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柴北缘大柴旦滩间山花岗斑岩体锆石 U-Pb 年代学、地球化学及 Hf 同位素

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摘要:为了研究柴北缘大柴旦地区在华力西期构造演化特征,对大柴旦地区滩间山花岗斑岩进行了锆石 U-Pb 年代学、岩石地球化学以及 Hf 同位素的研究.花岗斑岩中锆石 LA-ICP-MS U-Pb 定年结果表明,该岩体形成于晚泥盆世(356.0±2.8 Ma,MSWD=0.53).地球化学分析显示花岗斑岩属于中钾钙碱性-钙碱性系列,A/CNK 值为 0.97~1.10,属弱过铝质,为 I 型花岗岩,富集大离子亲石元素(如 K、Ba、Rb)和轻稀土元素(LREE)以及 Th、U,相对亏损高场强元素(如 Ta、Nb、Ti、P).岩石的 $\varepsilon_{Hf}(t)$ 值和二阶段模式年龄(T_{DM2})分别介于±5.43~±8.38 和 1 017~1 284 Ma 之间.上述特征表明,滩间山花岗斑岩的原始岩浆源于中元古代新增生陆壳的部分熔融.综合区域地质演化背景,认为滩间山花岗斑岩形成于柴达木地块与南祁连地块碰撞后伸展构造环境.

关键词:锆石 U-Pb 年龄;锆石 Hf 同位素;滩间山;地球化学;年代学.
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Geochronology, Geochemistry and Zircon Hf Isotopes of the Tanjianshan Granite Porphyry Intrusion in Dachaidan Area of the North Margin of Qaidam Basin, NW China

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Abstract: In order to research the Variscan tectonic evolution features of Dachaidan region in North Qaidam, this paper presents LA-ICP-MS zircon U-Pb dating, geochemical and Hf isotopic data of the granite porphyry from Tanjianshan intrusion in Dachaidan region, with the aim of constraining its formation time, petrogenesis and the regional tectonic setting. The LA-ICP-MS U-Pb dating results of zircons from the granite porphyry indicate that the intrusion formed in the Late Devonian Epoch (356.0±2.8 Ma, MSWD=0.53). Geochemically, these rocks fall into the calc-alkaline to middle-K calc-alkaline series, with an A/CNK ratio of 0.97-1.10, which are weakly peraluminous granites, being of the characteristics of I type granitoids, enriched in LILE(such as K, Ba, Rb), LREE, Th and U, relatively depleted in HFSE (such as Ta, Nb, Ti, P). The $\varepsilon_{Hf}(t)$ values of the granite porphyry vary from ±5.43 to ±8.38, and two-stage model ages (T_{DM2}) range from 1 017 to 1 284 Ma. These characteristics suggest that the primary magma was derived from the remelting of juvenile crustal materials in Mesoproterozoic. In context of its regional geological background, we conclude the granite porphyry from Tanjianshan intrusion were formed extensional tectonic setting after the collision between Qaidam block and Qilian block.

Key words: zircon U-Pb chronology; Zircon Hf isotopes; Tanjianshan; geochemistry; geochronology.

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0　引言

柴达木盆地北缘(以下简称“柴北缘”)位于青藏高原，东部以哇洪山－温泉断裂为界，北部接祁连地块，西北以阿尔金断裂为界，南部与柴达木地块相接(陆松年等，2002，2004；李怀坤等，2003).20 世纪 90 年代学者们在柴北缘地区发现榴辉岩，在后续的地质研究成果中发现在榴辉岩及其片麻岩中的超高压变质矿物——金刚石、柯石英和超高压矿物显微出溶结构，确立了柴北缘为我国又一条高压/超高压变质(HP/UHP)带，从而使柴北缘成为中外地学界关注的热点地区之一.近年来，柴北缘 HP/UHP 变质带的研究已经取得了丰硕成果(杨经绥等，1998，2000，2001；宋述光和杨经绥，2001；Yang *et al*.，2002；Song *et al*.，2003a，2003b，2004，2005a，2005b，2009，2014a，2014b，2015a；陈能松等，2007；宋述光等，2007，2015b；张建新等，2009；Yu *et al*.，2012，2013，2014，2015；Wang *et al*.，2014；查显锋等，2016).除此之外，在柴北缘分布着大量花岗岩类(李德发等，1991)，其中以早古生代岩浆岩类最为发育，相关学者进行了较多的年代学、地球化学及成因方面的研究(吴才来等，2001a，2001b，2004，2006，2007，2008，2014；肖庆辉等，2003，孟繁聪等，2005；卢欣祥等，2007；周宾等，2013；朱小辉等，2013).Song *et al*.(2014a，2014b)对柴北缘榴辉岩的研究讨论了从大洋俯冲、大陆碰撞/俯冲、造山坍塌完整的造山旋回.同时，认为柴北缘埃达克质岩石(英云闪长岩－奥长花岗岩)由大陆碰撞作用对应的俯冲变质洋壳或陆壳折返过程中榴辉岩的减压熔融作用形成.Wang *et al*.(2014)通过对柴北缘超高压变质带上的二云母花岗岩、英云闪长岩、花岗闪长岩、黑云母二长花岗岩、斑状黑云母花岗岩和闪长岩以及同时期基性岩脉的研究，认为超高压变质地体折返引起岩浆作用形成的岩体具有不同的源区和演化机制.Yu *et al*.(2014，2015)通过对古生代都兰高压麻粒岩相研究认为：柴北缘的都兰单元经历了志留纪(432～438 Ma)的高压麻粒岩相变质和相关的部分熔融，角闪石的 Ar-Ar 定年结果表明高压麻粒岩的角闪岩相逆变质作用发生在 423～432 Ma，表明都兰南部单元的高压麻粒岩经历了快速冷却和折返.依据早古生代岩浆岩的研究的相关成果可大致可分为 3 个阶段：一阶段俯冲型(晚寒武世—早－中奥陶世)，代表滩间山群火山岩(袁桂邦等，2002)、嗷唠山花岗岩(吴才来等，2001a)、赛什腾山岩体和团鱼山岩体(吴才来等，2008)；二阶段同碰撞型(晚奥陶世)，代表柴达木山花岗岩(吴才来等，2001b)；三阶段碰撞后拉伸型(早志留世—早泥盆世)，代表塔榜河环斑花岗岩(卢欣祥等，2007)、锡铁山花岗岩(孟繁聪等，2005)、绿梁山花岗岩(Song *et al*.，2004)等.晚古生代出露的岩浆岩主要为早中泥盆世和二叠纪花岗岩，主要研究成果嗷唠河石英闪长岩、大头羊沟花岗闪长岩、巴嘎柴达木湖岩体、都兰的野马滩岩体(吴才来等，2004，2007，2008)、盐场北山二长花岗岩(董增产等，2015)，相关学者认为晚古生代石炭—二叠纪柴北缘存在洋盆(孙延贵等，2004；寇晓虎等，2007；王绘清等，2010).

