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东天山大白石头南新元古代片麻状花岗岩锆石 U-Pb 年代学、岩石地球化学及地质意义

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摘要:对东天山大白石头南片麻状花岗岩的研究,可以为新元古代早期 Rodinia 超大陆汇聚事件提供约束.在野外调查和岩相学研究的基础上,对该片麻状花岗岩开展了 LA-ICP-MS 锆石 U-Pb 定年、全岩地球化学和锆石原位 Hf 同位素分析.研究显示,片麻状花岗岩 LA-ICP-MS 锆石 U-Pb 年龄为 922.7±7.9 Ma.岩石富 SiO_2(70.04%~71.60%)、碱(Na_2O+K_2O=5.93%~6.58%)、Al_2O_3(13.88%~14.91%)和低 MgO(1.13%~1.29%).岩石 Al_2O_3/TiO_2(25~27)小于 100,CaO/Na_2O(0.7)大于 0.3,K_2O/Na_2O(1.6~2.2)大于 1.0,富集大离子亲石元素 Rb、Th、K 及 La 等,亏损 Ba、Ta、Nb 和 Sr 等,$(La/Yb)_N$(7.29~8.11)小于 10,δEu 小于 0.5,均显示出 S 型花岗岩特征.锆石 $\varepsilon_{Hf}(t)$均为正值(3.226 78~13.727 46),二阶段模式年龄为 920~1 598 Ma,表明新元古代花岗岩形成于大陆边缘构造环境.综合已有研究结果,可以推断天山地区出露的该期构造岩浆事件可能对应于新元古代的罗迪尼亚(Rodinia)超大陆汇聚事件.

关键词:东天山;片麻状花岗岩;同位素年代学;Hf 同位素;地球化学.
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Zircon U-Pb Age, Geochemistry and Tectonic Implications of Neoproterozoic Granite from South of Dabaishitou, East Tianshan

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Abstract: Researches on the south of Dabaishitou gneissic granite can provide constraints on early Neoproterozoic Rodinia supercontinent convergence in the East Tianshan. In this paper, zircon LA-ICP-MS U-Pb dating, in-situ Hf isotope and whole-rock geochemical composition analyses are presented for the gneissic granite. The results show that the LA-ICP-MS zircon U-Pb isotopic dating on the gneissic granite yields a mean U-Pb age of 922.7±7.9 Ma, which approximately represents the intrusive age of the granite. Geochemical characteristics of major elements of the granite exhibit high SiO_2 (70.04%-71.60%), Na_2O+K_2O (5.93%-6.58%) and Al_2O_3 (13.88%-14.91%) contents, and low MgO(1.13%-1.29%) contents. Al_2O_3/TiO_2 (25-27) ratios are less than 100, while CaO/Na_2O (0.7) and K_2O/Na_2O (1.6-2.2) ratios are more than 0.3 and 1.0, respectively. The gneissic granite is characterized by relative

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enrichment in Rb, Th, K, La, and depletion in Ba, Ta, Nb and Sr. All the samples are slightly enriched in LREE with $(La/Yb)_N$ ratios ranging from 7.29 to 8.11 (less than 10), and all the gneissic granite show clear negative Eu abnormalies ($\delta Eu < 0.5$). These characteristics are similar to values of typical S-type granite. Additionally, zircon $\varepsilon_{Hf}(t)$ values fall in the range of 3.226 78−13.727 46, with the two stage mode age from 920−1 598 Ma. Based on the chemical characteristics and Hf isotopic compositions, the Neoproterozoic gneissic granite was likely generated in a continental margin tectonic setting. With consideration of the age information on the ancient terranes from several areas, we suggest that the Tianshan ancient blocks probably formed a part of Rodinia during early Neoproterozoic period.

Key words: East Tianshan; gneissic granite; isotopic chronology; Hf isotope; geochemistry.

