 在SiO₂-K₂O图上(图4-b), 样品点全部落在钾玄岩系列岩石范围内; 二长花岗岩铁含量较低, Fe₂O₃^T为1.94%~2.59%, TiO₂含量为0.09%~0.17%, MgO含量为0.18%~0.49%, Mg[#]=15~37, 平均为23。上述特征表明柴达木山二长花岗岩具有富硅、铝、钾, 贫铁、镁的特点, 总体具有富钾准铝质花岗岩的特征。

3.2 微量元素

似斑状二长花岗岩稀土元素总量较高, Σ REE=249.19×10⁻⁶~259.92×10⁻⁶, (La/Sm)_N=3.92~3.91, (La/Yb)_N=12.05~12.69, (Gd/Yb)_N=1.91~1.99, 具有轻稀土富集, 重稀土平坦的稀土配分模式(图5-a), 同时显示了轻微的Eu负异常(δEu=0.45~0.48); 微量元素原始地幔标准化蛛网图显示(图5-b), 似斑状二长花岗岩富集大离子亲石元素(如Rb、Th、U、K等), 亏损高场强元素(如Nb、Ta、Ti等), 具有轻微的Ba以及明显的Sr负异常, Zr、Hf无明显分异。

二长花岗岩稀土元素总量相对较低, Σ REE=108.73×10⁻⁶~186.22×10⁻⁶, (La/Sm)_N=2.02~3.36, (La/Yb)_N=1.62~5.17, (Gd/Yb)_N=0.62~1.13, 具有轻稀土略微富集, 重稀土平坦型稀土配分模式(图5-c), 同时具有明显的Eu负异常(δEu=0.06~0.27); 微量元素原

表1 柴达木山似斑状二长花岗岩、二长花岗岩主量元素(%),微量元素(10^{-6})分析结果
Table 1 Major element (%) and trace element ($\times 10^{-6}$) compositions of porphyritic monzogranite and monzogranite from Qaidam Basin

分析项目	二长花岗岩													
	HPM3-3-1	HPM4-8-1	HPM1 26-1	HPM1 30-1	HPM1 38-1	HPM1 46-1	HPM1 64-1	HPM1 74-1	L154 D1552-1	L157 D1558-1	L157 D1554-1	L157 D1557-1		
SiO ₂	68.61	70.11	75.03	75.07	75.34	74.35	74.79	74.02	74.73	73.95	72.52	74.19		
TiO ₂	0.34	0.37	0.10	0.09	0.12	0.17	0.12	0.13	0.16	0.10	0.16	0.10		
Al ₂ O ₃	14.07	14.09	11.77	11.75	11.61	12.16	11.69	12.14	11.58	11.93	12.93	11.81		
Fe ₂ O ₃	1.72	1.30	0.50	0.55	0.56	0.56	0.34	0.85	0.51	0.57	0.28	0.44		
FeO	1.28	1.55	1.75	1.25	1.58	1.48	1.73	1.28	1.63	1.82	1.87	1.53		
MnO	0.045	0.044	0.024	0.018	0.028	0.029	0.021	0.026	0.027	0.031	0.029	0.024		
MgO	0.9	0.56	0.24	0.49	0.36	0.33	0.32	0.35	0.28	0.19	0.25	0.18		
CaO	1.72	1.68	0.79	0.94	0.96	0.93	0.77	0.98	1.11	0.93	1.35	1.09		
Na ₂ O	2.56	2.61	2.85	2.87	2.83	2.81	2.44	2.78	2.52	2.86	2.64	2.58		
K ₂ O	5.68	5.41	5.31	5.73	5.41	5.58	6.09	5.78	5.67	5.97	6.42	6.21		
P ₂ O ₅	0.11	0.11	0.058	0.057	0.065	0.066	0.064	0.065	0.055	0.059	0.057	0.059		
LOI	2.03	1.03	0.40	0.83	0.50	0.62	0.51	0.56	0.73	0.60	0.32	0.64		
H ₂ O ⁺	0.08	0.02	0.12	0.28	0.14	0.16	0.03	0.11	0.09	0.32	0.33	0.15		
Total	96.15	96.03	96.69	98.13	97.36	97.21	96.85	96.94	96.95	96.94	97.01	97.03		
Rb	212.0	205.0	446.0	464.0	461.0	451.0	454.0	435.0	436.0	390.0	444.0	460.0		
Ba	1156	1103	118.0	92.80	95.00	156.0	65.00	184.0	147.0	351.0	36.60	78.20		
Th	23.30	24.40	20.60	19.00	19.20	24.50	18.30	20.00	27.80	24.50	20.60	19.70		
U	1.40	2.15	4.02	6.65	4.79	3.87	5.34	5.64	2.81	2.43	2.26	2.19		
Ta	1.06	1.16	3.41	4.05	3.09	2.45	1.03	2.01	1.71	1.50	1.79	1.76		
Nb	18.10	17.70	16.10	16.90	16.20	16.60	15.80	15.60	16.00	14.00	16.40	16.60		
Sr	145.3	133.9	27.00	23.00	28.00	34.00	28.00	40.00	31.00	50.00	22.00	22.00		
Zr	234.0	227.0	96.10	80.60	92.30	116.0	96.30	101.0	125.0	117.0	96.30	106.0		
Hf	6.80	6.22	5.10	3.00	2.61	4.27	4.51	4.22	6.63	3.75	3.03	5.32		
Y	33.00	31.10	53.60	49.10	51.90	54.50	58.60	58.60	76.00	60.80	51.30	68.80		
Be	2.86	2.25	10.00	4.00	6.00	5.00	6.00	4.00	5.00	2.00	4.00	5.00		
Bi	0.75	0.32	1.82	1.09	1.72	1.28	2.48	0.69	0.39	0.31	0.75	0.68		
Co	4.32	4.92	3.00	2.00	3.00	3.00	3.00	2.00	3.00	4.00	3.00	4.00		
Cr	17.80	19.80	17.00	27.00	15.00	20.00	20.00	13.00	13.00	24.00	12.00	17.00		

