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中天山白石头泉岩体年代学、岩石成因及构造意义*

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Abstract The Baishitouquan (BST) granite pluton is situated in the gobi area of Hami County, Xinjinag Uygur Autonomous Region, northwestern China. This pluton exhibits five lithological zones gradational from the bottom upwards: leucogranite (zone a), amazonite-bearing granite (zone b), amazonite granite (zone c), topaz-bearing amazonite granite (zone d) and topaz albite granite (zone e). Preview studies have shown that this pluton was formed overwhelmingly by crystallisation from a melt and magma crystallisation was commenced from lower parts of the pluton and progressed upwards from zone a to zone e. U-Pb age determination of zircon by La-ICP/MS shows that the BST pluton was intruded at 295.6 ± 1.3Ma and affected by an Indosinian thermal event (about 214Ma). Geochemically, the leucogranite is rich in silicon, alkali and fluorine, poor in calcium and magnesium, and shows enrichment of LILE (K, Rb, Cs etc), HFSE (Th, U, Nb, Ta, Zr, Hf etc), HREE (ΣLREE/ΣHREE = 0.39 ~ 0.49) and depletion of Sr, Ba, Eu (δEu = 0.002 ~ 0.009), P and Ti with low Al/Ga (2217 ~ 3134), K_2O/Na_2O (0.82 ~ 0.89) ratioes and high Rb/Sr ratio (57.75 ~ 182.24). These geochemical characteristics indicate that the BST magama were derived most probably from melting of muscovite-dominant schist or gneiss at > 860℃ and low pressure. For the granites derived from mid-upper crust, partial melting of source rocks is unlikely to have been induced by heat conduction of an underplating mantle magama body or by higher temperature raised by geothermal gradient after crust thicking, but was caused by intraplating of mafic-ultramafic magama. It should also be true for the genesis of the BST magama. Combined chemical characteristics of the pluton with regional geology, it is suggested that the BST pluton was formed in an extensional tectonic setting following the closure of the Paleo-Tianshan ocean.

Key words Amazonite; Leucogranite; LA-ICP-MS zircon dating; Intraplating; Middle Tianshan; Xinjiang; NW China

摘 要 白石头泉岩体位于中天山北缘边界断裂(沙泉子断裂)南侧。该岩体从下至上可分为五个连续过渡的岩相带,即淡色花岗岩(a 带),含天河石花岗岩(b 带),天河石花岗岩(c 带),含黄玉天河石花岗岩(d 带)以及黄玉钠长花岗岩(e 带),其中,b、c、d 和 e 带均为 a 带分异的产物。白石头泉岩体的 LA-ICP-MS 锆石 U-Pb 定年结果表明,该岩体侵位于早二叠世早期(295.6 ± 1.3Ma),并于印支期(~214Ma)经历了一次热事件的改造。淡色花岗岩在主量元素上富硅(SiO_2 = 74.93% ~ 76.18%)、富碱($K_2O + Na_2O$ = 8.07% ~ 8.80%)、富钠(K_2O / Na_2O = 0.82 ~ 0.89),贫钙、镁,而在微量元素上富 Rb、F 和 Ga

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(Al/Ga 比值为 2217～3134)，贫 Ba、Sr 和 Eu 并具强烈的铕负异常(δEu＝0.0020～0.0091)，反映出其源区为富含白云母的片岩(或片麻岩)，成岩压力较低，温度大于 860℃。结合区域地质特征，作者等认为白石头泉岩体形成于相对拉张的构造背景，是中-上地壳源岩经历高温贫水熔融的产物，其形成与幔源岩浆内侵作用有关。