中天山位于塔里木板块和吐哈地块之间,呈狭长的带状展布,是中亚造山带众多具有古老基底的微陆块之一(肖序常等,1992;李锦轶等,2006;舒良树等,2013),在中亚造山带的地壳演化和碰撞过程中起着重要的作用.前人对中亚造山带大量花岗岩的研究,反映了新生地壳形成事件和前寒武纪地壳的存在,并且基底地质体遭受了与洋壳有关的俯冲消减、增生和碰撞作用且发生强烈的构造改造(Jahn *et al.*, 2000, 2004; Hong *et al.*, 2004; 徐学义等, 2014).中天山的岩浆活动、构造演化和成矿作用也是国内外地质学界关注的焦点.随着同位素测年技术的发展,近些年来在中天山地区获得了大量的古生代花岗岩体的同位素测年资料,但对前寒武纪基底地质体的研究还很薄弱,对中天山地块前寒武纪基底的起源和构造归属的认识存在较大分歧,主要有以下几种观点:①天山的前寒武纪基底属于哈萨克斯坦板块的一部分(李春昱等,1982;肖序常等,1992;何国琦等,2001;Windley *et al.*, 2007; Xiao *et al.*, 2008),对哈萨克斯坦板块的起源也存在着西伯利亚板块(Levashova *et al.*, 2011)、东冈瓦纳大陆(Kheraskova *et al.*, 2003; Dobretsov and Buslov, 2007)、东欧板块(Heinhorst *et al.*, 2000; Biske and Seltmann, 2010)等认识;②天山前寒武纪基底是从塔里木板块分离出来的(郭召杰和李茂松,1993; Chen *et al.*, 1999; Khain, 2003; Lei *et al.*, 2011; Ma *et al.*, 2012a);③天山的前寒武纪基底与塔里木克拉通变质基底没有明显的相关性,应是一个独立的大地构造单元或是另有起源(胡霭琴等,1999;李铨等,2002;刘树文等,2004).另一方面,在天山西段广泛分布的蛇绿混杂岩、高压变质岩被认为是代表缝合带(Gao and Klemd, 2003; Klemd *et al.*, 2005, 2011; Su *et al.*, 2010; Han *et al.*, 2011; Wang *et al.*, 2011),相比之下,在天山东段则少见,也缺乏很好的岩石学和同位素年代学资料,但中天山基底岩石可以为板块俯冲、碰撞和东天山演化历史研究提供重要线索(Alexeiev *et al.*, 2011; Konopelko *et al.*, 2012),精确的锆石U-Pb年龄结果对于认识其基底性质是十分必要的.

本文通过对中天山东段大白石头地区晚元古代片麻状花岗岩锆石U-Pb年代学、岩石地球化学和Lu-Hf同位素组成分析,并结合野外地质调查和室内岩相学研究,在花岗岩的形成时代、岩石成因、岩浆源区及成岩构造环境研究基础上,精确厘定新元古代片麻状花岗岩时代,探索其产出构造环境,并结合中天山及邻区已有研究资料,进而探讨对天山构造带构造演化的意义.

1　地质背景与样品特征

中天山地块北侧艾比湖−阿其克库都克断裂带及其东延部分的白山泉−三眼泉(马鬃山地块北缘断裂带)断裂带与北天山弧盆系和板内裂谷系相邻接,南侧乌瓦门−拱拜子断裂带及红柳河−洗肠井断裂带与南天山北缘−红柳河−洗肠井缝合带相邻,西延进入吉尔吉斯,东端没入额济纳内陆盆地之下.研究区位于中天山地块东段,阿其克库都克断裂以南的大白石头地区(图1),采样位置坐标为95.225°E,42.056°N.研究区内仅出露有蓟县纪卡瓦布拉克群和少量二叠纪阿其克布拉克组地层,岩体主体以晚奥陶世和晚石炭世侵入岩为主,另有少量新元古代和晚志留世侵入岩出露.新元古代侵入体主要出露在大白石头地区,呈北东−南西向条带状分布,与沙泉子断裂走向近一致,出露面积约为29.6 km^2,岩性为灰色片麻状花岗岩,侵入于蓟县纪卡瓦布拉克群变质碎屑岩中(图2a),并被晚志留世和晚石炭世中酸性花岗岩侵入.

岩性为灰色片麻状花岗岩,岩石呈花岗结构,片麻状构造(图2b).岩石主要由斜长石、石英、黑云母和白云母组成.斜长石含量约占45%～50%,他形不等粒状,晶粒粒径为0.6～1.6 mm.石英约占35%～40%,呈他形压扁不等粒状.黑云母和白云母约占