续表1

分析项目	似斑状二长花岗岩										二长花岗岩													
	IPM3-3-1	IPM4-8-1	IPM1 26-1	IPM1 30-1	IPM1 38-1	IPM1 46-1	IPM1 64-1	IPM1 74-1	L154 D1552-1	L157 D1558-1	L157 D1554-1	L157 D1557-1	IPM3-3-1	IPM4-8-1	IPM1 26-1	IPM1 30-1	IPM1 38-1	IPM1 46-1	IPM1 64-1	IPM1 74-1	L154 D1552-1	L157 D1558-1	L157 D1554-1	L157 D1557-1
Cs	12.60	4.80	26.60	23.10	15.40	18.70	19.20	19.30	13.40	15.30	20.30	17.40	12.60	4.80	26.60	23.10	15.40	18.70	19.20	19.30	13.40	15.30	20.30	17.40
Cu	16.30	11.10	14.00	7.00	12.00	10.00	7.00	9.00	19.00	11.00	15.00	22.00	16.30	11.10	14.00	7.00	12.00	10.00	7.00	9.00	19.00	11.00	15.00	22.00
Ga	19.60	17.20	16.00	16.00	14.30	15.40	17.20	13.80	15.20	17.90	13.40	16.00	19.60	17.20	16.00	16.00	14.30	15.40	17.20	13.80	15.20	17.90	13.40	16.00
Li	44.70	34.40	41.00	31.00	25.00	30.00	28.00	30.00	29.00	50.00	29.00	26.00	44.70	34.40	41.00	31.00	25.00	30.00	28.00	30.00	29.00	50.00	29.00	26.00
Mo	3.09	6.34	6.00	6.00	12.00	8.00	7.00	3.00	2.00	2.00	1.00	2.00	3.09	6.34	6.00	6.00	12.00	8.00	7.00	3.00	2.00	2.00	1.00	2.00
Ni	6.40	8.90	5.00	4.00	7.00	2.00	6.00	4.00	4.00	3.00	3.00	2.00	6.40	8.90	5.00	4.00	7.00	2.00	6.00	4.00	4.00	3.00	3.00	2.00
Pb	27.90	33.60	93.00	98.00	88.00	91.00	92.00	96.00	98.00	100.0	99.00	92.00	27.90	33.60	93.00	98.00	88.00	91.00	92.00	96.00	98.00	100.0	99.00	92.00
Sn	3.50	3.40	19.00	23.00	17.00	19.00	16.00	12.00	13.00	10.00	13.00	16.00	3.50	3.40	19.00	23.00	17.00	19.00	16.00	12.00	13.00	10.00	13.00	16.00
W	1.98	1.38	5.00	3.00	4.00	4.00	5.00	3.00	2.00	3.00	1.00	2.00	1.98	1.38	5.00	3.00	4.00	4.00	5.00	3.00	2.00	3.00	1.00	2.00
Zn	56.40	49.60	46.00	37.00	44.00	48.00	45.00	50.00	69.00	36.00	45.00	44.00	56.40	49.60	46.00	37.00	44.00	48.00	45.00	50.00	69.00	36.00	45.00	44.00
La	54.10	55.90	20.70	17.00	19.60	28.20	16.90	24.20	29.50	19.90	36.50	19.20	54.10	55.90	20.70	17.00	19.60	28.20	16.90	24.20	29.50	19.90	36.50	19.20
Ce	99.80	106.0	44.70	37.80	41.80	59.30	36.20	48.40	62.00	41.30	70.50	41.80	99.80	106.0	44.70	37.80	41.80	59.30	36.20	48.40	62.00	41.30	70.50	41.80
Pr	12.71	13.23	5.81	5.01	5.43	7.71	5.06	6.31	7.64	5.34	9.02	5.55	12.71	13.23	5.81	5.01	5.43	7.71	5.06	6.31	7.64	5.34	9.02	5.55
Nd	48.45	50.45	20.70	18.10	19.60	27.60	17.20	21.70	27.60	19.40	31.60	20.40	48.45	50.45	20.70	18.10	19.60	27.60	17.20	21.70	27.60	19.40	31.60	20.40
Sm	8.92	9.23	5.79	5.25	5.13	6.75	5.05	5.71	6.67	5.75	7.02	6.15	8.92	9.23	5.79	5.25	5.13	6.75	5.05	5.71	6.67	5.75	7.02	6.15
Eu	1.24	1.36	0.23	0.19	0.18	0.35	0.14	0.38	0.29	0.19	0.62	0.13	1.24	1.36	0.23	0.19	0.18	0.35	0.14	0.38	0.29	0.19	0.62	0.13
Gd	7.44	7.62	5.64	5.04	4.97	6.49	4.89	5.74	7.26	5.70	6.91	6.36	7.44	7.62	5.64	5.04	4.97	6.49	4.89	5.74	7.26	5.70	6.91	6.36
Tb	1.26	1.22	1.48	1.32	1.19	1.40	1.19	1.29	1.63	1.33	1.29	1.68	1.26	1.22	1.48	1.32	1.19	1.40	1.19	1.29	1.63	1.33	1.29	1.68
Dy	6.38	6.20	9.33	8.61	7.74	9.77	8.10	9.09	11.80	9.79	8.76	11.80	6.38	6.20	9.33	8.61	7.74	9.77	8.10	9.09	11.80	9.79	8.76	11.80
Ho	1.18	1.16	1.94	1.74	1.58	2.00	1.72	1.94	2.63	1.98	1.85	2.56	1.18	1.16	1.94	1.74	1.58	2.00	1.72	1.94	2.63	1.98	1.85	2.56
Er	3.52	3.45	5.95	5.53	4.96	6.20	5.40	6.12	8.46	6.53	5.54	8.34	3.52	3.45	5.95	5.53	4.96	6.20	5.40	6.12	8.46	6.53	5.54	8.34
Tm	0.51	0.49	0.93	0.92	0.77	0.97	0.82	0.96	1.30	1.11	0.82	1.34	0.51	0.49	0.93	0.92	0.77	0.97	0.82	0.96	1.30	1.11	0.82	1.34
Yb	3.22	3.16	5.86	5.86	4.92	6.25	5.28	6.18	7.98	7.10	5.06	8.49	3.22	3.16	5.86	5.86	4.92	6.25	5.28	6.18	7.98	7.10	5.06	8.49
Lu	0.46	0.45	0.85	0.88	0.73	0.86	0.78	0.85	1.17	1.03	0.73	1.24	0.46	0.45	0.85	0.88	0.73	0.86	0.78	0.85	1.17	1.03	0.73	1.24