关键词 天河石；淡色花岗岩；LA-ICP-MS 锆石 U-Pb 定年；内侵；中天山；新疆

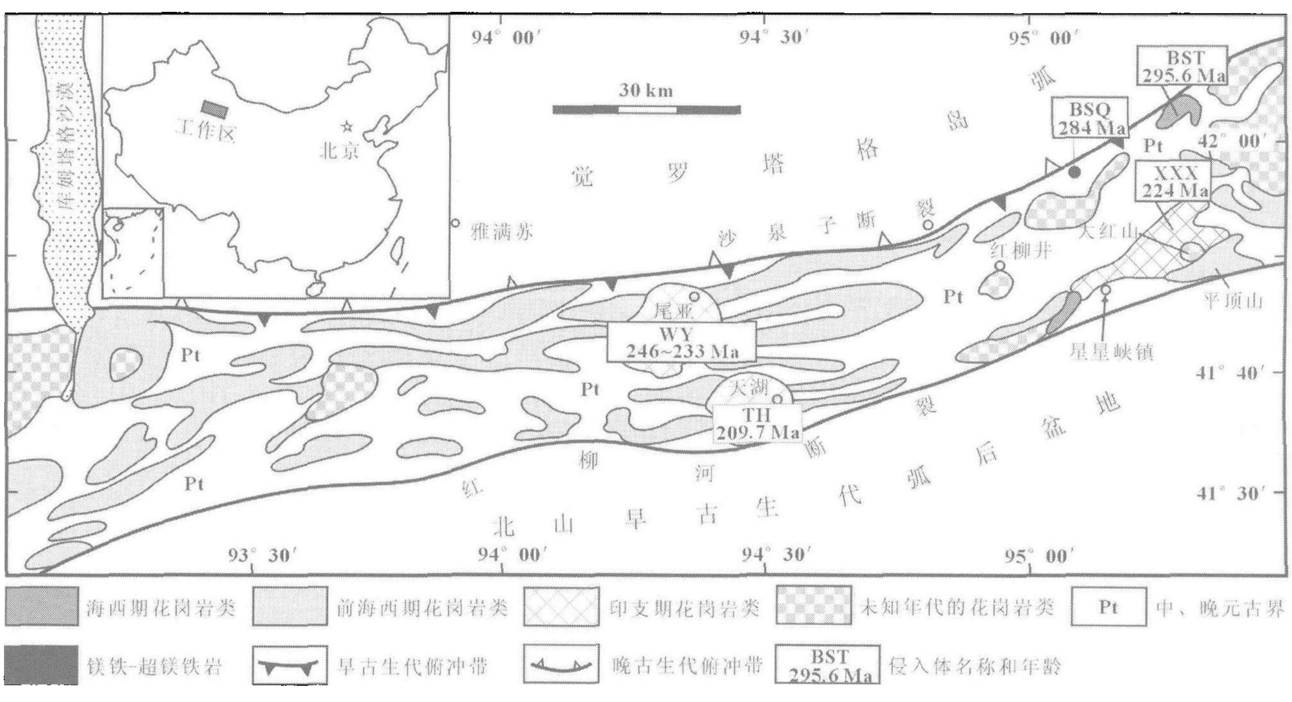
中图法分类号 P588.121；P597.3

“中亚造山带”位于西伯利亚板块和东欧—卡拉库姆—塔里木—中朝板块之间，是全球显生宙大陆地壳增生最显著的地区(Gu *et al.*, 1999；Jahn *et al.*, 2000；Hu *et al.*, 2000；Jahn, 2004；Zhu *et al.*, 2006, 2007；顾连兴等,2006；朱永峰和宋彪,2006；朱永峰等, 2007)。东天山位于中亚造山带南缘，是研究中亚造山带和古亚洲洋最终闭合时间的关键地区之一(Coleman, 1989；肖序常等,1992；何国琦等,1994；顾连兴等,2001a, b, 2007a；张遵忠等,2006；唐俊华等,2006, 2007；吴昌志等,2006；Zhang *et al.*, 2007；胡霭琴等,2007；郭召杰等,2007)，但目前关于古天山洋的闭合时间仍有较大争议：晚石炭纪(胡霭琴等,1995, 1997；Li *et al.*, 2003；顾连兴等,2006)；晚石炭—早二叠(舒良树等,2001)；早二叠晚期或以后(肖文交等,2006)。

白石头泉花岗岩体位于星星峡北东三十余千米处，中天山北缘边界断裂(沙泉子断裂)附近(图 1)。对于该岩体多相带的演化特征和演化机制，前人已做较多工作，并得出该岩体的不同岩相分带是分离结晶和流体搬运共同作用的结果(顾连兴等,1990, 1994, 2003, 2007b；王银喜等,1991；张遵忠等,2004)。然而，前人对该岩体的源区特征及其形成的地球动力学过程研究甚少。此外，前人所采用的定年方法主要为 K-Ar 法(王润民等,1984；顾连兴等,1994)和 Rb-Sr 等时线法(顾连兴等,1990)。众所周知，云母的封闭温度较低，易受后期热事件扰动，其 K-Ar 年龄仅能代表最后一次明显热事件的时代。此外，白石头泉岩体特别富 Rb 而贫 Sr，因而其演化过程中极少量围岩的混染便会造成 Rb/Sr 比值的巨大偏差，进而得出不可靠的 Rb-Sr 等时线年龄。本文在对白石头泉岩体进行 LA-ICP-MS 锆石 U-Pb 定年的基础上，结合对该岩体淡色花岗岩(a 带)的岩石地球化学分析结果，探讨该岩体的源区特征、成岩过程及其构造意义。

1 区域地质概况

白石头泉岩体位于中天山前寒武纪构造带东部北缘，甘-新边界星星峡镇北东约 30km 处(图 1)。中天山夹于沙泉子断裂和红柳河断裂之间，出露的岩石主要是一套变质的前寒武系火山—沉积岩系，即中元古界星星峡群，卡瓦布拉克群和新元古界天湖群，岩性主要为片岩、片麻岩、混合岩、



BST-白石头；TH-天湖；WY-尾亚；XXX-星星峡；BSQ-白石泉（尾亚岩体年龄引自Zhang *et al.*, 2005；星星峡和天湖岩体年龄引自李华芹和陈富文等，2004；白石泉镁铁-超镁铁岩体年龄引自吴华等，2005）

图 1 东天山东段区域地质略图(据顾连兴等,1990)

Fig. 1 Regional geology of the eastern section of the Middle Tianshan belt (data from Gu *et al.*, 1990)

大理岩及角闪岩等。星星峡群和卡瓦布拉克群的变质作用大约发生在1000Ma前，而天湖群的变质时代大约为700Ma(胡霭琴等,1986, 1997)。中天山的地质特征可与塔里木地块北缘的中-新元古代出露区相对比，因此被认为是早古生代天山洋沿沙泉子断裂向南俯冲的过程中因弧后扩张而从塔里木大陆裂离的产物，并被视作早古生代天山造山带的中间地块(胡受奚等,1990;舒良树等,1998)。古生代期间，天山洋的消减方向发生反转，向北俯冲于准噶尔—吐鲁番—哈密地块之下，形成觉罗塔格弧(吴昌志等,2006)。石炭纪末，天山洋俯冲殆尽，觉罗塔格岛弧与中天山被动陆缘沿沙泉子断裂发生碰撞，研究区从此进入了大陆内部环境(顾连兴等,1990, 2001a, b)。