已有的研究成果对区内晚泥盆世花岗岩年代学及成因方面的研究资料较少，制约了对本地区大地构造背景演化的认识，通过本次研究可以丰富区域上花岗质岩浆活动的年代学格架，本次取样岩石的锆石 LA-ICP-MS U-Pb 定年结果(356.0±2.8 Ma)显示其为晚泥盆世，因此，本文通过对研究区内花岗斑岩的年代学、岩石地球化学和 Hf 同位素研究，旨在揭示其形成时代及构造背景，为完善柴北缘晚古生代构造演化史提供依据.

1　地质背景及样品描述

1.1　地质背景

青藏高原长期以来一直认为是冈瓦纳大陆和劳亚大陆之间的古、新特提斯洋的俯冲、碰撞和碰撞后汇聚而成(Li *et al*.，2006；Guillot *et al*.，2008；Royden *et al*.，2008；Zhai *et al*.，2011).早新生代印度板块持续的向北汇聚与碰撞构成了复杂的中国大陆构造格架(Yin *et al*.，2008a，2008b).祁连－柴达木造山系位于青藏高原北缘，南部以柴达木盆地为界，西接塔里木盆地，东部以中朝克拉通相接.这一地区包括多个陆块、高压和超高压缝合带、变质带和世界上最大的左行走滑断层－阿尔金断裂带.青藏高原北部的柴达木北缘超高压变质带记录了从新元古代到古生代的海底俯冲→大陆碰撞和俯冲→造山带的去根和坍塌的大陆造山带演化的完整地质构造运动历史(Song *et al*.，2014a).

柴北缘构造带前寒武系由一套中高级变质岩系组成，主要由斜长角闪岩、片麻岩和云母片岩组成，上覆地层为早古生代奥陶纪的火山岩和灰岩、砂岩.晚古生代由晚泥盆世陆相碎屑岩、火山岩和石炭纪海相沉积岩组成，缺少早－中泥盆世沉积记录，区内