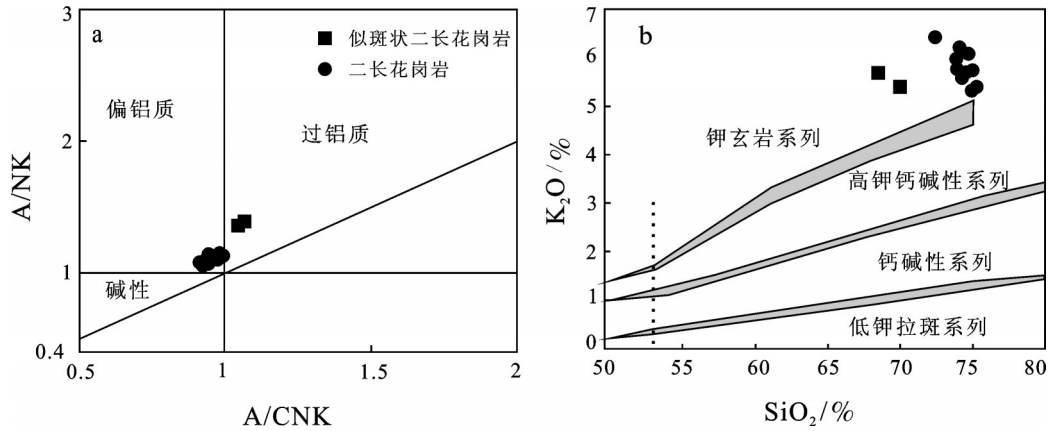


图4 柴达木山似斑状二长花岗岩及二长花岗岩 A/CNK-A/NK 图解(a)^[28]与 SiO₂-K₂O 图解(b)^[29]
 Fig. 4 A/CNK-A/NK diagram (a)^[28] and SiO₂-K₂O diagram (b)^[29] for porphyritic monzogranite and monzogranite from Qaidam Basin

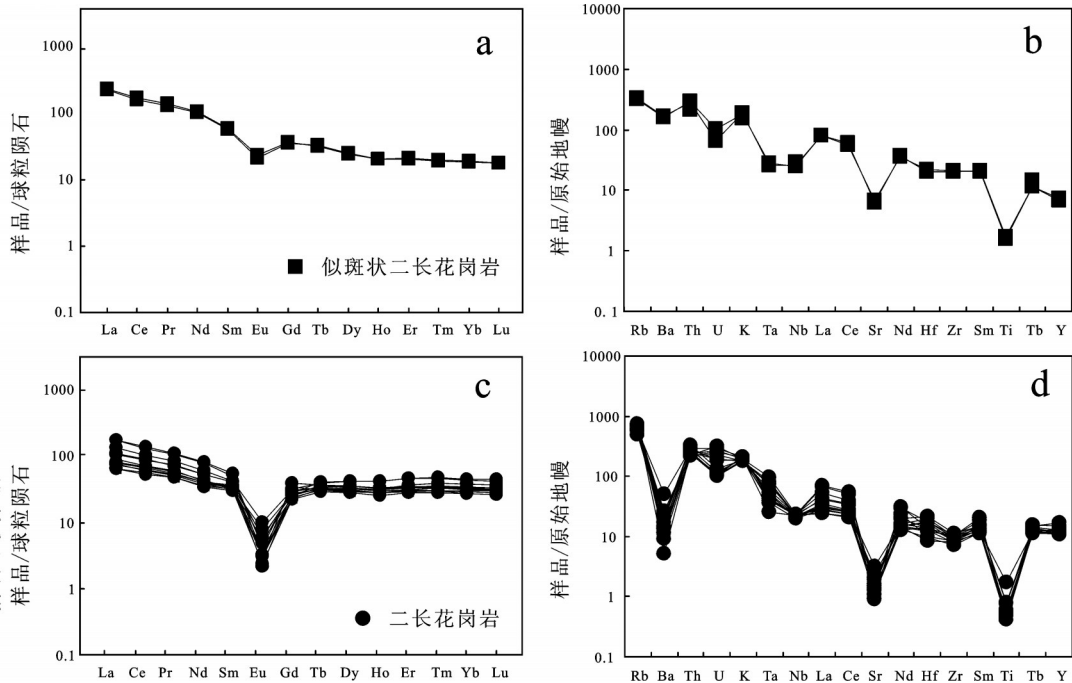


图5 柴达木山似斑状二长花岗岩及二长花岗岩石球粒陨石标准化稀土配分模式图(a、c)和微量元素原始地幔标准化蛛网图(b、d)(标准化数值据^[30])
 Fig.5 Chondrite-normalized REE-patterns (a, c) and primitive-mantle normalized spider diagram (b, d) for porphyritic monzogranite and monzogranite from Qaidam Basin (normalized data after reference^[30])

始地幔标准化蛛网图上(图5-d),二长花岗岩富集大离子亲石元素(如Rb、Th、U、K等),亏损高场强元素(如Nb、Ta、Ti等),具有明显的Sr、Ba负异常。

4 锆石 U-Pb 年代学

似斑状二长花岗岩中的锆石为多为无色、淡黄

色,以半自形-自形长柱状为主,长宽比介于3:1~1.5:1,边界清晰、平直,柱面发育,发育明显的岩浆震荡环带。微量元素分析结果显示(表2、表3),测点的U、Th含量分别为 $35.0 \times 10^{-6} \sim 290 \times 10^{-6}$ 、 $35.2 \times 10^{-6} \sim 125 \times 10^{-6}$,Th/U值在0.28~1.39,绝大部分大于0.4(平均为0.64),且均具有较高的稀土元素总量和重稀土含

表2 柴达木山似斑状二长花岗岩、二长花岗岩锆石稀土元素分析结果(10^{-6})Table 2 REE concentrations of zircons from porphyritic monzogranite and monzogranite from Qaidam Basin (10^{-6})