2 岩体地质和岩相学

白石头泉岩体露头面积约7km^2，沿山岗呈NE向展布，其南部被第四纪沉积物覆盖。哈密板材厂在开采石料过程中，对该岩体的各个相带作了充分揭露。当地戈壁气候干旱，山坡几无植被、化学风化以及土壤覆盖，取样条件甚佳。

该岩体与中元古界片岩、片麻岩、混合岩以及加里东期花岗闪长岩呈突变接触，其分枝穿插于围岩花岗闪长岩中，岩体中热液蚀变微很弱。将该岩体从SW侧山脚向NE山顶可划分出五个渐变的相带，即淡色花岗岩相(a带)、含天河石花岗岩相(b带)、天河石花岗岩相(c带)、含黄玉天河石花岗岩相(d带)以及黄玉钠长花岗岩相(e带)，其中d带和e带间的界面相对清楚，其它相带间为渐变关系。顾连兴等(2003,2007b)对白石头泉岩体的上述岩相进行了详细的岩相学、矿物学和包裹体的研究，并得出淡色花岗岩相母岩浆的进一步演化形成了其后四个岩相的认识。本次研究对象主要为为白石头泉岩体中的淡色花岗岩相。

白石头泉岩体淡色花岗岩为灰白色中-细粒块状岩石，主要成分为白云母(3% ~5%)、石英(28% ~35%)、钠长石(22% ~36%)和钾长石(22% ~35%)。石英多为1mm ~2.5mm的半自形晶;白色云母在手标本上显墨绿色，显微镜下则无色，在薄片中常可见其内有黑云母的反应残留体;钾长石多呈它形，粒径0.8mm ~1.2mm;钠长石多呈0.5mm ~1.5mm板条状半自形，聚片双晶清晰。矿物共生结构表明，石英是最早结晶的矿物，钠长石次之，而白云母、钾长石、石榴子石和萤石等形成于岩浆结晶的较晚阶段(顾连兴等,2003)。

3 分析方法

测试用锆石来自于白石头泉岩体天河石花岗岩相。锆石分离系野外所采新鲜样品(3kg ~5kg)粉碎至0.2mm ~0.5mm，经磁选和重力分选后，在双目镜下仔细挑选透明、无裂隙和无包裹体的锆石，再将这些锆石用环氧树脂胶住，待环氧树脂充分固化后抛光至锆石露出一个平面。

阴极发光图像在中国科学院广州地球化学研究所同位素年龄学和地球化学重点实验室(JXA-8100)拍摄。单颗粒锆石LA-ICP-MS法定年在西北大学大陆动力学教育部重点实验室进行。实验由ICP-MS Elan6100DRC与193 nm的ArF的准分子激光剥蚀系统GeoLas200M联机完成。激光斑束直径可于4 ~120μm之间变化，本次试验斑束直径为30μm。采用He作为剥蚀物质载气，用美国国家标准技术研究院研制的人工合成硅酸盐玻璃标准参考物质NIST SRM610进行仪器最佳化，使仪器达到最高的灵敏度、最小的氧化物产率、最低的背景值和稳定的信号。采样方式为单点剥蚀，数据采集选用一个质量峰一点的跳峰方式(peak jumping)。每5个样品分析点测一次标准样，以便保证标准和样品的仪器条件完全一致。以Si作为内标测定锆石中的U、Th和Pb含量，以国际标准91500锆石作为外标，其详细分析方法参见Yuan *et al.* (2004)。样品的同位素比值及元素含量计算采用GLITTER程序;年龄及谐和图的的绘制采用Isopot完成。详细的数据处理及方法参见Yuan *et al.* (2003)。

全岩样品细碎至200目以上后进行元素-同位素组成分析。T1、T2和T3三个样品的主量元素含量在南京大学地球科学系化验室用湿化学法测定，分析精度优于0.5% ~1%。X-188和X-199两个样品的主量元素含量在南京大学现代分析测试中心用VF320单道荧光光谱仪(XRF)测定，分析精度优于5%。微量元素含量在内生金属矿床成矿机制研究国家重点实验室(南京大学)用Element 2型HR-ICP-MS仪器测试，测试方法见高剑锋等(2003)，分析精度优于10%。T1、T2和T3三个样品的F和Cl含量在南京大学地球科学系化验室用离子选择电极法测定，分析精度优于5%。

4 锆石U-Pb年代学

本次研究对白石头泉岩体天河石花岗岩相带进行了锆石LA-ICP-MS U-Pb年龄测定。该岩相锆石颗粒较小，一般为100μm ~150μm，少数可达200μm以上，长短轴之比约为2.4。所测锆石样靶的阴极发光(CL)图像示于图2a。从图中可以看出，锆石多呈柱状，晶型完整，振荡环带发育。对19粒锆石的分析结果见表1。