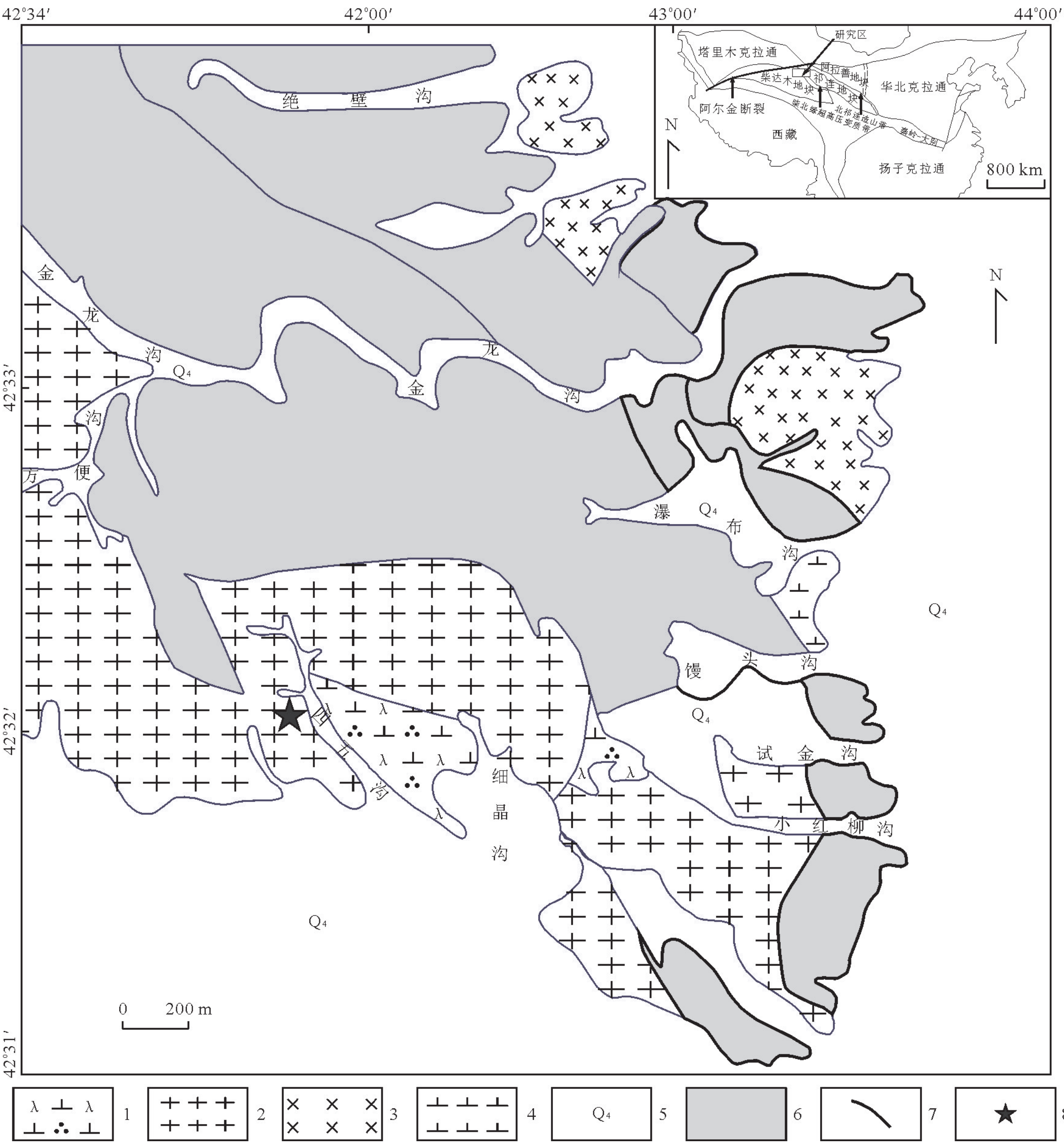

图 1 研究区地质简图

Fig.1 Geological sketch map of the study area

1.花岗闪长岩；2.花岗斑岩；3.辉长岩；4.闪长岩；5.第四系；6.中元古代万洞沟群；7.断层；8.取样位置

处于隆升状态(郝国杰等，2004).晚古生代地层之上为侏罗纪和白垩纪地层(李德发等，1991).柴北缘超高压变质带榴辉岩、石榴橄榄岩及相关片岩主体被认为是大陆深俯冲产物(Song *et al*.，2003a，2003b，2007；Yu *et al*.，2013，2014).柴北缘超高压变质带分为 4 个次级变质单元：鱼卡－落凤坡榴辉岩－片麻岩单元；绿梁山石榴橄榄岩－高压麻粒岩单元；锡铁山榴辉岩－片麻岩和都兰榴辉岩－片麻岩(Zhang *et al*.，2008).研究区位于青海省大柴旦滩间山地区，锡铁山北西约 140 km，出露的地层主要为中元古代万洞沟群(Pt_2wd)和第四系(Q_4).中元古代万洞沟群按岩性组合分为上、下两个岩组，之间为连续沉积；下岩组为白云质大理岩、绢云石英片岩等，上岩组以斑点状千枚岩、炭质绢云千枚岩、钙质白云母片岩为主.本区出露岩浆岩主要为花岗斑岩、石英闪长岩、辉长岩和闪长岩(图 1).

1.2 样品描述

滩间山锆石 U-Pb 定年的花岗斑岩取样位置为：N38°13′33″、E94°37′15″.样品呈灰白色，块状构造，斑状结构，整个岩石中斑晶含量 20%，其中石英斑晶约占 8%，斜长石斑晶约占 4%，正长石斑晶约占 2%，黑云母约占 2%，基质为显微长英质矿物.石

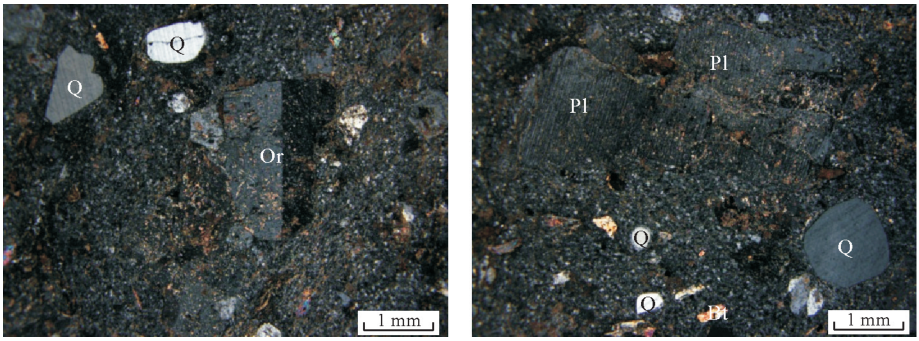

图 2　花岗斑岩显微照片

Fig.2　Microphotographs of the granite porphyry in Tanjianshan

花岗斑岩(+);Bt.黑云母;Or.正长石;Pl.斜长石;Q.石英

英斑晶主要呈他形一半自形粒状,粒度为 0.2～3.5 mm,局部出现熔蚀,发育波状消光.斜长石斑晶主要呈半自形一自形长柱状,粒度为 1.5～4.5 mm,可见聚片双晶.正长石斑晶呈半自形一自形长柱状,粒度在 1.0～2.5 mm,卡式双晶明显.黑云母斑晶为片状,粒度 1.6～2.0 mm,具绿泥石化(图 2).

2　分析方法

2.1　锆石 LA-ICP-MS U-Pb 年代学

本次选用的样品破碎与锆石挑选工作由河北省廊坊区域地质调查研究所实验室完成,利用标准重矿物分离技术完成锆石分选,在双目镜下仔细挑选表面平整光洁、不同长宽比例、不同柱锥面的锆石颗粒,之后将锆石粘在双面胶上,用无色透明的环氧树脂固定,固化之后将表面抛光至锆石中心.原位分析前,利用反射光和 CL 图像仔细研究锆石的晶体形貌与内部结构特征,从而选择最佳测试点.锆石制靶、反射光、阴极发光以及锆石 U-Pb 年龄测定在中国科学院地质与地球物理研究所进行.详细测试过程见 Yuan *et al*.(2004).普通铅校正采用 Andersen (2002)推荐的方法.样品的同位素比值及元素含量计算采用 ICP-MS-DATECAL 程序(Liu *et al*., 2008,2010),年龄计算及谐和图的绘制采用 Isoplot 程序(Ludwig,2003).

2.2　岩石地球化学测试

本次实验主量及微量元素的分析测试在吉林大学测试实验中心完成.主量元素采用 X-射线荧光光谱法(XRF)测定,相对标准偏差为 2%～5%.微量元素和稀土元素采用美国安捷伦科技有限公司 Agilent7500A 型耦合等离子体质谱仪测试(Z/T0223-2001),样品测试经过国际标样 BHWO-2、BCR-2 和国家标样 GBW07103、GBW07104 监控.微量元素与稀土元素分析精度为:元素含量大于10×10^{-6}的误差小于5%,小于 10×10^{-6}误差小于 10%.

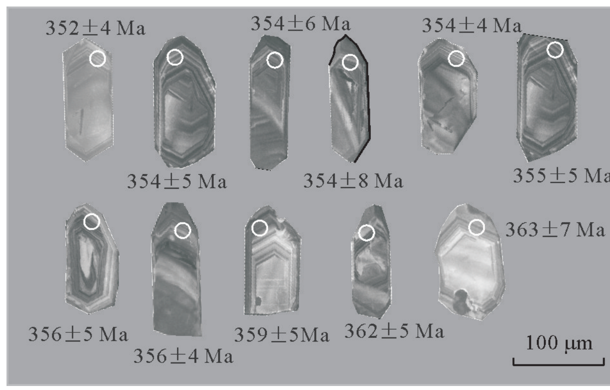

图 3　花岗班岩锆石 CL 图像

Fig.3　CL images of zircons from the granite porphyry

2.3　锆石 Hf 同位素测试

原位微区锆石 Hf 同位素比值测试在中国地质大学(武汉)地质过程与矿产资源国家重点实验室(GPMR)利用激光剥蚀多接收杯等离子体质谱(LA-MC-ICP-MS)完成.仪器操作详细条件和分析方法参照(Hu *et al*.,2012).数据的离线处理采用软件 ICP-MS Data Cal 完成(Liu *et al*.,2010).