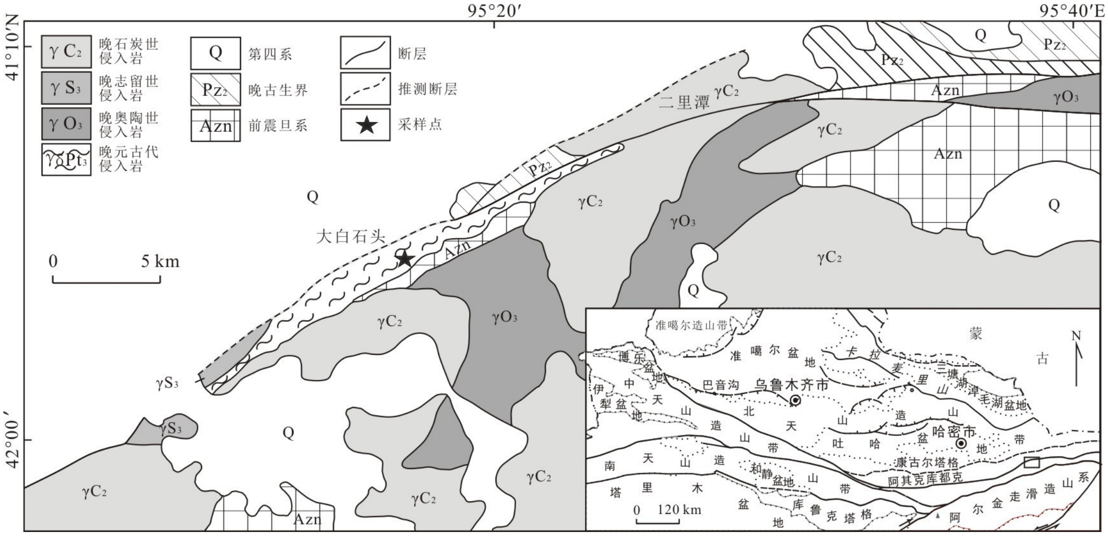

图 1　大白石头地区构造地质简图

Fig.1　Geological sketch of Dabaishitou area

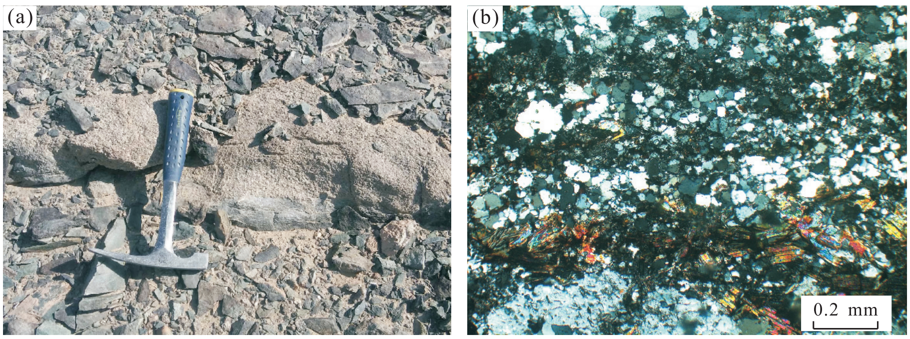

图 2　样品野外照片(a)和显微照片(b)

Fig.2　Field photo (a) and microstructure photo (b) of the sample

10%～15%,晶体粒径一般大于 1 mm,矿物呈连续片状集合体与石英集合体相间半定向排列.岩石中还有一些斜长石、石英晶体残留碎斑,形态呈眼球状或透镜状,粒径大小为 0.6～1.6 mm,碎斑也沿其长轴方向呈半定向分布.

2　实验方法

锆石样品在河北省地质勘查局廊坊实验室内完成处理.首先经过破碎,经淘洗、浮选和电磁选方法富集锆石,再在双目镜下用手工方法逐个挑选晶型完好、无裂隙、干净透明的锆石颗粒制作样靶,用环氧树脂固定,固化后将靶上的锆石颗粒打磨至中心部位露出后进行抛光,然后进行阴极发光(CL)研究和 LA-ICP-MS 锆石 U-Pb 同位素定年分析.阴极发光、透射光显微照片和锆石 U-Pb 同位素定年分析在中国地质调查局西安地质调查中心自然资源部岩浆作用成矿与找矿重点实验室完成.激光剥蚀系统为 GeoLas Pro,ICP-MS 为 Agilent 7700x.激光剥蚀过程中采用氦气作载气、氩气为补偿气以调节灵敏度,二者在进入 ICP 之前通过一个 T 型接头混合.每个时间分辨分析数据包括大约 10 s 的空白信号和 40 s 的样品信号.对分析数据的离线处理(包括对样品和空白信号的选择、仪器灵敏度漂移校正、元素含量及 U-Th-Pb 同位素比值和年龄计算)采用软件 Glitter 4.4 完成,详细仪器参数和测试过程可参考李艳广等(2015).U-Pb 同位素定年中采用锆石标准 91500 作外标进行同位素分馏校正.对于与分析时间有关的 U-Th-Pb 同位素比值漂移,利用 91500 的变化采用线性内插的方式进行了校正.锆石样品的 U-Pb 年龄谐和图绘制和年龄权重平均计算均采用 Isoplot/Ex_ver 3 完成(Ludwig, 2003).

锆石原位微区 Hf 同位素测试是在中国地质调

查局西安地质调查中心自然资源部岩浆作用成矿与找矿重点实验室利用 Neptune 型多接收等离子体质谱仪和 Geolas Pro 型激光剥蚀系统联用的方法完成的，详细测试流程可参照侯可军等（2007）.测试束斑直径为 32 μm，激光剥蚀的样品气溶胶由氦气作为载气输送到质谱仪中进行测试，为了调节和提高仪器灵敏度，气路中间引入了氩气和少量氮气.所有测试位置与 U-Pb 定年点位相同或靠近.每分析 10 个样品测点分析一次锆石标准 GJ-1 作为监控，本次实验 GJ-1 的测试精准度为 0.281 990～0.282 070（2SE）.

元素地球化学分析测试在中国地质调查局西安地质调查中心自然资源部岩浆作用成矿与找矿重点实验室完成，主量元素采用 Panalytical 公司产 PW4400 型 X 荧光光谱仪（XRF）测定，分析误差低于 5%；微量元素和稀土元素采用 Thermo Fisher 公司产 X-series Ⅱ 型电感耦合等离子体质谱仪（ICP-MS）测定，相对标准偏差优于 5%.