本次测定的数据点沿水平方向不同程度的偏离协和线(图2b)，这一分布形式在相对年轻的锆石中较为常见，其主要原因是由于年轻锆石中的^{207}Pb丰度较低而难以测准，另一方面也可能与锆石中存在微量普通铅有关(Yuan *et al.*, 2003)。在上述情况下，^{206}Pb/^{238}U年龄更能准确反映其成岩年龄。本次测试的20个锆石点，Th/U比值介于0.28 ~0.71之间，年龄值为214Ma ~415Ma。除点01、10、14、15和20外，其余均集中在291 ~298Ma之间，变化幅度较小，由14个相对集中测点(03号点偏离协和线较远，计算时不予考虑)的数据所得出的^{206}Pb/^{238}U加权平均年龄为295.6 ± 1.3Ma (MSWD = 1.5, 2σ)，精度较高，可以准确地反映岩体的形成

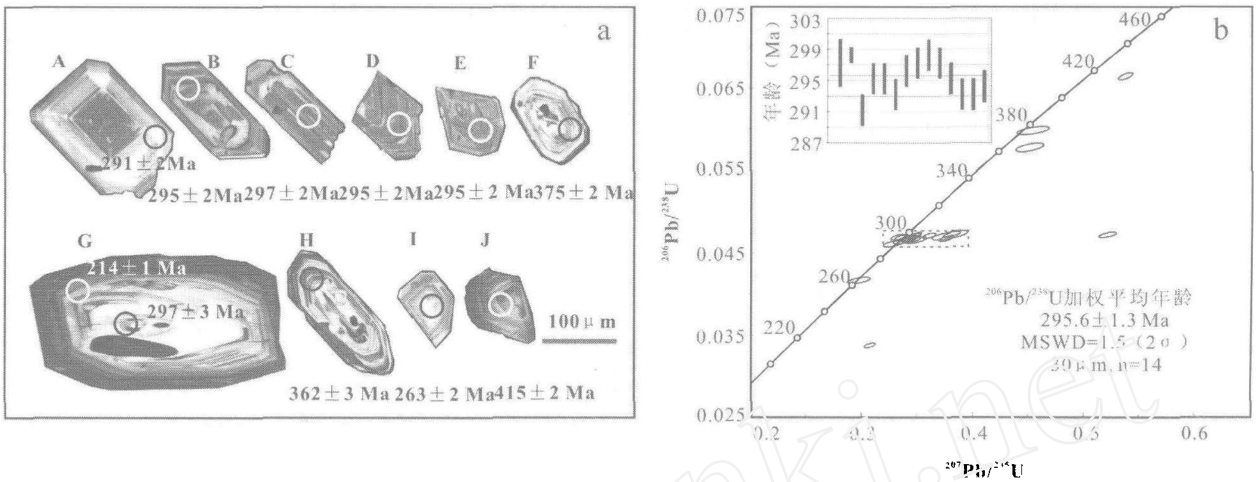


图 2 白石头泉岩体锆石阴极发光图像和 U-Pb 协和图

Fig. 2 Cathodoluminescence images and U-Pb Concordia diagram of zircons from the BST pluton

年龄，表明白石头泉岩体为海西晚期的产物。

10 号点、14 号点和 20 号点获得了较老的年龄，分别为 375Ma、362Ma 和 415Ma，这三颗锆石颗粒较小，外部形态和内部韵律环带特征也不同于其他锆石（图 2a-F，H，J），推测是捕获或者继承的锆石。15 号点具有最低的协和年龄（267Ma），可能是受到了岩浆后期的蚀变或者近期内有铅丢失所致（Da Silva *et al.*，2000）。01 号点位于锆石边部，其 $^{206}Pb/^{238}U$ 年龄（214Ma）明显低于其核部年龄（02 号点，297Ma），可能是受该时段热事件影响所致。有意义的是，此年龄与与前人所测的白云母 K-Ar 年龄（226.6Ma，王润民等，1984；221.6Ma，顾连兴等，1994）在误差范围内一致。众所周知，云母的封闭温度较低，易受后期热事件扰动，其 K-Ar 年龄仅能代表最后一次明显热事件的时代。结合东天山及其邻区内存在印支期的岩浆活动和成矿作用（许志琴等，2001；江思宏等，2003；李华芹等，2004；Li *et al.*，2005；Zhang *et al.*，2005；朱永峰，2007），作者等认为白石头泉花岗岩体侵位时代为 295.6±1.3Ma，并于印支期（~214Ma）经历了一次热事件的改造。