3　分析结果

3.1　锆石 LA-ICP-MS 年代学

花岗斑岩中挑选的锆石多呈无色透明,金刚光泽,晶体多为长柱状,少数为短柱状.多数锆石颗粒自形程度较好.由阴极发光(CL)图像可见(图 3),锆石具有清晰的韵律环带结构,具岩浆结晶锆石特征. 11个分析点测试结果(表1)显示Th的含量变化范

表 1 花岗斑岩中锆石 U-Pb 同位素分析结果

Table 1 Zircon U-Pb analyses of the granite porphyry

样品	Th	U	Th/U	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{206}Pb/^{238}U$	
	10^{-6}			比值	1σ	比值	1σ	比值	1σ	年龄(Ma)	1σ
XJG-N1	408	1023	0.40	0.073 385	0.002 213	0.421 631	0.017 651	0.056 094	0.000 712	352	4
XJG-N2	202	451	0.45	0.064 487	0.002 807	0.414 923	0.021 425	0.056 369	0.000 752	354	4
XJG-N3	189	426	0.44	0.055 518	0.003 134	0.425 024	0.021 744	0.056 384	0.000 857	354	6
XJG-N4	41	88	0.47	0.064 909	0.005 129	0.424 216	0.014 781	0.056 387	0.000 653	354	7
XJG-N5	203	403	0.50	0.076 04	0.002 895	0.415 678	0.019 986	0.056 414	0.000 656	354	4
XJG-N6	198	444	0.45	0.052 461	0.002 33	0.407 076	0.017 546	0.056 626	0.000 838	355	5
XJG-N7	209	504	0.41	0.051 271	0.002 702	0.402 974	0.021 623	0.056 732	0.000 757	356	4
XJG-N8	205	493	0.42	0.055 962	0.001 978	0.408 925	0.014 645	0.056 826	0.000 588	356	3
XJG-N9	335	804	0.42	0.056 416	0.001 648	0.414 312	0.012 994	0.057 268	0.000 740	359	4
XJG-N10	246	565	0.44	0.057 981	0.002 648	0.414 513	0.021 865	0.057 832	0.000 747	362	4
XJG-N11	102	245	0.42	0.059 846	0.003 280	0.425 621	0.025 976	0.057 889	0.000 785	363	6

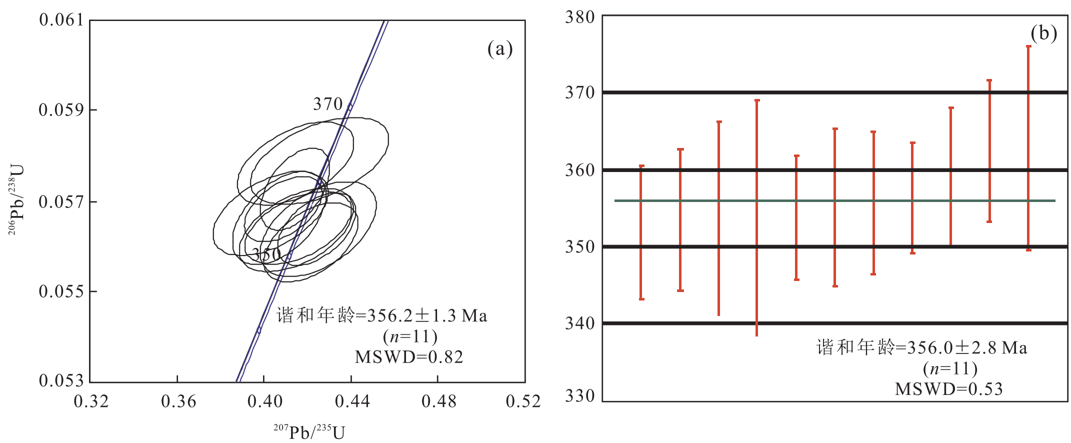

图 4 花岗斑岩 U-Pb 年龄谐和图(a)和加权平均年龄(b)

Fig.4 Zircon U-Pb concordia diagram (a) and weighted average ages diagram (b) from the granite porphyry

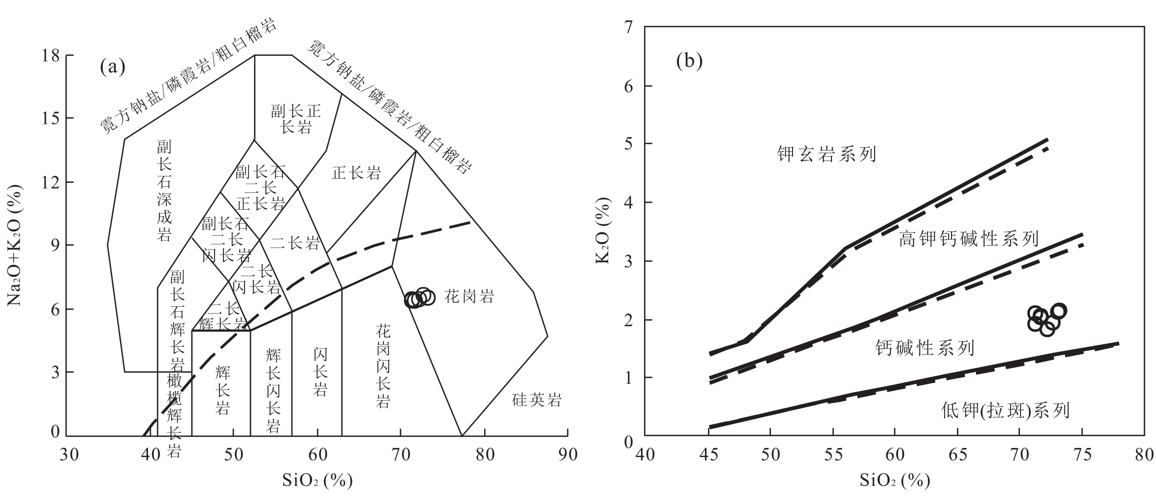

图 5 岩石 TAS 图解(a)和 K_2O-SiO_2 图解(b)