3　分析结果

3.1　锆石 U-Pb 年龄

锆石 U-Pb 测试数据结果见表 1.样品的锆石 CL 图像多呈长柱状（图 3），粒度多为 105～160 μm.阴极发光图像表现出典型的岩浆韵律环带和明暗相间的条带状结构，属于岩浆结晶产物（Cawood and Nemchin，2000，2001；Cawood *et al*.，2003，2004；吴元保和郑永飞，2004）.为研究锆石形成年龄，测点均选择在锆石结晶时形成的环带部位.总体上 Th、U 含量较高，分别为 48.37×10^{-6}～494.98×10^{-6} 和 160.12×10^{-6}～890.75×10^{-6}，Th/U 值变化范围为 0.073～0.764，应属岩浆成因锆石（Hoskin and Black，2002）.

样品共 24 个分析点，大部分点落在谐和线上或其附近（图 4），其中两个点不协和度大于 6（表 1），不参与计算，剩余 22 个点加权平均年龄为 922.7±7.9 Ma（MSWD=3.2），说明该片麻状花岗岩形成时代为晚元古代早期.

3.2　锆石 Hf 同位素数据

片麻状花岗岩锆石 Hf 同位素测试是在 U-Pb 定年的基础上进行的，样品 24 颗锆石测点的数据结果列于表 2.样品中 24 个测点的 ^{176}Yb/^{177}Hf 比值范围为 0.044 910～0.191 629，^{176}Lu/^{177}Hf 比值范围为 0.001 000～0.004 339.其中 13 个点 ^{176}Lu/^{177}Hf 比值小于 0.002，大部分锆石在形成以后基本没有放射性成因 Hf 同位素的积累.因此，所测定的 13 个点的 ^{176}Hf/^{177}Hf 比值可以代表其形成的 Hf 同位素组成（吴福元等，2007）.花岗岩中 13 个点的锆石 ^{176}Hf/^{177}Hf 变化范围为 0.282 621～0.282 983，对应的 $\varepsilon_{Hf}(t)$ 值为 3.226 78～13.727 46，地壳模式年龄 t_{DM}^{C} 为 920～1 598 Ma（表 2）.