表 1 白石头泉岩体锆石 U-Pb 年龄分析结果

Table 1 U-Pb dating results for zircons from amazonite granite of the BST pluton

测试点号	Th/U	同位素比值（1σ）			年龄值（Ma，1σ）		
		$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$
X-601-01	0.28	0.06620±0.00097	0.30811±0.00354	0.03376±0.00019	813±15	273±3	214±1
X-601-02	0.51	0.05842±0.00208	0.37977±0.01289	0.04715±0.00045	546±57	327±9	297±3
X-601-03	0.39	0.08018±0.00118	0.52181±0.00608	0.04720±0.00027	1201±14	426±4	297±2
X-601-04	0.43	0.05385±0.00063	0.35092±0.00275	0.04726±0.00024	365±9	305±2	298±1
X-601-05	0.45	0.05172±0.00127	0.32912±0.00739	0.04615±0.00033	273±38	289±6	291±2
X-601-06	0.45	0.05206±0.00097	0.33662±0.00543	0.04689±0.00029	288±25	295±4	295±2
X-601-07	0.39	0.05839±0.00104	0.37663±0.00572	0.04678±0.00028	544±23	325±4	295±2
X-601-08	0.41	0.05441±0.00126	0.34942±0.00737	0.04657±0.00033	388±35	304±6	293±2
X-601-09	0.54	0.05150±0.00098	0.33334±0.00557	0.04694±0.00029	263±27	292±4	296±2
X-601-10	0.71	0.05677±0.00138	0.45238±0.01007	0.05779±0.00043	483±36	379±7	362±3
X-601-11	0.54	0.05355±0.00086	0.34764±0.00465	0.04708±0.00027	352±20	303±4	297±2
X-601-12	0.47	0.05853±0.00110	0.38135±0.00623	0.04725±0.00030	550±25	328±5	298±2
X-601-13	0.56	0.05560±0.00090	0.36124±0.00487	0.04711±0.00027	436±20	313±4	297±2
X-601-14	0.71	0.05872±0.00077	0.53820±0.00522	0.06646±0.00035	557±12	437±3	415±2
X-601-15	0.52	0.05190±0.00146	0.29811±0.00815	0.04166±0.00028	281±66	265±6	263±2
X-601-16	0.44	0.05318±0.00115	0.34300±0.00712	0.04678±0.00028	336±50	299±5	295±2
X-601-17	0.44	0.05282±0.00129	0.33866±0.00799	0.04650±0.00030	321±57	296±6	293±2
X-601-18	0.43	0.05335±0.00085	0.34259±0.00450	0.04657±0.00026	344±20	299±3	293±2
X-601-19	0.41	0.05395±0.00093	0.34705±0.00509	0.04664±0.00027	369±23	302±4	294±2
X-601-20	0.71	0.05519±0.00146	0.45544±0.01165	0.05985±0.00040	420±60	381±8	375±2

表 2 白石头泉淡色花岗岩带主量元素(wt%)和微量元素($\times 10^{-6}$)测试结果

Table 2 Chemical analyses of major (wt %) and trace ($\times 10^{-6}$) elements for leucogranite of the BST pluton

样号	T1C	T2C	T3C	X-188	X-189
SiO_2	75.72	74.93	75.9	75.66	76.18
TiO_2	u. d.	u. d.	u. d.	0.01	0.01
Al_2O_3	13.03	13.26	12.92	13.26	13.00
Fe_2O_3	1.09	1.31	1.16	0.86	0.88
MnO	0.05	0.05	0.05	0.15	0.16
MgO	0.28	0.28	0.28	0.07	0.08
CaO	0.50	0.56	0.56	0.43	0.42
Na_2O	4.54	4.64	4.32	4.82	4.73
K_2O	4.05	3.95	3.75	3.95	4.07
P_2O_5	u. d.	u. d.	u. d.	<0.01	<0.01
LOI	0.49	0.67	0.5	0.34	0.33
Total	99.71	99.59	99.4	99.54	99.87
ASI	1.02	1.03	1.06	1.02	1.00
Li	88.65	79.57	131.33	92.12	97.52
Sc	1.110	1.703	1.580	1.193	1.051
Ga	28.78	29.92	30.84	23.96	21.96
Rb	661.8	618.4	695.8	543.0	550.7
Sr	3.812	6.589	12.051	4.421	3.022
Y	148.6	187.9	195.0	172.4	161.7
Zr	118.7	126.9	131.6	96.43	110.4
Nb	45.28	32.36	43.68	19.59	22.51
Sn	16.87	18.99	20.35	14.48	15.07
Cs	26.27	24.85	23.48	20.78	21.24
Ba	7.142	5.393	7.946	6.367	3.641
Hf	9.321	10.34	10.81	10.11	11.52
Ta	7.811	4.079	6.097	4.489	4.209
Th	29.22	34.82	31.75	22.36	18.70
U	9.433	13.12	16.86	6.718	6.501
La	3.102	3.585	4.087	5.563	5.315
Ce	10.95	10.76	12.85	16.15	15.52
Pr	1.771	2.037	2.281	2.868	2.760
Nd	9.406	11.24	12.23	15.34	14.53
Sm	6.793	8.345	8.817	9.969	9.650
Eu	0.026	0.024	0.032	0.013	0.008
Gd	11.23	14.40	15.32	16.43	15.97
Tb	2.694	3.336	3.626	3.336	3.171
Dy	21.68	26.27	28.65	26.87	25.29
Ho	4.416	5.432	5.854	6.278	5.815
Er	15.45	18.76	20.40	20.33	18.87
Tm	2.311	2.821	2.983	3.394	3.118
Yb	15.43	18.87	19.75	23.75	21.66
Lu	2.395	2.903	3.049	3.461	3.172
F	2560	3400	3040	n. d.	n. d.
Cl	50.00	120.0	50.00	n. d.	n. d.
ΣREE	107.7	128.8	139.9	153.7	144.9
Eu/Eu*	0.009	0.007	0.008	0.003	0.002
$(La/Lu)_{CN}$	0.13	0.13	0.14	0.17	0.17