测点	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
似斑状二长花岗岩														
1	0.031	5.68	0.106	2.06	4.95	0.231	27.77	9.31	107.21	39.12	165.28	33.05	309.29	55.76
2	0.031	2.33	0.079	1.04	3.63	0.092	29.69	13.9	203.95	85.81	409.73	87.91	846.09	150.98
3	0.026	2.003	0.027	0.64	2.68	0.059	19.89	9.73	140.66	59.52	287.81	62.88	607.05	108.51
4	0.026	4.5	0.08	2.32	5.18	0.127	32.28	12.55	157.8	60.71	269.77	57.07	537.09	93.46
5	0.0216	4.06	0.051	1.14	3.39	0.084	20.95	8.93	116.09	47.09	216.3	46.63	453.3	80.99
6	0.0253	4.55	0.112	2.13	4.55	0.289	24.94	8.74	103.57	38.87	169.25	34.48	328.1	58.09
7	0.0132	2.403	0.0311	0.67	2.34	0.063	18.35	8.23	113.67	46.52	217.99	47.37	465.28	84.16
8	0.04	4.89	0.216	2.77	5.9	0.427	33.93	12.73	157.62	59.45	261.21	54.41	510.35	89.47
9	0.0254	2.64	0.0638	0.96	3.08	0.098	25.15	11.87	164.13	68.1	318.15	70.29	680.98	120.13
10	0.025	4.24	0.141	1.86	4.79	0.182	30.89	11.82	149.99	58.47	264.46	55.97	537.01	94.01
11	0.036	4.39	0.078	1.76	4.35	0.156	30.4	11.85	152.34	59.72	265.98	55.75	532.72	94.17
12	0.028	5.29	0.0437	1.11	2.45	0.164	16.78	6.62	82.38	32.42	146.68	31.12	299.39	53.93
13	0.04	3.43	0.138	2.07	4.69	0.172	22.66	7.78	90.74	32.81	139.41	28.4	265.52	46.99
14	0.041	4.33	0.054	1.27	3.41	0.144	20.73	8.15	99.5	38.08	170.46	35.93	345.31	61.31
15	0.034	6.14	0.165	2.63	4.12	0.275	27.52	9.15	102.6	37.6	161.53	33.5	312.76	57.34
16	0.029	2.95	0.0423	0.78	2.71	0.091	17.94	7.59	98.07	39.21	177.86	37.77	369.27	66.65
17	0.1	3.08	0.129	1.35	3.19	0.373	16.42	5.49	61.26	23.03	97.83	20.14	195.85	36.72
18	0.0183	6.48	0.129	1.94	4.94	0.457	29.43	10.9	137.03	51.56	222.01	46.07	436.35	76.97
19	0.046	3.78	0.092	1.74	3.6	0.172	24.68	8.77	108.68	41.51	182.44	38.2	368.02	66.41
20	0.028	3.06	0.033	0.75	2.62	0.091	17.55	7.66	105.42	41.48	193.84	42.64	407.45	72.77
21	0.0191	3.35	0.073	1.19	4.33	0.098	30.34	12.86	172.84	69.82	318.8	67.81	654.55	115.3
22	0.179	5.82	0.265	3.72	6.46	0.455	31.79	9.93	109.23	39.07	159.13	32.23	304.24	53.76
二长花岗岩														
1	0.04	3.4	0.077	0.98	2.89	0.119	21.3	10.29	141.78	58.75	274.46	62.11	602.67	99.54
2	128.12	351.21	48.66	241.2	68.13	0.971	91.08	21.36	197.3	64.84	262.89	52.83	485.82	79.53
3	0.034	6.18	0.062	1.05	3.12	0.115	23.08	10.17	131.11	51.88	233.74	50.92	483.63	79.23
4	2.66	27.64	1.637	11.71	19.04	1.2	66.97	25.14	251.77	72.7	279.89	56.09	497.98	78.34
5	0.034	5.15	0.096	1.45	3.55	0.188	22.22	8.5	108.61	41.71	184.62	40.14	385.65	63.69
6	0.511	24.68	0.212	2.66	6.38	0.046	40.49	15.11	182.89	68.73	292.47	61.28	573.14	95.69
7	17.21	57.17	7.37	40.37	16.94	0.393	47.87	14.58	155.45	54.9	220.09	43.12	398.98	62.86
8	0.289	5.73	0.144	1.24	3.37	0.125	22.17	9.49	121.75	48.05	215.86	47.05	448.06	73.91
9	0.0244	6.63	0.039	1.14	3.75	0.13	23.59	10.25	131.53	52.04	231.67	50.96	484.73	78.48
10	0.639	13.74	0.336	3.32	5.92	0.522	35.57	15.53	204.82	81.94	371.18	81.24	773.63	128.25
11	0.052	5	0.0344	0.71	2.6	0.095	17.73	7.83	104.13	41.23	187.26	41.33	393.82	65.44
12	0.701	5.5	0.366	3.14	5.25	0.394	25.3	9.74	122.19	45.55	199.31	42.46	403.44	66.89
13	0.065	5.35	0.106	1.58	2.7	0.102	18.55	7.43	96.3	37.74	166.31	36.5	347.85	59.13
14	0.066	2.84	0.078	1.5	3.77	0.094	26.08	11.78	156.2	61.27	275.75	59.76	560.92	91.3
15	0.023	6.26	0.053	1.49	4.06	0.089	24.71	10.48	138.18	53.14	234.77	52.67	499	80.74
16	0.602	5.01	0.288	2.08	2.96	0.16	17.21	5.94	70.31	25.84	115.59	26.35	262.32	44.41
17	0.046	8.11	0.082	1.49	2.78	0.808	13.31	4.29	50.63	19.32	90.46	20.82	217.94	40.49
18	4.45	18.75	1.796	10.61	7.91	0.167	34.07	13.11	162.89	62.08	277.45	59.08	546.17	88.85
19	0.0166	4.83	0.059	0.73	2.21	0.133	19.26	7.94	106.24	43.05	194.17	42.43	406.7	66.86
20	0.034	2.264	0.058	1.63	4.54	0.056	36.3	18.02	257.08	106.05	496.16	112.72	1107.34	182.56
21	0.036	2.5	0.055	1.07	4.05	0.073	32.97	16.88	245.19	102.07	481.59	107.14	1027.47	169.25
22	0.044	4.66	0.031	0.8	2.33	0.101	18.41	7.6	100.16	40.64	187.83	41.23	398.4	67.85
23	0.172	6.68	0.189	1.64	3.81	0.177	21.25	8.72	106.56	39.71	174.99	38.09	362.68	60.46
24	0.035	7.79	0.191	3.21	6.14	0.594	27.86	9.53	106.3	38.29	155.8	31.83	291.15	46.48
25	0.038	6.23	0.077	1.84	5.3	0.172	37.06	15.79	205.85	80.43	360.3	77.85	729.82	120.13