3.3　岩石地球化学分析结果

岩石地球化学分析结果见表3.花岗岩 SiO_2 含

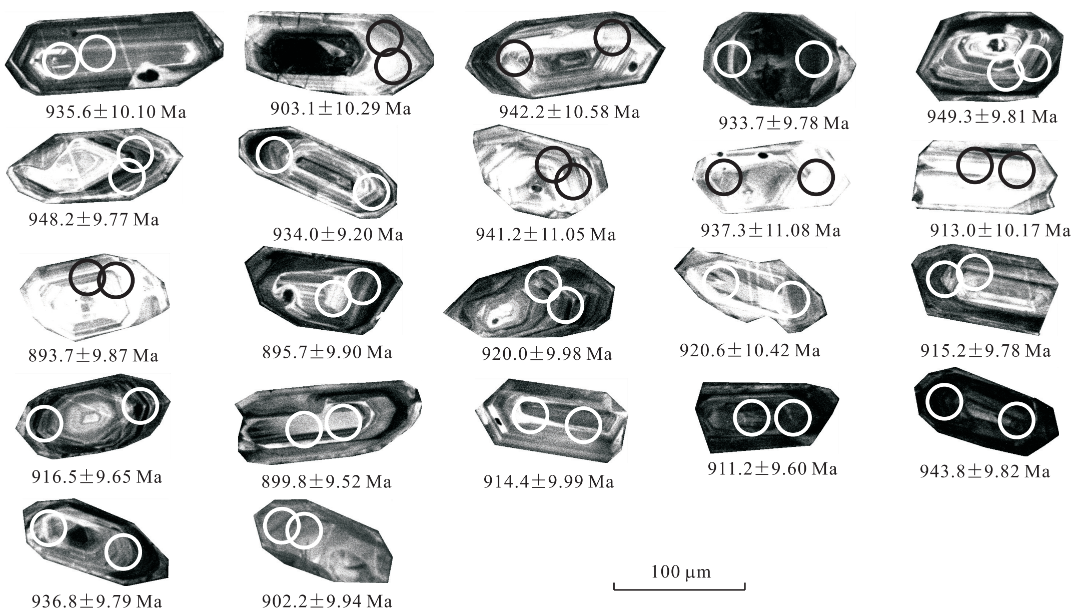

图 3　锆石 CL 图像及 U-Pb 年龄

Fig.3　CL images and U-Pb ages of zircons

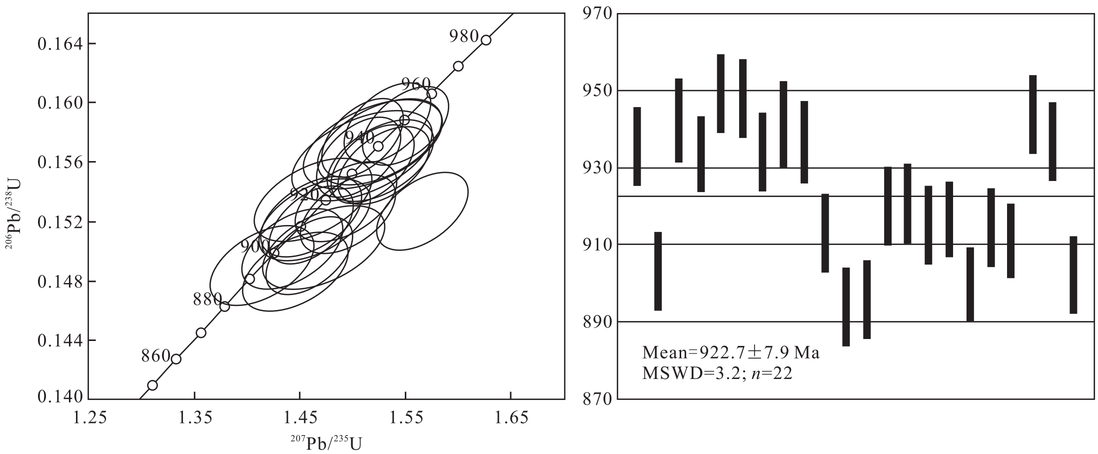

图4　研究区花岗岩锆石 U-Pb 年龄谐和图和年龄加权平均值

Fig.4　Zircon U-Pb concordia diagram and histogram for the granite

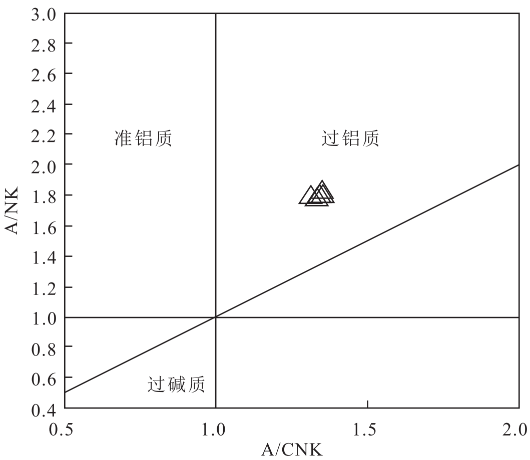

图5　A/CNK－A/NK 图解

Fig.5　A/CNK－A/NK diagram

据 Maniar and Piccoli(1989)

量为 70.04%～71.60%，全碱（Na_2O+K_2O）为 5.93%～6.58%，Al_2O_3 含量较高，介于 13.88%～14.91%，MgO 含量为 1.13%～1.29%，FeO^T 含量为 2.5%～3.1%，CaO 含量为 1.45%～1.53%，TiO_2 含量为 0.52%～0.57%. A/CNK 比值＞1.1，介于 1.31～1.36，为强过铝质花岗岩(图5). Al_2O_3/TiO_2 比值为 25～27，FeO/MgO 比值为 2.07～2.65，两组比值均小于 100；K_2O/Na_2O 比值为 1.6～2.2，比值均大于 1；CaO/Na_2O 比值为 0.7，均大于 0.3. 以上几组数据显示该套岩石与地壳沉积岩部分熔融形成的S型花岗岩地球化学特征类似.

岩石碱度率 *AR* 为 2.23～2.34，里特曼指数 σ 为 1.22～1.60，显示钙碱系列岩石特征，在 SiO_2-K_2O 图解中岩石全部落入高钾钙碱性系列与钾玄岩系列范围(图6a)，在 SiO_2-AR 图解中样品全部落入钙碱性岩石范围内(图6b). 该套片麻状花岗岩样品均显示出高硅、富碱、低镁、强过铝质的钙碱性花岗岩特征，与S型花岗岩主量元素特征一致. 在 Na_2O-K_2O 图解中(图6c)，样品投影也均落入S