u. d. -低于检测限, n. d. -未检测; ASI = $Al_2O_3/(Na_2O + K_2O + CaO)$分子比

5 地球化学

5.1 主量元素

白石头泉淡色花岗岩的主量元素分析结果列于表2。如表2所示,白石头泉淡色花岗岩以高硅(SiO_2 = 74.93% ~ 76.18%)、富碱($K_2O + Na_2O$ = 8.07% ~ 8.80%)和弱过铝(A/CNK = 1.00 ~ 1.06)为特征,并有较低的Ti、Fe、Ca和Mg含量。P_2O_5含量极低(0.001% ~ 0.009%),可与富F花岗岩的低P组(P_2O_5 < 0.1%, Taylor, 1992)相对比。淡色花岗岩的K_2O < Na_2O(K_2O/Na_2O = 0.82 ~ 0.89),CaO/Na_2O比值变化于0.09 ~ 0.13之间。低的P和Ti含量(~0.01%)可能反映源区部分熔融时存在磷灰石和钛铁矿残留相。淡色花岗岩具有较高的$Al_2O_3/(FeO^T + MgO)$和$(Na_2O + K_2O/(FeO^T + MgO + TiO_2)$值,在源区判别图解(图3)分别集中于两个不同的区域。这可能是它们之间所采用分析方法的系统误差所致,但总体上仍均落同一区域,表明淡色花岗岩的源岩可能为富白云母的泥质岩。

5.2 稀土元素

白石头泉淡色花岗岩的稀土元素分析结果列于表2。稀土元素球粒陨石标准化配分图示于图4。由表2可知,稀土总量(Σ14 REE)介于107.67 $\times 10^{-6}$ ~153.74 $\times 10^{-6}$之间。稀土的球粒陨石标准化配分曲线呈平坦的翼型,Eu具明显负异常(δEu = 0.002 ~ 0.009,表2和图4),这些特征可与其它地区一些低P的含黄玉花岗岩(Taylor, 1992)相类比。ΣLREE/ΣHREE变化与0.39 ~ 0.49,$(La/Lu)_{CN}$和La/Sm比值分别为0.13 ~ 0.17和0.43 ~ 0.56(表2),在稀土配分图上显示左低右高的特征(图4),与岩石中石榴子石作为主要副矿物相一致。这一方面说明淡色花岗岩源区不存在石榴子残留相,另一方面可能是由于该母岩浆富F,而重稀土相对轻稀土更容易与F形成稳定络合物而在富集的缘故(Hanson, 1978)。淡色花岗岩具强烈的负Eu异常,表明其源区以斜长石为残留相,且岩浆演化过程中发生了大量的斜长石分离结晶作用(Cullers and Graf, 1984; Taylor, 1992)。但是,也有人认为,如此强烈的Eu负异常可能是Eu大量进入挥发份而被输运的结果(Irber, 1999; 刘丛强和张辉, 2003)。

5.3 微量元素

白石头泉淡色花岗岩微量元素分析结果列于表2,微量元素原始地幔标准化蛛网图示于图5。由图5可知,白石头泉淡色花岗岩总体上富集大离子亲石元素(LILE,如K、Rb和Cs等)和高场强元素(HFSE,如Th、U、Nb、Ta、Zr和Hf),贫Ba和Sr。

F含量变化于2560 $\times 10^{-6}$ ~3400 $\times 10^{-6}$之间,Cl含量

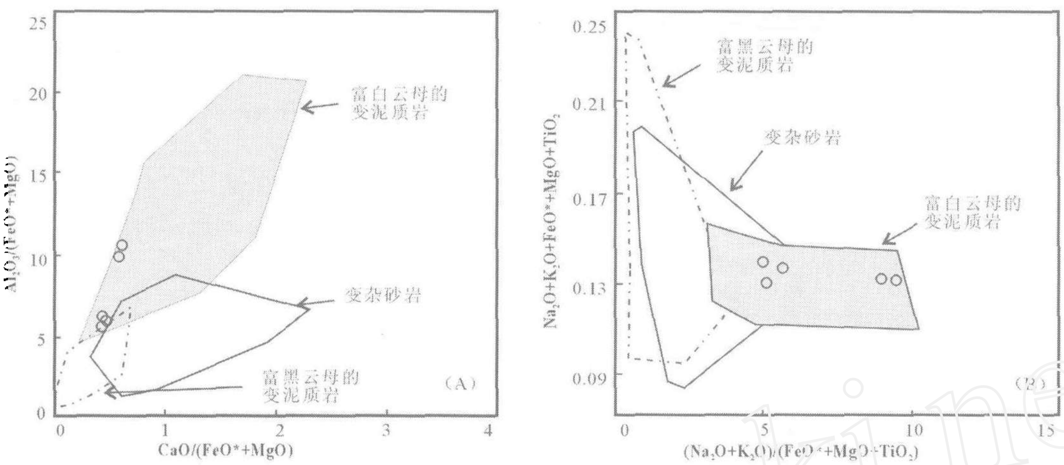


图 3 白石头泉淡色花岗岩源区判别图解(据 Lee *et al.*, 2003)

Fig. 3 Discrimination diagram of source for leucogranite of the BST pluton (after Lee *et al.*, 2003)