Fig.5 TAS diagram (a) and K_2O-SiO_2 (b) diagram of the granite porphyry

a.分界线上方为碱性，下方为亚碱性据 Irvine and Baragar(1971)；b.据 Peccerillo and Taylor(1976)

围为(41～408)×10^{-6}，U 含量变化范围为(88～1 023)×10^{-6}，Th/U 比值为 0.40～0.50(均大于 0.4)，显示为岩浆成因的锆石特征(Weaver，1991)。11 个锆石分析点比较集中，均落在谐和线上及其附

表 2　滩间山花岗斑岩主量元素、稀土元素和微量元素含量及有关参数

Table 2　Major, REE and trace element content and parameter of the granite porphyry in Tanjianshan

样品	XJG-Y1-1	XJG-Y1-2	XJG-Y1-3	XJG-Y1-4	XJG-Y1-5	XJG-Y1-6	XJG-Y1-7	XJG-Y1-8
SiO_2	68.64	71.61	70.08	68.72	71.72	69.52	69.27	71.05
TiO_2	0.29	0.32	0.30	0.31	0.32	0.31	0.30	0.31
Al_2O_3	14.55	15.39	14.53	14.72	15.10	14.85	14.62	15.08
Fe_2O_3	0.82	0.86	0.93	0.94	1.12	0.96	1.02	0.95
FeO	1.43	1.33	1.23	1.25	1.06	1.23	1.31	1.33
MnO	0.07	0.06	0.07	0.07	0.04	0.06	0.08	0.07
MgO	0.83	0.73	0.73	0.80	0.66	0.82	0.85	0.74
CaO	3.27	2.98	2.59	2.91	2.88	2.37	2.64	2.68
Na_2O	4.30	4.32	4.51	4.21	4.28	4.24	4.20	4.63
K_2O	1.85	2.08	1.77	2.02	2.10	1.98	1.99	1.90
P_2O_5	0.08	0.08	0.08	0.08	0.09	0.08	0.08	0.08
LOI	3.77	2.11	3.02	3.61	2.05	3.11	3.38	2.23
Total	99.91	101.86	99.83	99.65	101.43	99.53	99.73	101.04
ALK	6.15	6.39	6.29	6.24	6.39	6.22	6.19	6.52
Na_2O/K_2O	2.33	2.08	2.54	2.08	2.04	2.14	2.12	2.44
A/CNK	0.97	1.04	1.03	1.02	1.04	1.10	1.05	1.04
$Mg^{\#}$	42.09	39.70	40.13	41.89	37.58	42.60	41.95	39.04
La	11.28	6.63	10.42	12.38	13.11	13.97	12.20	11.14
Ce	25.00	16.35	22.24	26.85	27.14	28.96	25.76	24.26
Pr	2.70	1.83	2.58	2.95	3.05	3.27	3.02	2.68
Nd	11.09	7.65	10.62	11.02	12.32	12.98	12.23	9.06
Sm	2.13	1.41	2.16	2.30	2.41	2.43	2.35	2.07
Eu	0.60	0.34	0.54	0.59	0.53	0.67	0.63	0.51
Gd	1.77	1.05	1.75	1.77	2.05	1.98	2.04	1.72
Tb	0.28	0.17	0.28	0.25	0.30	0.28	0.31	0.24
Dy	1.54	0.97	1.59	1.41	1.74	1.64	1.66	1.33
Ho	0.23	0.15	0.23	0.21	0.25	0.24	0.26	0.20
Er	0.72	0.49	0.73	0.62	0.80	0.72	0.77	0.61
Tm	0.09	0.06	0.10	0.08	0.09	0.10	0.10	0.07
Yb	0.59	0.43	0.67	0.61	0.68	0.65	0.66	0.55
Lu	0.08	0.06	0.10	0.08	0.09	0.09	0.10	0.07
Y	7.12	3.04	7.31	6.15	7.53	7.65	8.11	4.89
ΣREE	58.10	37.59	54.01	61.12	64.56	67.98	62.09	54.51
LREE	52.80	34.21	48.56	56.09	58.56	62.28	56.19	49.72
HREE	5.30	3.38	5.45	5.03	6.00	5.70	5.90	4.79
LREE/HREE	9.96	10.12	8.91	11.15	9.76	10.93	9.52	10.38
La_N/Yb_N	12.89	10.40	10.49	13.68	13.00	14.49	12.46	13.66
δEu	0.92	0.82	0.82	0.86	0.71	0.91	0.86	0.80
δCe	1.06	1.11	1.01	1.04	1.00	1.00	0.99	1.04
Rb	87.58	92.35	94.15	96.31	88.98	94.12	98.78	101.12
Ba	207.90	228.20	195.30	325.20	277.80	241.80	249.30	221.30
Th	5.97	2.40	5.78	6.46	6.81	7.17	6.62	6.22
U	1.76	1.74	2.24	1.84	2.65	2.33	2.15	2.13
Nb	2.57	2.62	2.63	2.54	2.74	2.69	2.67	2.60
Ta	0.68	0.71	0.72	0.76	0.69	0.56	0.69	0.74
Sr	215.10	137.00	180.40	174.10	174.50	195.60	217.10	173.00
Nd	11.09	7.65	10.62	11.02	12.32	12.98	12.23	9.06
Zr	55.47	62.07	107.90	48.97	99.63	67.24	95.57	49.55
Hf	1.57	1.79	2.86	1.46	2.54	1.87	2.50	1.54
Nb/Ta	3.78	3.69	3.65	3.34	3.97	4.80	3.87	3.51
Rb/Sr	0.41	0.67	0.52	0.55	0.51	0.48	0.45	0.58
Hf/Th	0.26	0.75	0.50	0.23	0.37	0.26	0.38	0.25
La/Nb	4.40	2.53	3.96	4.88	4.78	5.19	4.57	4.29

注：主量元素单位为 10^{-2}；微量、稀土元素单位为 10^{-6}.