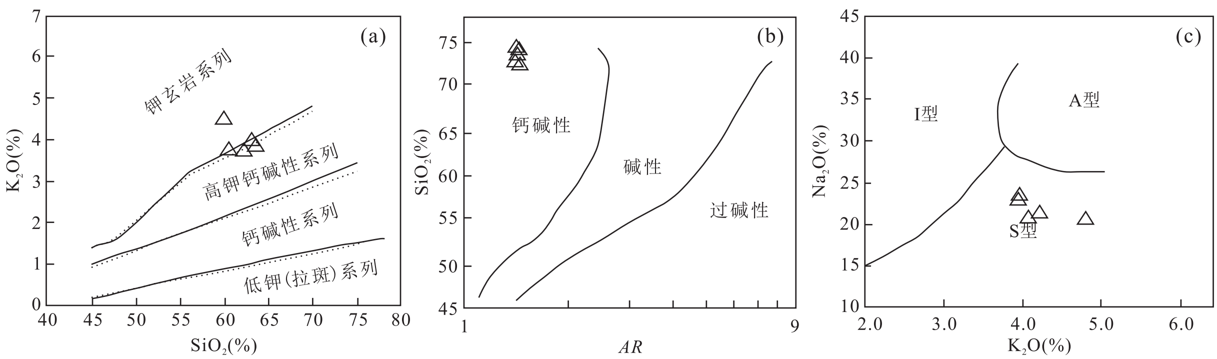

图6　SiO_2-K_2O(a)、SiO_2-AR(b) 和 Na_2O-K_2O(c)图解

Fig.6　SiO_2-K_2O (a), SiO_2-AR (b) and Na_2O-K_2O (c) diagrams

a.据 Rickwood(1989)；b.据 Wright(1969)；c.据 Rollinson (1993)

表 1 片麻状花岗岩锆石 U-Pb 数据

Table 1 U-Pb isotopic compositions of the gneissic granite

测点号	含量(10^{-6})		Th/U	同位素比值								年龄(Ma)	
	Th	U		$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{208}Pb/^{232}Th$	1σ	$^{206}Pb/^{238}U$	1σ
DMZ1601	129.84	375.41	0.35	0.156 19	0.001 81	0.070 66	0.001 54	1.526 33	0.032 96	0.048 67	0.000 86	935.6	10.10
DMZ1602	72.03	216.32	0.33	0.150 38	0.001 84	0.070 83	0.001 85	1.472 88	0.038 05	0.044 68	0.000 99	903.1	10.29
DMZ1603	84.88	215.71	0.39	0.157 38	0.001 90	0.070 09	0.001 78	1.525 34	0.038 41	0.045 20	0.000 89	942.2	10.58
DMZ1604	69.11	532.17	0.13	0.155 85	0.001 75	0.070 96	0.001 33	1.529 06	0.028 62	0.050 10	0.001 08	933.7	9.78
DMZ1605	290.32	549.57	0.53	0.158 66	0.001 76	0.069 90	0.001 23	1.533 46	0.027 01	0.048 01	0.000 60	949.3	9.81
DMZ1606	90.71	605.89	0.15	0.158 46	0.001 76	0.070 78	0.001 21	1.550 67	0.026 75	0.049 79	0.000 91	948.2	9.77
DMZ1607	51.81	705.55	0.07	0.155 91	0.001 72	0.070 48	0.001 17	1.518 95	0.025 52	0.046 74	0.001 14	934.0	9.60
DMZ1608	122.39	160.12	0.76	0.157 20	0.001 98	0.069 91	0.002 01	1.519 19	0.043 07	0.044 82	0.000 77	941.2	11.05
DMZ1609	494.98	890.75	0.56	0.198 95	0.002 18	0.088 13	0.001 31	2.423 63	0.036 69	0.058 64	0.000 66	1 169.7	11.74
DMZ1610	79.92	166.84	0.48	0.156 49	0.001 99	0.069 77	0.002 04	1.509 00	0.043 56	0.048 34	0.000 98	937.3	11.08
DMZ1611	124.85	285.96	0.44	0.152 16	0.001 82	0.069 65	0.001 67	1.464 63	0.034 81	0.045 47	0.000 81	913.0	10.17
DMZ1612	226.00	340.18	0.66	0.148 70	0.001 76	0.070 33	0.001 62	1.445 31	0.032 99	0.042 13	0.000 64	893.7	9.87
DMZ1613	48.37	270.85	0.18	0.149 07	0.001 76	0.068 68	0.001 59	1.414 60	0.032 46	0.044 74	0.001 11	895.7	9.90
DMZ1614	124.17	346.72	0.36	0.153 40	0.001 79	0.070 50	0.001 50	1.494 25	0.031 68	0.045 89	0.000 79	920.0	9.98
DMZ1615	58.62	261.43	0.22	0.153 52	0.001 86	0.068 98	0.001 74	1.463 03	0.036 58	0.044 88	0.001 11	920.6	10.42
DMZ1616	238.95	483.96	0.49	0.152 55	0.001 75	0.070 99	0.001 39	1.496 17	0.029 30	0.041 40	0.000 60	915.2	9.78
DMZ1617	437.82	870.44	0.50	0.152 77	0.001 73	0.074 22	0.001 32	1.566 22	0.028 10	0.045 66	0.000 62	916.5	9.65
DMZ1618	146.58	498.97	0.29	0.212 68	0.002 40	0.085 70	0.001 44	2.517 86	0.042 82	0.062 87	0.001 02	1 243.1	12.77
DMZ1619	165.83	665.61	0.25	0.149 79	0.001 70	0.070 57	0.001 29	1.460 13	0.026 95	0.040 93	0.000 70	899.8	9.52
DMZ1620	231.67	383.74	0.60	0.152 40	0.001 79	0.069 39	0.001 50	1.460 48	0.031 50	0.042 92	0.000 64	914.4	9.99
DMZ1621	100.66	608.97	0.17	0.151 84	0.001 72	0.069 68	0.001 24	1.461 05	0.026 32	0.043 70	0.000 84	911.2	9.60
DMZ1622	97.78	836.98	0.12	0.157 67	0.001 76	0.069 34	0.001 16	1.509 73	0.025 65	0.045 80	0.000 87	943.8	9.82
DMZ1623	65.96	697.53	0.09	0.156 42	0.001 76	0.069 72	0.001 19	1.505 91	0.025 99	0.050 15	0.001 12	936.8	9.79
DMZ1624	61.12	355.76	0.17	0.150 22	0.001 77	0.069 57	0.001 53	1.443 12	0.031 69	0.044 86	0.001 07	902.2	9.94