续表 3

测点	^{232}Th		Th/U	同位素比值				年龄值/Ma					
	^{238}U	含量/ 10^{-6}		$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	1σ	1σ	
二长花岗岩													
1	99.28	440.7	0.23	0.54542	0.0175	0.07069	0.00067	450	54	442	11	440	4
2	154.8	284.8	0.54	0.55452	0.01671	0.07034	0.00064	498	50	448	11	438	4
3	135.8	310.8	0.44	0.52176	0.01436	0.07018	0.00058	367	47	426	10	437	3
4	913.1	719.4	1.27	0.55288	0.0249	0.07057	0.0009	484	77	447	16	440	5
5	82.59	166.6	0.50	0.55251	0.02192	0.07005	0.00079	499	67	447	14	436	5
6	518.0	716.8	0.72	1.01188	0.01397	0.11473	0.00067	740	19	710	7	700	4
7	156.8	203.4	0.77	0.55504	0.02764	0.07094	0.00098	481	86	448	18	442	6
8	106.9	220.6	0.48	0.55178	0.01813	0.06973	0.00067	506	55	446	12	435	4
9	142.9	355.9	0.40	0.54328	0.01466	0.06982	0.00058	469	45	441	10	435	3
10	275.8	812.3	0.34	0.54099	0.00756	0.07008	0.00039	452	21	439	5	437	2
11	98.92	260.4	0.38	0.5245	0.01839	0.06993	0.0007	388	61	428	12	436	4
12	88.00	233.4	0.38	0.59333	0.03593	0.07574	0.00127	484	104	473	23	471	8
13	123.2	238.1	0.52	0.58712	0.04537	0.07425	0.00158	505	133	469	29	462	9
14	70.17	223.3	0.31	0.58109	0.02712	0.07428	0.00097	481	80	465	17	462	6
15	138.4	322.7	0.43	0.54778	0.01339	0.06982	0.00054	487	40	444	9	435	3
16	89.58	372.1	0.24	0.54965	0.01205	0.07078	0.0005	465	36	445	8	441	3
17	98.03	234.0	0.42	0.54948	0.01358	0.07034	0.00054	478	41	445	9	438	3
18	212.6	366.0	0.58	0.5559	0.01449	0.07069	0.00057	492	43	449	9	440	3
19	97.39	229.5	0.42	0.5416	0.01645	0.07016	0.00062	451	52	439	11	437	4
20	104.5	555.3	0.19	0.53643	0.01153	0.06981	0.00049	441	35	436	8	435	3
21	99.67	482.4	0.21	0.54541	0.01024	0.07023	0.00045	465	30	442	7	438	3
22	88.29	222.2	0.40	0.55009	0.01978	0.06991	0.00073	493	61	445	13	436	4
23	144.8	236.9	0.61	0.55958	0.04041	0.07007	0.00138	526	124	451	26	437	8
24	107.7	136.6	0.79	0.58984	0.02164	0.0754	0.00078	480	63	471	14	469	5
25	219.1	585.8	0.37	0.54643	0.01226	0.06983	0.0005	481	37	443	8	435	3

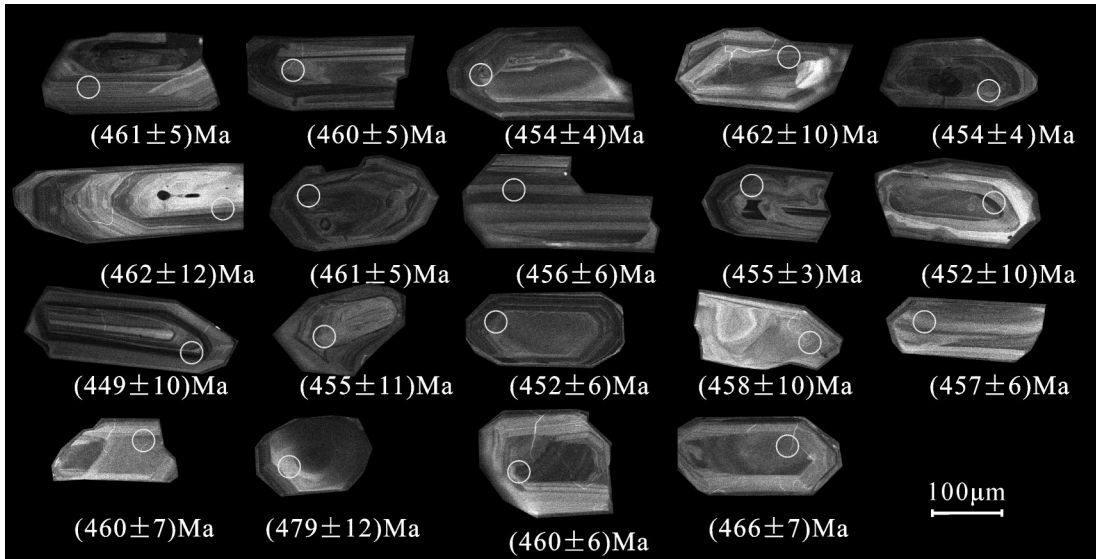


图6 柴达木山似斑状二长花岗岩锆石 CL 图像
Fig.6 CL images of the zircons of porphyritic monzogranite from Qaidam Basin

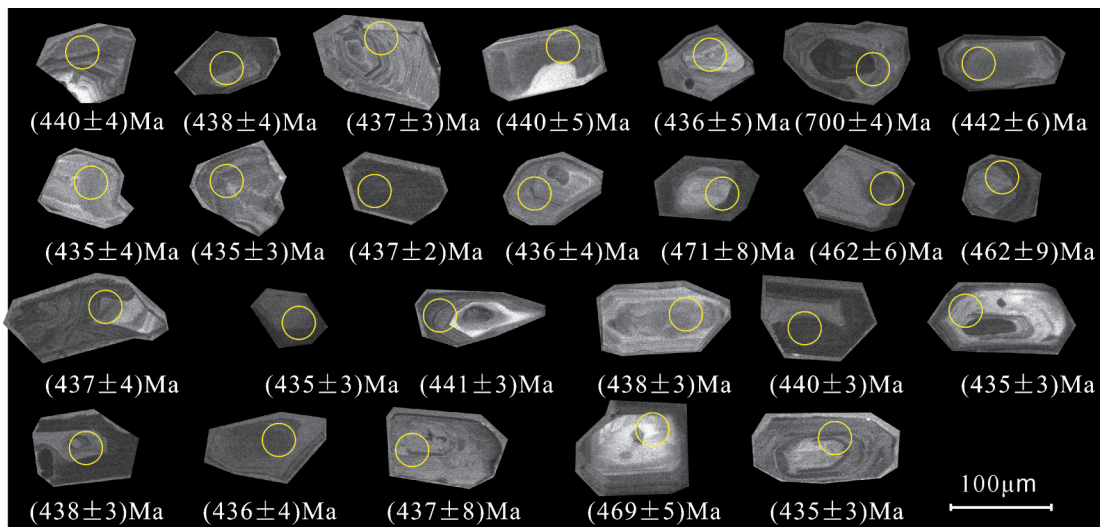


图7 柴达木山二长花岗岩锆石 CL 图像
Fig.7 CL images of the zircons of monzogranite from Qaidam Basin