近，11 个锆石 $^{206}Pb/^{238}U$ 分析数据的加权平均年龄为356.0±2.8 Ma(MSWD＝0.53)(图 4a，4b)，该年龄代表了岩体侵位年龄(属晚泥盆世).

3.2　地球化学特征

3.2.1　主量元素　滩间山花岗斑岩主量、微量元素含量及特征值见表2.其中，样品的SiO_2含量变化

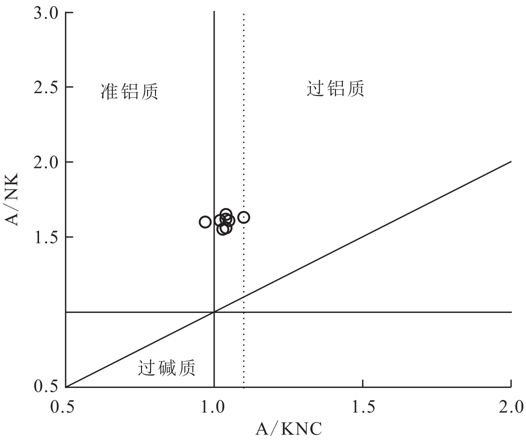

图 6　A/KNC-A/NK 图解

Fig.6　A/KNC-A/NK diagram of the granite porphyry

据 Maniar and Piccoli(1989)

于 68.64%～71.72%,平均含量为 70.08%,在 TAS 图解中落入亚碱性范围,为花岗岩区域(图 5a);Al_2O_3 含量为 14.53%～15.39%,Na_2O 含量为 4.20%～4.63%,K_2O 含量为 1.77%～2.10%,全碱含量为 6.15%～6.52%,岩石位于钙碱性系列区域(图 5b).铝饱和指数 A/CNK 为0.97～1.10,样品落入准铝质－弱过铝质范围(图 6).

3.2.2　微量元素　滩间山花岗斑岩稀土总量为(37.37～67.55)×10^{-6},平均值为 57.46×10^{-6},LREE 的含量为(33.99～61.85)×10^{-6},平均为 52.27×10^{-6},HREE 含量为(3.38～6.0)×10^{-6},平均为 5.20×10^{-6},在稀土配分模式图上曲线基本一致,配分曲线明显右倾(图 7).$(La/Yb)_N$ 为 13.00～14.49,LREE 强烈富集,HREE 极度亏损,轻重稀土元素显示分馏明显(图 7a).Eu/Eu* 值为 0.71～0.92,具有弱 Eu 负异常.

图 7b 显示,微量元素的配分模式近似一致.相对于原始地幔,微量元素表现出了富集大离子亲石元素(如 K、Ba、Rb)和活泼的不相容元素(如 Th、U)的特征,相对亏损高场强元素(如 Nb、Ta、P、Ti).

3.3　锆石 Lu-Hf 同位素

滩间山花岗斑岩中锆石的$^{176}Hf/^{177}Hf$ 比值为 0.282 710～0.282 797,$\varepsilon_{Hf}(t)$值为±5.43～±8.38,Hf 同位素单阶段模式年龄(T_{DM1})和二阶段模式年龄(T_{DM2})分别变化于 647～762 Ma 和 1 017～1 284 Ma之间(表 3).

所有测试点的$^{176}Lu/^{177}Hf$ 比值为 0.000 414～0.001 172,远小于 0.002,表明锆石在岩体形成之后漫长的演化历程中具有较低的放射成因 Hf 积累,因而可以用锆石$^{176}Hf/^{177}Hf$ 比值探讨岩体形成时的成因信息(Patchett *et al*.,1982;Knudsen *et al*.,2001).$f_{Lu/Hf}$值为－0.96～－0.99,明显小于铁镁质地壳 $f_{Lu/Hf}$值(0.34;Amelin *et al*.,2000)和硅铝质地壳 $f_{Lu/Hf}$值(－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或其源区物质在地壳的平均存留年龄.

4　讨论

4.1　岩浆源区

在地球化学上,滩间山花岗斑岩属高硅弱过铝质钙碱性系列,Al_2O_3 含量为 14.53～15.39,Na_2O/K_2O的值为2.08～2.54(＞1.17),MgO、CaO含量

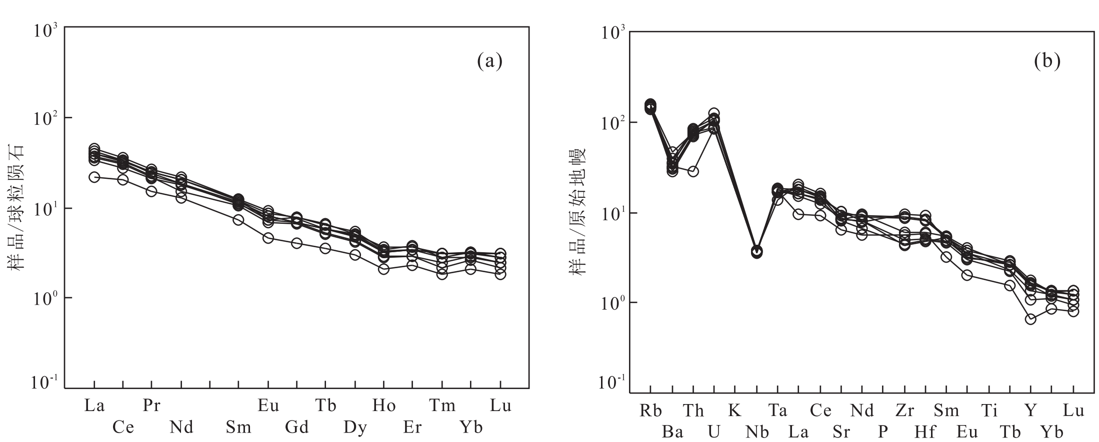

图 7　花岗斑岩稀土元素球粒陨石标准化配分图解(a)和微量元素原始地幔标准化蛛网图(b)

Fig.7　Chondrite-normalized REE distribution patterns (a) and primitive mantle-normalized trace element spider diagrams of the granite porphyry (b)

a.标准化值据 Boynton(1984);b.标准化值据 Sun and Mcdonough(1989)