表 2　片麻状花岗岩锆石 Hf 同位素分析结果

Table 2　Zircon Hf isotopic compositions of the gneissic granite

样品	T(Ma)	$^{176}Yb/^{177}Hf$	1σ	$^{176}Lu/^{177}Hf$	1σ	$^{176}Hf/^{177}Hf$	1σ	$\varepsilon_{Hf}(t)$	1σ	T_{DM}(Ga)	1σ	T_{DM}^{C}(Ga)	1σ	$f_{Lu/Hf}$
Hf-DMZ-01	935.6	0.072 548	0.004 513	0.001 604	0.000 089	0.282 465	0.000 026	8.828 03	0.916 98	1.131 93	0.037 37	1.251 69	0.037 37	−0.951 68
Hf-DMZ-02	903.1	0.065 190	0.001 182	0.001 514	0.000 016	0.282 427	0.000 021	6.839 23	0.723 12	1.183 48	0.029 37	1.354 14	0.029 37	−0.954 39
Hf-DMZ-03	942.2	0.058 122	0.000 694	0.001 312	0.000 016	0.282 441	0.000 017	8.291 06	0.597 09	1.157 49	0.024 13	1.291 32	0.024 13	−0.960 50
Hf-DMZ-05	949.3	0.083 186	0.000 453	0.001 834	0.000 010	0.282 493	0.000 018	9.975 74	0.622 47	1.098 37	0.025 54	1.188 50	0.025 54	−0.944 77
Hf-DMZ-06	948.2	0.096 117	0.001 334	0.002 268	0.000 013	0.282 527	0.000 027	10.886 46	0.951 21	1.061 85	0.039 53	1.128 99	0.039 53	−0.931 68
Hf-DMZ-07	934.0	0.049 232	0.000 405	0.001 032	0.000 011	0.282 346	0.000 022	4.937 44	0.764 51	1.281 59	0.030 59	1.499 96	0.030 59	−0.968 92
Hf-DMZ-08	941.2	0.094 719	0.000 471	0.002 059	0.000 017	0.282 636	0.000 023	14.717 51	0.818 83	0.898 58	0.033 93	0.876 11	0.033 93	−0.937 98
Hf-DMZ-10	937.3	0.106 080	0.001 137	0.002 443	0.000 019	0.282 589	0.000 028	12.722 80	0.984 90	0.977 26	0.041 19	1.002 06	0.041 19	−0.926 42
Hf-DMZ-11	913.0	0.191 629	0.005 154	0.004 339	0.000 120	0.282 983	0.000 038	25.029 42	1.342 94	0.419 14	0.059 90	0.182 50	0.059 90	−0.869 30
Hf-DMZ-12	893.7	0.081 784	0.001 171	0.001 924	0.000 010	0.282 461	0.000 024	7.597 26	0.844 12	1.147 83	0.034 69	1.298 20	0.034 69	−0.942 04
Hf-DMZ-14	920.0	0.057 918	0.000 234	0.001 304	0.000 009	0.282 311	0.000 019	3.226 78	0.659 95	1.340 27	0.026 58	1.598 42	0.026 58	−0.960 71
Hf-DMZ-15	920.6	0.081 325	0.001 338	0.001 893	0.000 018	0.282 435	0.000 022	7.265 53	0.762 68	1.184 04	0.03130	1.34039	0.03130	−0.94298
Hf-DMZ-16	915.2	0.087 136	0.001 246	0.001 922	0.000 011	0.282 621	0.000 023	13.727 46	0.807 60	0.916 78	0.033 33	0.919 99	0.033 33	−0.942 11
Hf-DMZ-17	916.5	0.080 228	0.001 107	0.001 882	0.000 027	0.282 454	0.000 024	7.861 95	0.830 50	1.156 28	0.034 09	1.298 92	0.034 09	−0.943 32
Hf-DMZ-19	899.8	0.111 358	0.002 171	0.002 548	0.000 046	0.282 541	0.000 024	10.205 91	0.832 03	1.049 57	0.034 85	1.135 25	0.034 85	−0.923 24
Hf-DMZ-20	914.4	0.146 224	0.005 927	0.003 296	0.000 097	0.282 679	0.000 031	14.938 13	1.084 78	0.864 83	0.046 56	0.841 04	0.046 56	−0.900 72
Hf-DMZ-21	911.2	0.157 528	0.002 011	0.003 571	0.000 020	0.282 863	0.000 020	21.203 34	0.699 59	0.593 18	0.030 43	0.431 32	0.030 43	−0.892 43
Hf-DMZ-22	943.8	0.063 551	0.000 993	0.001 409	0.000 032	0.282 367	0.000 021	5.667 26	0.747 34	1.264 34	0.030 22	1.460 86	0.030 22	−0.957 57
Hf-DMZ-23	936.8	0.044 911	0.000 740	0.001 000	0.000 026	0.282 357	0.000 025	5.390 26	0.874 93	1.265 81	0.034 99	1.473 15	0.034 99	−0.969 87
Hf-DMZ-24	902.2	0.084 347	0.003 151	0.001 899	0.000 051	0.282 383	0.000 037	5.044 50	1.311 29	1.258 39	0.053 73	1.468 40	0.053 73	−0.942 79