量($\sum \text{REE}=464 \times 10^{-6} \sim 1835 \times 10^{-6}$ 、 $\sum \text{HREE}=440 \times 10^{-6} \sim 1798 \times 10^{-6}$), $(\text{Gd}/\text{Yb})_N < 1$, 指示这些锆石为岩浆成因锆石^[31]。利用 LA-ICP-MS 锆石 U-Pb 定年方法, 对似斑状二长花岗岩中的锆石共进行 22 次分析(表 3), 锆石 U-Pb 表面年龄为 438~479 Ma, 其中有 21 个测点在谐和线上构成了一个年龄集中区, 其 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(456.2 \pm 3) \text{ Ma}$ (图 8-a), 代表了似斑状二长花岗岩的结晶年龄。

二长花岗岩所选锆石为无色、淡黄色, 以半自形-自形短柱状为主, 长宽比在 1:1~1.5:1, 边界清

晰、平直, 柱面发育, 同样发育明显的岩浆震荡环带。微量元素分析结果(表 2、表 3)显示, 测点的 U、Th 含量分别为 $136 \times 10^{-6} \sim 812 \times 10^{-6}$ 、 $70.2 \times 10^{-6} \sim 913 \times 10^{-6}$, Th/U 值在 0.28~1.39, 绝大部分大于 0.4(平均为 0.47), 具有较高的稀土元素总量和重稀土含量($\sum \text{REE}=470 \times 10^{-6} \sim 2324 \times 10^{-6}$ 、 $\sum \text{HREE}=443 \times 10^{-6} \sim 2279 \times 10^{-6}$), $(\text{Gd}/\text{Yb})_N < 1$, 指示这些锆石为岩浆成因锆石^[31]。利用 LA-ICP-MS 锆石 U-Pb 定年方法, 对似斑状二长花岗岩中的锆石共进行 25 次分析(表 3), 锆石 U-Pb 表面年龄为 435~700 Ma, 含有中奥陶

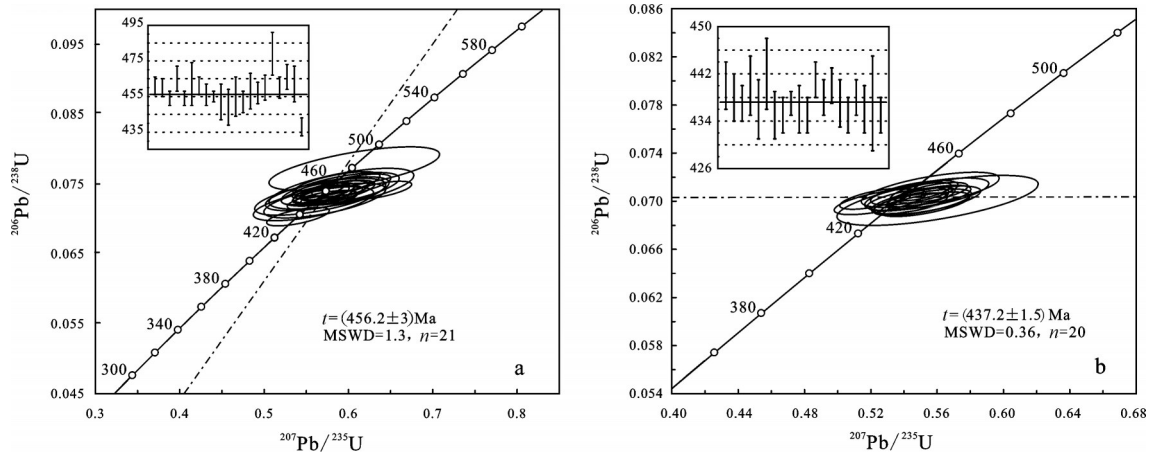


图8 柴达木山似斑状二长花岗岩及二长花岗岩锆石U-Pb年龄谐和图

Fig. 8 Zircon U-Pb concordia diagram of the porphyritic monzogranite (a) and monzogranite (b) from Qaidam Basin

世(466.4 ± 6.3) Ma及新元古代南华纪(700 ± 4) Ma捕虏锆石年龄信息,其中有20个测点在谐和线上构成了一个年龄集中区,其 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为(437.2 ± 1.5) Ma(图8-b),代表了二长花岗岩的结晶年龄。

5 讨论

5.1 岩浆源区性质

柴达木山复式岩体中的似斑状二长花岗岩及二长花岗岩主要由碱性长石、斜长石、石英和黑云母组成,无角闪石;同时具有高硅、高碱,低钛、铁、镁、钙的特点, $\text{K}_2\text{O}/\text{Na}_2\text{O} > 1.43$, $\text{FeO}^{\text{T}}/\text{CaO} > 1$,为准铝质-弱过铝质钾玄岩系列岩石,与S型花岗岩的矿物组合及岩石地球化学特征相似^[32-33]。研究表明,I型花岗岩的 P_2O_5 与 SiO_2 呈明显的负相关关系,S型花岗岩的 P_2O_5 将随着 SiO_2 的增加而呈增高或基本不变的趋势,这一方法已被成功地用于区分I型和S型花岗岩^[34-35]。柴达木山复式岩体中的似斑状二长花岗岩及二长花岗岩 P_2O_5 含量较为稳定,随 SiO_2 含量的增加基本保持不变,指示似斑状二长花岗岩及二长花岗岩为S型花岗岩。

实验岩石学研究证明花岗岩的源区具有多样性,中基性岩石部分熔融通常会形成化学成分偏中性的花岗闪长质的准铝质花岗岩类^[36-37],碎屑沉积岩类部分熔融则会形成偏酸性的过铝质花岗岩类^[36,38],而泥砂质沉积岩类部分熔融则可能形成强烈富铝和富钾的花岗岩^[36,39]。柴达木山似斑状二长花岗岩与二

长花岗岩均为富Al的钾玄质系列花岗岩(A/CNK分别为1.04~1.07和0.91~0.99, K_2O 含量分别为5.41%~5.68%和5.31%~6.42%, $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 分别为2.07~2.22和1.86~2.50),暗示其源岩可能为泥砂质沉积岩类。Sylvester^[40]研究表明,花岗岩的 $\text{CaO}/\text{Na}_2\text{O}$ 比值能够有效示踪其源区成分,一般来说贫长石、富黏土的泥质岩部分熔融产生的熔体 $\text{CaO}/\text{Na}_2\text{O}$ 较低(< 0.30),而富长石、贫黏土的砂质岩部分熔融产生的熔体 $\text{CaO}/\text{Na}_2\text{O}$ 较高(> 0.30)。柴达木山似斑状二长花岗岩的 $\text{CaO}/\text{Na}_2\text{O}$ 值为0.64~0.67,在C/MF-A/MF图解(图9-a)和Rb/Ba-Rb/Sr图解中(图9-b),2个样品点均落在砂质岩源岩范围内;而二长花岗岩的 $\text{CaO}/\text{Na}_2\text{O}$ 较低,介于0.28~0.51,平均为0.36,在C/MF-A/MF图解(图9-a)和Rb/Ba-Rb/Sr图解中(图9-b),样品点落在或接近泥质岩源岩的范围,个别落在砂质岩源岩范围。因此,柴达木山似斑状二长花岗岩与二长花岗岩的源区可能存在差异,其中前者可能为地壳杂砂质沉积岩部分熔融的产物,而二长花岗岩的源岩泥质含量更高,可能为砂泥质沉积岩部分熔融形成。