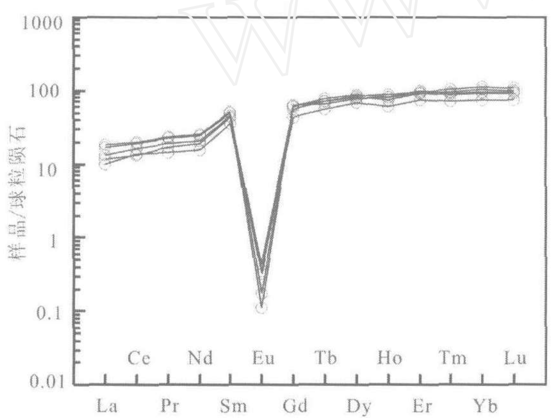


图 4 白石头泉淡色花岗岩球粒陨石标准化配分图(球粒陨石标准值据 Boynton, 1984)

Fig. 4 Chondrite-normalised REE distribution pattern for leucogranite of the BST pluton (Normalization values are from Boynton, 1984)

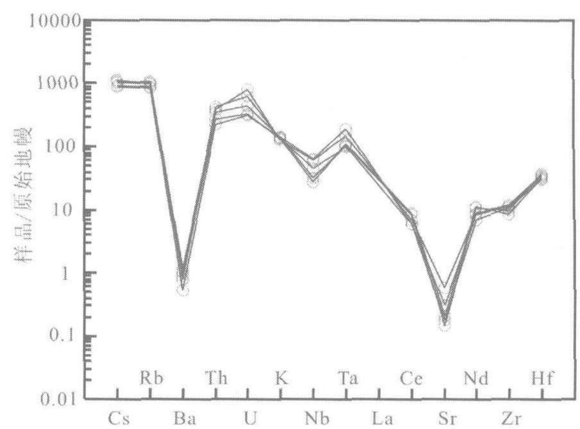


图 5 白石头泉淡色花岗岩原始地幔标准化蛛网图(原始地幔标准值据 Mcdonough *et al.*, 1992)

Fig. 5 The primitive mantle-normalized spidergrams for leucogranite of the BST pluton (Normalization values are from Mcdonough *et al.*, 1992)

($50\times10^{-6}\sim120\times10^{-6}$)明显低于其 F 含量(表 2)。F 相对于 Cl 的富集可能由以下两种因素或其中之一引起:源岩相对富 F 而贫 Cl;岩浆进入地壳浅部后,Cl 比 F 更容易进入出溶的流体相而更容易逸散(Webster and Holloway, 1990)。

Rb 和 Zr 的含量较高,分别为 $543\times10^{-6}\sim696\times10^{-6}$ 和 $96.4\times10^{-6}\sim132\times10^{-6}$。Ba 和 Sr 含量较低,分别为 $3.64\times10^{-6}\sim7.95\times10^{-6}$ 和 $3.02\times10^{-6}\sim12.05\times10^{-6}$(表 2),远低于中国花岗岩的平均值(Ba 为 557×10^{-6},Sr 为 174×10^{-6}, 史长义等,2005),而与某些地区的稀有金属花岗岩和伟晶花岗岩(Tischendorf, 1977;Černý *et al.*, 1985)的含量相近,在微量元素蜘网图上具明显 Ba 和 Sr 负异常。结合淡色花岗岩强烈的 Eu 负异常,其源区应以斜长石为残留相,且岩浆演化过程中发生了大量的斜长石分离结晶作用(Cullers and Graf, 1984;Taylor, 1992)。Rb/Sr 比值变化于 58 ~ 182,远高于全球上地壳平均值(0.32, Taylor and Mclennan, 1995)。

Nb 和 Ta 较为富集,含量分别为 $19.59\times10^{-6}\sim45.28\times10^{-6}$ 和 $4.21\times10^{-6}\sim7.81\times10^{-6}$,高于上地壳平均值(Nb 为 25×10^{-6},Ta 为 2.2×10^{-6}, Taylor and McLennan, 1985),结合较高的高场强元素含量,表明岩体形成与洋壳俯冲无关。

Ga 含量($21.96\times10^{-6}\sim30.84\times10^{-6}$)略高于大多数火成岩($<1\times10^{-6}\sim40\times10^{-6}$, Černý *et al.*, 1985)和中国花岗岩平均值(18×10^{-6}, 史长义等,2005);Al/Ga 比值(2217 ~ 3134,表 2)低于 Černý *et al.* (1985)提供的花岗岩平均值(2000 ~ 8000)和史长义等(2005)提供的中国花岗岩平均值(~7900)。相对于 Ga 而言,Al 更易进入钙长石的结构

之中(Goodman, 1972),因此低的 Al/Ga 比值也进一步指示富钙斜长石可能是白石头泉岩体淡色花岗岩的源区残留相。

6 讨论

6.1 岩石成因

白石头泉岩体淡色花岗岩富碱,贫 Fe、Mg 和 Ti 等,CaO 含量低而 ASI 高,结合高的 Rb/Sr 比值,表明其源岩具有很高的成熟度。较低的 CaO/Na_2O 比值(0.09~0.13)表明其源岩富含泥质(Sylvester, 1998)。淡色花岗岩的 CaO 含量较低,表明富钙的斜长石是源区残留相,与富钙斜长石的平衡导致岩浆具强烈的 Eu 亏损和低 Al/Ga 比值。同时,源岩在部分熔融时的所需水主要来自源区的脱水,这是因为源岩在熔融时若有大量水的加入,斜长石将发生一致熔融,从而导致熔体中的 Ca 大量增加(Castro *et al.*, 2000)。此外,白石头泉岩体淡色花岗岩高度富 Rb 和 F,难以用普通成分岩浆的分异演化来解释,因而其源区应当富集这两种元素。F 和 Rb 类似,易富集于片状矿物云母中(Černy *et al.*, 1985;刘英俊等,1984),因此白石头泉岩体可能是富含云母的片岩(或片麻岩)部分熔融的产物。从该岩体较低的 K_2O/Na_2O 比值(0.82~0.89)和 Mg、Fe 含量来看,源岩中的云母应以白云母为主(Patino Douce and MCCarthy, 1998),这与其源区判别图解落在富含白云母的变泥质岩区(图3)相一致。