表 3　滩间山花岗斑岩锆石 Hf 同位素分析结果

Table 3　LA-ICPMS zircon U-Pb analyses of the granite porphyry in Tanjianshan

样品	年龄(Ma)	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	1σ	$\varepsilon_{Hf}(t)$	T_{DM1}(Hf)(Ma)	T_{DM2}(Hf)(Ma)	$f_{Lu/Hf}$
XJG-N1-01	352	0.054 353	0.001 117	0.282 797	0.000 026	8.38	647	1 017	−0.97
XJG-N1-02	354	0.020 430	0.000 414	0.282 783	0.000 024	8.08	655	1 044	−0.99
XJG-N1-03	354	0.034 401	0.000 712	0.282 710	0.000 021	5.43	762	1 284	−0.98
XJG-N1-04	354	0.025 633	0.000 574	0.282 710	0.000 036	5.46	759	1 281	−0.98
XJG-N1-05	354	0.038 097	0.000 767	0.282 781	0.000 018	7.91	664	1 060	−0.98
XJG-N1-06	355	0.033 948	0.000 720	0.282 755	0.000 022	7.05	699	1 139	−0.98
XJG-N1-07	356	0.033 248	0.000 728	0.282 763	0.000 019	7.32	689	1 115	−0.98
XJG-N1-08	356	0.048 840	0.001 110	0.282 745	0.000 017	6.60	722	1 180	−0.97
XJG-N1-09	359	0.028 541	0.000 880	0.282 754	0.000 018	7.05	704	1 142	−0.97
XJG-N1-10	362	0.031 018	0.000 780	0.282 764	0.000 044	7.51	688	1 102	−0.98
XJG-N1-11	363	0.042 696	0.001 172	0.282 775	0.000 018	7.82	679	1 075	−0.96

较高，在 A/CNK-A/NK 图解中(图 6)，大部分样品为弱过铝质，一个样品落在准铝质范围，认为滩间山花岗斑岩属 I 型花岗岩.Mg、Co、Ni、Cr 含量与地壳值一致，Mg# 值为 39.04～42.60，Nb/Ta(3.51～4.80)值接近壳源岩浆值，认为岩石主要来自于深部地壳.

研究表明，花岗岩源区残留相组成与 Sr、Yb 元素含量有关(Defant and Drummond，1990；Defant *et al*.，2002)，在花岗岩中容纳 Sr 的矿物主要为斜长石，容纳 Yb 的矿物主要为石榴子石、角闪石(张旗等，2008)，本次研究花岗斑岩贫 Sr($137.00\times10^{-6}\sim217.10\times10^{-6}$)，Eu/Eu* 值(0.71～0.92)弱负铕异常，暗示长石结晶分异不明显.贫 Yb($0.43\times10^{-6}\sim0.68\times10^{-6}$)，表明花岗岩熔融的源区残留有石榴子石和角闪石.综上认为，花岗岩源区熔融后的残留相有石榴子石和角闪石，可能有斜长石存在.

就岩浆岩而言，除 Sr-Nd 同位素外，锆石 Hf 同位素对岩浆岩源区性质提供很好证据(Amelin *et al*.，1999，2000；Griffin *et al*.，2002).本次测试结果显示岩石中岩浆锆石 $\varepsilon_{Hf}(t)$ 值为±5.43～±8.38(均>0)，且位于球粒陨石演化线和亏损地幔演化线之间，Hf 同位素成分变化范围较小，表明岩石源区均一(图 8).结合其二阶模式年龄 T_{DM2}(1 017～1 284 Ma)，笔者认为岩石岩浆源区应是中元古代新增生的年轻地壳部分熔融的产物.

4.2　构造背景

滩间山花岗斑岩 SiO_2 较高(>68.64%)，里特曼指数平均为 1.47，属钙碱性火成岩，铝饱和指数平均为 1.04，具弱过铝质特征，岩石矿物组分上碱性长石含量较低，显示造山花岗岩类特征.岩石化学特征 Na_2O+K_2O 含量为 6.15～6.52，K_2O/Na_2O 含量为 0.41～0.49，富集大离子亲石元素，相对亏损高场强元素，Nb 含量为(2.57～2.74)$\times10^{-6}$(<11×10^{-6})，Ta 含量为(0.68～0.76)$\times10^{-6}$(<1×10^{-6})，Zr 含量为(49.55～107.90)$\times10^{-6}$(<116)，Hf 含量为 1.46～2.86(<3)，所有数据的值都符合碰撞造山后环境.图 9 中，岩石落入造山后花岗岩区域.吴才来等(2001a，2008)对嗷唠河南边花岗岩锆石的 SHRIMP U-Pb 年龄测定结果为 445～496 Ma，指示花岗岩时代属早古生代；在嗷唠河北边获取的石英闪长岩锆石 SHRIMP U-Pb 年龄为 372 Ma，显示为晚古生代代泥盆纪.结合本文在嗷唠河西边滩间山取得的锆石 U-Pb 年龄(356.0±2.8 Ma)，说明滩间山花岗斑岩形成于晚古生代华力西期晚泥盆世，同时暗示该地区存在多期岩浆侵入形成的杂岩体.

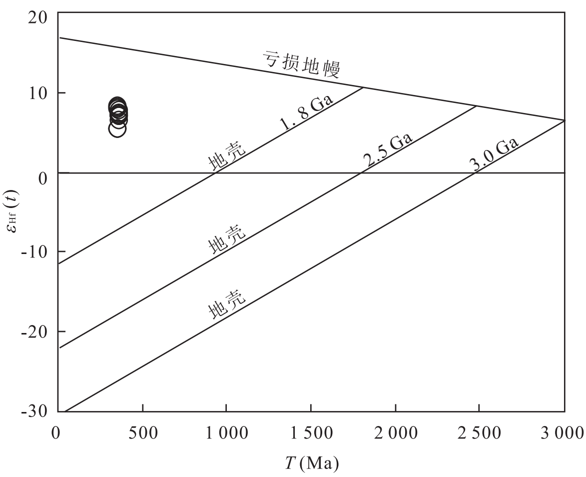

图 8　岩石的 Hf 同位素特征

Fig.8　Hf isotopic compositions of the granite porphyry

据吴福元等(2007)