5.2 部分熔融条件

研究表明,花岗岩的地球化学特征不仅与其源区成分密切相关,同时还与源区岩石发生熔融时的温压条件有关。Brown^[42]指出变质沉积岩的熔融作用主要有饱和水固相线上的熔融、白云母脱水熔融和黑云母脱水熔融3种机制,不同的部分熔融机制通常会产生不同类型的熔体。通常由白云母脱水

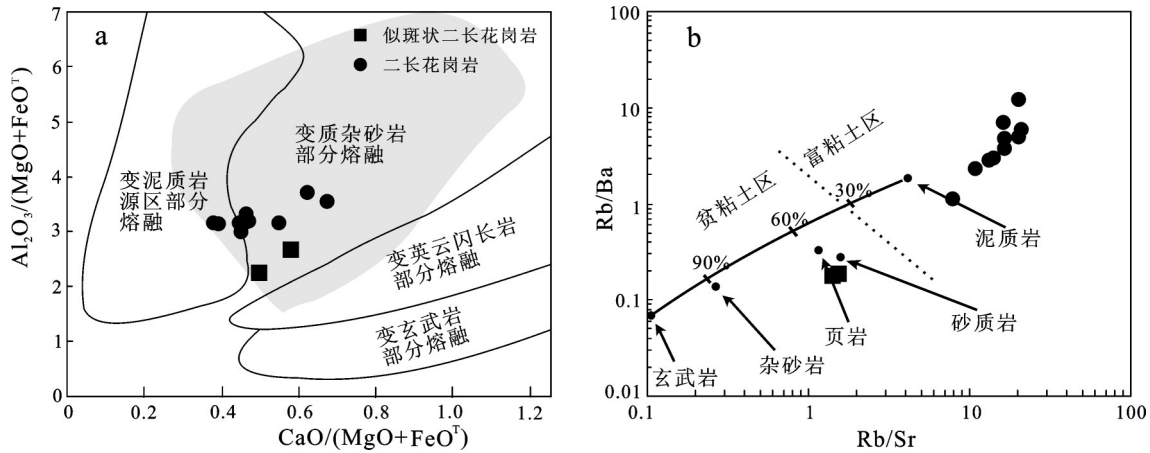


图9 柴达木山似斑状二长花岗岩及二长花岗岩的C/MF-A/MF图解(a)^[41]和Rb/Sr-Rb/Ba图解(b)^[40]
 Fig.9 C/MF-A/MF diagram (a) and Rb/Sr-Rb/Ba diagram (b) of porphyritic monzogranite and monzogranite from Qaidam Basin^[39]

熔融产生的熔体具有较低Fe、Mg、Ti以及较高的K含量^[43],同时熔体的Rb/Sr比值较高^[44-45];而黑云母脱水熔融产生的熔体通常具有较高的Fe、Mg以及Ti含量,Rb/Sr值普遍较低(一般小于4.5)^[46]。柴达木山似斑状二长花岗岩具有较高的TFe₂O₃+MgO+TiO₂含量(3.95~4.38,平均为4.17),以及低的Rb/Sr值(1.46~1.53,平均为1.50),K₂O含量较低(5.41%~5.68%,平均为5.55%);而二长花岗岩的TFe₂O₃+MgO+TiO₂含量(2.42~2.88,平均为2.71),Rb/Sr值以及K₂O含量较高(Rb/Sr值为7.80~20.91,平均为15.6;K₂O含量为5.31%~6.42%,平均为5.82%)。这说明二者源岩的部分熔融机制也存在差异,其中似斑状二长花岗岩可能主要经黑云母脱水熔融形成,而二长花岗岩的形成可能以白云母脱水熔融为主。

锆石是花岗岩中较早结晶的副矿物,而锆石中Zr的分配系数对温度十分敏感,其在岩浆中的含量与温度存在相关性,因而岩浆中锆的饱和温度可近似代表花岗质岩石近液相线的温度^[47-48],另外花岗岩大多是绝热上升就位的,岩浆早期结晶时的温度

表4 柴达木山似斑状二长花岗岩、二长花岗岩的锆石饱和温度计

Table 4 Results from saturated Zr thermometer of porphyritic monzogranite and monzogranite from Qaidam Basin

岩性	主微量样号	M/10 ⁻⁶	D _{Zr}	t _{Zr} /°C
似斑状二长花岗岩	IIPM3-3-1	2120	1.4	816.8
	IIPM4-8-1	2185	1.4	818.2
二长花岗岩	IIPM1 26-1	5161	1.4	743.3
	IIPM1 30-1	6154	1.5	722.7
	IIPM1 38-1	5374	1.5	735.6
	IIPM1 46-1	4276	1.4	756.8
	IIPM1 64-1	5151	1.4	741.5
	IIPM1 74-1	4911	1.5	742.9
	L154 D1552-1	3968	1.5	759.4
	L157 D1558-1	4239	1.5	750.9
	L157 D1554-1	5151	1.5	734.4
	L157 D1557-1	4679	1.5	741.8

注:t_{Zr}=12900/[lnD_{Zr}+0.85M+2.95]-273.15;D_{Zr}近似为496000/全岩锆含量;M=(2Ca+K+Na)/(Si×Al),令Si+Al+Fe+Mg+Ca+Na+K+P=1,均为原子数分数。