富含云母类源岩发生部分熔融时,主要涉及到以下两个反应(Harris and Inger, 1992;Nabelek *et al.*, 1992;Castro *et al.*, 2000):

$$Ms + Qtz + Pl \rightarrow Al-silicate + Melt \pm Kfs \pm Bt \quad (1)$$

$$Bt + Qtz + Pl + Al-silicate \rightarrow Grt(Crd) + Melt \pm Kfs \quad (2)$$

当熔融温度在 700~800℃之间时,主要是白云母的脱水熔融(反应(1)),而当温度超过 800℃时,白云母将全部消耗并转入反应(2)。在白石头泉岩体淡色花岗岩中,石英是最早结晶的矿物(顾连兴等,2003),因而石英熔体包裹体的均一温度(860~810℃,顾连兴等,2003)可视为初始岩浆的形成温度的下限。因此,白石头泉岩体淡色花岗岩的源区熔融温度应大于 860℃,反应(2)已经进行。对于有黑云母参与的部分熔融,在较高的压力下残留相中将出现石榴子石。白石头泉岩体淡色花岗岩重稀土强烈富集的特征(图4)表明,其源区不存在石榴子石残留相,进而表明白石头泉花岗岩体淡色花岗岩的源区压力较低。

6.2 构造意义

拆沉和底侵是壳幔相互作用和花岗岩浆生成的重要方式,也是陆壳生长的重要机制(Herzberg *et al.*, 1983;McKenzie, 1984;Rudnick and Fountain, 1995;Pitcher, 1993;Kay and Kay, 1993;金振民和高山,1996;王德滋和周金城,1999)。底侵体带来的热量很好地解释了下地壳熔融产生花岗岩的机制,但是有些来源于中-上部地壳的花岗岩,就很难用底侵体的热传导来解释。地热增温也不能提供足够的热量,因为正常的 35km 厚的陆壳在无水和正常地温梯度下不能产生大量花岗质岩浆(Petford *et al.*, 2000)。因此,近年来已有作者(Pitcher, 1993;Vaughan *et al.*, 1997;Snoke *et al.*, 1999;Gu *et al.*, 1999;Petford *et al.*, 2000;White *et al.*, 2008)注意到了幔源岩浆可以直接进入地壳内部,并发生侧向漫流而成内侵(intraplating)的可能性。前人(顾连兴等,2006;张遵忠等,2005;唐俊华等,2007)提供了东天山镜儿泉和尾亚地区两个幔源岩浆内侵的研究实例,并将内侵定义为幔源岩浆直接上侵于地壳内部,其热量足以使地壳岩石重熔并形成具有上升能力的新生岩浆(顾连兴等,2006)。

白石头泉岩体淡色花岗岩为富白云母的源岩(片岩或片麻岩)在中-上地壳,经历高温(>860℃)无水熔融而成。如果只靠放射性热或地壳加厚导致的地热增温(England and Thompson, 1984, 1986)很难达到,必须借助于外部热源(Castro *et al.*, 2000)。对于成岩压力较小,源于中-上地壳的白石头泉岩体,下地壳底侵体的热传导作用显然不足于导致其源区的高温贫水熔融,必需借助于高温幔源岩浆。前人的研究也表明,区域内的确存在同时期的基性-超基性岩浆活动(吴华等,2005;毛启贵等,2006)。因此,作者等认为白石头泉岩体淡色花岗岩是幔源岩浆内侵到中-上地壳,并造成富白云母的片岩(或片麻岩)发生高温贫水熔融而形成。

干墩组和梧桐窝子组是东天山最年轻的碰撞前海相地层,其地质年代相当于 316.5~305Ma(周守沄,2005),古天山洋的闭合时间应晚于此年龄。此外,白石头泉淡色花岗岩相对富集高场强元素(Nb、Ta 和 Y 等),白云母的源岩成分,较高温度和贫水的熔融条件,表明该岩体形成与洋壳俯冲作用无关,而应处于相对拉张的构造背景。因此,作者等支持晚石炭世末中天山地区已不存在洋壳俯冲作用的认识(胡霭琴等,1997;Li *et al.*, 2003;Zhu *et al.*, 2005;顾连兴等,2006;朱永峰和宋彪,2006)。

7 结论

白石头泉岩体侵位于早二叠世(295.6±1.3Ma),并于印支期(~214Ma)经历了一次热事件的改造,与中亚成矿域发生的印支期岩浆活动和成矿作用事件相对应。白石头泉岩体的岩浆为中-上地壳富含白云母的源岩(片岩或片麻岩)经历高温(>860℃)无水熔融而生成。白石头泉岩体形成于相对拉张的构造背景,与幔源岩浆内侵作用有关。

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