柴达木地块与南祁连地块在拼贴碰撞前存在早

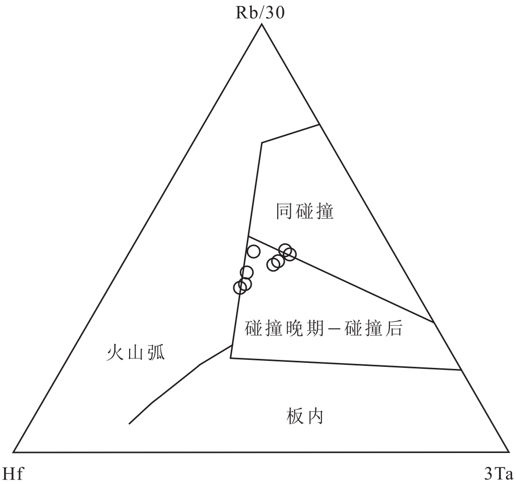

图 9　岩石 Hf-Rb/30-3Ta 判别图解

Fig.9　Hf-Rb/30-3Ta diagram of the granite porphyry

据 Brown *et al*.(1984)

古生代大洋(南祁连洋)(Xu *et al*.,2006),在早古生代存在大陆活动边缘的岛弧环境(陆松年等,2002;袁桂邦等,2002;史仁灯等,2003,2004).南祁连洋向北部南祁连地体俯冲过程中,岩石圈由绿片岩相→角闪岩相→榴辉岩相转变(赖绍聪等,1996;邱家骧等,1998),同时,此过程致矿物脱水放出大量流体(Peacock,1990),流体的上升引起岛弧下地幔和下地壳部分熔融,从而形成一套岛弧火山岩(赖绍聪等,1996).岩浆活动(460～475 Ma)形成的花岗质岩石即第一期岛弧火成岩和部分埃达克岩,说明当时的构造背景为岛弧环境(吴才来等,2008),同时存在洋壳俯冲熔融形成的埃达克岩(史仁灯等,2004).早古生代花岗岩形成于活动大陆边缘(Hugh and John,2005).大柴旦西南鱼卡和沙柳河榴辉岩的锆石 SHRIMP U-Pb 年龄为 484.0±3.0～496.4±6.5 Ma(张建新等,2000;辛后田等,2002;Yang *et al*.,2002;宋述光等,2007),说明洋壳俯冲早于第一期花岗岩的形成,此时花岗岩的形成与洋壳俯冲有关.

柴北缘含柯石英的片麻岩变质年龄为 452.0±13.8 Ma,退变质年龄为 419.0±6.7 Ma(Song *et al*.,2003b;杨经绥等,2003).都兰地区发育英云闪长岩和奥长花岗岩具有典型的埃达克岩特征,埃达克岩形成的时间范围与超高压变质时间吻合 435～420 Ma,埃达克质岩浆来源于洋壳的部分熔融(Song *et al*.,2009,2014b;Yu *et al*.,2012).团鱼山花岗岩(I 型)和柴达木山花岗岩(S 型)锆石 SHRIMP U-Pb 年龄为443 Ma、446 Ma(吴才来等,2004;Wu *et al*.,2006),说明此时洋壳俯冲和陆壳俯冲同时存在,随着陆块俯冲作用的持续,引起大陆地壳加厚并伴随热流值升高,来自深部板块脱水形成的流体作用,到陆壳发生部分熔融,形成了同造山陆—陆碰撞花岗质岩浆.即此时的岩浆作用与板块俯冲有关(吴才来等,2008).

吴才来等(2004,2014)通过对都兰野马滩花岗岩体、巴立给哈滩西花岗岩体和水文站的花岗岩研究后,分别获得了花岗岩 SHRIMP 年龄为 397 Ma、407.3±4.3～397.0±6.0 Ma 和 405±4 Ma、397±4 Ma,并将 397.0～407.3±4.3 Ma 因岩浆作用形成的花岗岩体归为柴北缘古生代第三期岩浆作用.同时,上述花岗岩体与含柯石英的片麻岩及榴辉岩共生.相关学者在都兰地区获得了糜棱岩化片麻岩黑云母 Ar-Ar 年龄为 402±1 Ma(杨经绥等,2000;Song *et al*.,2005a),此年龄代表了超高压片麻岩的折返时代.因此,说明第 3 期花岗岩为区内经受超高压变质作用的块体折返过程中,由于深部块体折沉促使地幔物质和热能直接作用块体底部而产生熔融,从而形成的花岗质岩浆(Martin,1986;许志琴等,2003;Wang *et al*.,2014).

与造山带去根的岩浆作用在本区普遍发育,如嗷唠山石英闪长岩锆石 SHRIMP U-Pb 年龄为 372 Ma(吴才来等,2001a,2001b)、大柴旦巴嘎柴旦湖花岗岩年龄为 374.5±1.6 Ma、大头羊沟花岗岩年龄为 372.0±2.7 Ma(吴才来等,2007)、都兰水文站岩体年龄为 380.5±5.0 Ma 和察察公麻 2 个侵入体年龄分别为 382.5±3.6 Ma、372.5±2.8 Ma(吴才来等,2014).而本文获得的滩间山花岗斑岩形成时代为 356.0±2.8 Ma,与区域上大柴旦巴嘎柴旦湖花岗岩、大头羊沟花岗岩、都兰水文站和察察公麻等地的花岗岩形成时代相近.柴北缘西段牛鼻子梁地区发育双峰式火山岩,其中辉长岩年龄为 367.0 Ma(凌锦兰等,2014),二长花岗岩年龄 359.9 Ma(数据待发表).说明在该阶段,造山带上不同块体在均衡调整过程中产生滑塌、拉伸,从而引起地壳部分熔融,形成该期的岩浆作用(吴才来等,2008;Wang *et al*.,2014).造山带花岗质岩浆与造山带伸展滑塌同时进行(Leake,1990),反映该地区晚泥盆世处于伸展构造背景.因此,滩间山晚泥盆纪花岗斑岩应形成于造山后伸展构造环境.

5　结论

(1)获得青海省大柴旦地区滩间山花岗斑岩锆

石 LA-ICP-MS U-Pb 加权平均年龄为 356.0±2.8 Ma，MSWD=0.53，属晚泥盆世；(2)滩间山花岗斑岩原始岩浆起源于新增生的年轻陆壳(中元古代)部分熔融，属于 I 型花岗质岩类；(3)滩间山花岗斑岩形成于柴达木地体与南祁连地体碰撞造山后伸展构造环境.

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