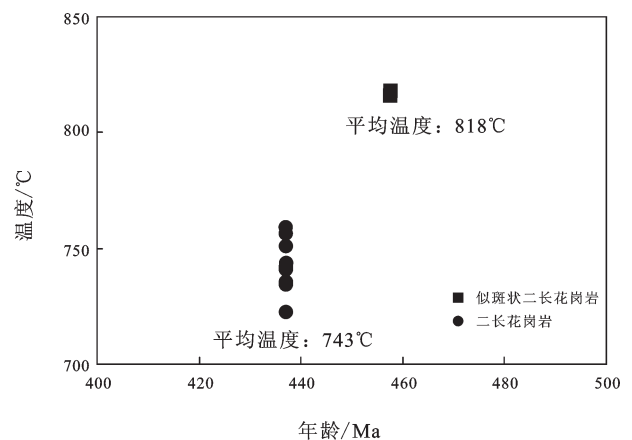


图10 柴达木山似斑状二长花岗岩以及二长花岗岩锆饱和温度计投点

Fig.10 Plots of saturated Zr thermometer for porphyritic monzogranite and monzogranite from

即可近似代表岩浆起源时的温度^[49]。笔者利用 Miller et al^[50]修正后的全岩锆石饱和温度计对似斑状二长花岗岩以及二长花岗岩的形成温度进行了估算(表4,图10)。结果显示晚奥陶世形成的似斑状二长花岗岩的起源温度较高,两个样品的平均温度为818℃;而早志留世形成的二长花岗岩的平均起源温度为743℃;这说明两类花岗岩的起源温度也存在差异。斜长石是沉积岩中重要的组成矿物,微量元素Eu、Sr在斜长石中的分配系数远远高于其他矿物,柴达木山似斑状二长花岗岩的Eu、Sr负异常较弱($\delta\text{Eu}=0.15\sim 0.16$, $\delta\text{Sr}=0.13\sim 0.15$),而二长花岗岩则具有较强的Eu、Sr负异常($\delta\text{Eu}=0.03\sim 0.09$, $\delta\text{Sr}=0.03\sim 0.13$),暗示两类花岗岩的源岩在发生部分熔融时在源区可能均有斜长石的残留,但是似斑状二长花岗岩的源区斜长石只是部分残留,其压力应位于斜长石的不稳定区,而二长花岗岩的起源压力可能位于斜长石稳定区。另外,石榴石是一种强烈富集HREE的矿物($D \gg 1$),似斑状二长花岗岩以及二长花岗岩均具有较为平坦的HREE配分模式($(\text{Gd}/\text{Yb})_n$ 分别为1.91~1.99和0.62~1.13),这说明二者的源区残留矿物均没有石榴石。实验岩石学资料显示700~800℃时斜长石不稳定的压力介于0.8~1.3 GPa^[51],而石榴石稳定线则在0.9~1.4 GPa内变化^[52]。指示似斑状二长花岗岩可能是在0.8~0.9 GPa的压力条件下形成的,而二长花岗岩的形成压力则<0.8 Gpa。

综上所述,可以推断柴达木山似斑状二长花岗岩是在温度约820℃,压力0.8~0.9 Gpa的条件下,由杂砂岩经黑云母脱水引发部分熔融形成;而二长花岗岩则是在温度约750℃,压力<0.8 Gpa的条件下,由砂泥质沉积岩经白云母脱水引发部分熔融形成。

5.3 构造意义

柴达木山岩体是柴北缘最大的复式岩体之一,前人已做了一定的研究工作,但对其形成时代和成因等上存在不同认识。吴才来等^[11]认为该岩体形成于陆-陆碰撞环境,其形成时代为446 Ma。周宾等^[21]通过进一步的工作,认为柴达木山岩体的形成时间介于436~446 Ma,是陆-陆碰撞环境下岩浆多期侵位形成的产物。而卢欣祥等^[18]则认为分布在柴达木山复式岩体南部的塔塔楞环斑花岗岩应形成于造山运动由挤压造山向后碰撞拉张体制的转折

构造环境,时代为440 Ma。胡能高^[19]则将柴达木山岩体划分成由早期的黑云母二长花岗岩、中期的正长花岗岩和晚期的环斑花岗岩组成复式岩体,并认为这3期侵入体具有同源演化的关系,可能形成于后碰撞或后造山环境。

近年来,详细的年代学研究确定柴北缘高压-超高压变质带不同地段的峰期变质时代介于420~458 Ma^[2,5-9],同时人们还获得带内麻粒岩相或高角闪岩相退变质时代以及超高压地体折返形成的浅色脉体的时代介于397~435 Ma^[53-58]。这说明虽然柴北缘地区在早古生代发生了陆壳深碰撞-俯冲-折返事件,但是不同地段的构造体制还是存在差异的,即局部地段先发生俯冲,随后才发生大规模的深俯冲事件;局部地段先行折返,随后又发生了大规模的陆壳折返。另外,吴才来等^[12,14-15]对柴北缘地区古生代花岗岩的研究结果表明,本地区岩浆活动时代主要有以下几个阶段:460~490 Ma、440~450 Ma、395~410 Ma以及370~380 Ma。其中I期岩浆活动对应于洋壳俯冲,形成在岛弧或活动大陆边缘环境;II期为陆陆碰撞形成的同碰撞S型花岗岩;III、IV期形成于碰撞后陆壳减薄阶段,兼具I型和S型花岗岩的双重特征。

本文获得柴达木山似斑状二长花岗岩的形成时代为(456.2±3)Ma,二长花岗岩的形成时代为(437.2±1.5)Ma,同时二者的源区特征,源岩部分熔融的温度、压力以及熔融机制也存在明显差异,暗示本地区的构造体制在这一阶段可能发生了较大变化。柴达木山似斑状二长花岗岩的形成时代与柴北缘高压-超高压变质带的峰期变质时代及II期岩浆活动时限一致,指示该岩石应形成在同碰撞环境。而二长花岗岩的形成时限滞后似斑状二长花岗岩约20 Ma,其形成环境可能已由挤压背景转换为伸展背景。

6 结 论

(1) 岩石学和地球化学研究表明,柴达木山复式花岗岩体中的似斑状二长花岗岩具有富硅、铝、钾、铁、镁的特点,总体显示了富钾弱过铝质S型花岗岩的特征,是杂砂岩在温度约820℃,压力0.8~0.9 Gpa的条件下,经黑云母脱水引发部分熔融形成;二长花岗岩具有富硅、铝、钾,贫铁、镁的特点,总体显示

富钾准铝质 S 型花岗岩的特征,是砂泥质沉积岩在温度约 750°C,压力 < 0.8 Gpa 的条件下,经白云母脱水引发部分熔融形成。

(2) 利用 LA-ICP-MS 微区原位锆石 U-Pb 定年获得该似斑状二长花岗岩的形成时代为 (456.2±3) Ma,二长花岗岩的形成时代为 (437.2±1.5) Ma,结合前人研究成果,认为似斑状二长花岗岩应形成在同碰撞环境,而二长花岗岩形成在伸展背景下。

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