表 3 片麻状花岗岩主量元素(%)及微量元素(10^{-6})化学组成

Table 3 Major element (%) and trace element (10^{-6}) compositions of the gneissic granite

样号	D01-1	D01-2	D01-3	D01-4	D01-5	样号	D01-1	D01-2	D01-3	D01-4	D01-5
SiO_2	70.32	71.60	71.15	70.04	71.83	Ho	1.77	1.50	1.92	1.57	1.51
Al_2O_3	14.46	13.94	13.96	14.91	13.88	Er	4.87	4.32	5.30	4.18	4.04
Fe_2O_3	1.37	1.09	1.27	1.11	1.00	Tm	0.74	0.64	0.82	0.63	0.64
FeO	2.20	2.05	2.12	1.82	1.98	Yb	4.75	4.08	5.34	4.15	4.04
MnO	0.048	0.045	0.046	0.048	0.050	Lu	0.74	0.63	0.78	0.62	0.60
MgO	1.29	1.21	1.13	1.22	1.18	Y	47.8	42.3	51.5	40.4	40.3
CaO	1.53	1.45	1.56	1.49	1.49	ΣREE	274.43	213.11	290.50	219.95	234.26
Na_2O	2.34	2.13	2.28	2.06	2.07	LREE	241.89	185.22	255.43	192.38	206.80
K_2O	3.76	4.00	3.75	4.52	3.86	HREE	32.54	27.89	35.07	27.57	27.46
TiO_2	0.57	0.52	0.55	0.57	0.53	LREE/HREE	7.43	6.64	7.28	6.98	7.53
P_2O_5	0.11	0.12	0.10	0.11	0.11	$(La/Yb)_N$	8.11	7.45	7.62	7.29	8.10
LOI	1.94	1.81	2.04	2.05	1.97	δEu	0.38	0.38	0.40	0.44	0.38
Total	99.94	99.97	99.96	99.95	99.95	Rb	139	136	142	162	118
$Mg^{\#}$	36.96	37.12	34.77	40.13	37.34	Sr	90.3	80.8	108	93.9	82.8
A/CNK	1.35	1.33	1.31	1.36	1.35	Ba	792	772	916	925	780
SI	11.77	11.55	10.71	11.37	11.69	Nb	15.5	14.5	15.6	15.6	12.5
AR	2.23	2.32	2.27	2.34	2.26	Ta	1.21	1.20	1.39	1.20	0.94
σ	1.36	1.31	1.29	1.60	1.22	Zr	291	275	290	269	228
A/MF	11.21	11.52	12.35	12.22	11.76	Hf	8.66	7.97	8.48	7.96	7.04
C/MF	1.19	1.20	1.38	1.22	1.26	U	3.75	3.36	4.83	3.42	3.34
La	53.7	42.4	56.7	42.2	45.6	Th	30.9	26.6	34.0	30.5	26.7
Ce	112	82.2	120	90.7	96.9	Th/U	8.24	7.92	7.04	8.92	7.99
Pr	13.6	10.8	14.4	10.9	11.7	Zr/Hf	33.60	34.50	34.20	33.79	32.39
Nd	50.5	40.0	52.6	39.1	42.4	Rb/Ba	0.18	0.18	0.16	0.18	0.15
Sm	10.8	8.75	10.4	8.32	9.13	Sr/Ba	0.11	0.10	0.12	0.10	0.11
Eu	1.29	1.07	1.33	1.16	1.07	Nb/Ta	12.81	12.08	11.22	13.00	13.30
Gd	9.46	7.98	9.81	7.66	7.93	Rb/Nb	8.97	9.38	9.10	10.38	9.44
Tb	1.50	1.30	1.57	1.24	1.26	La/Nb	3.46	2.92	3.63	2.71	3.65
Dy	8.71	7.44	9.53	7.52	7.44						

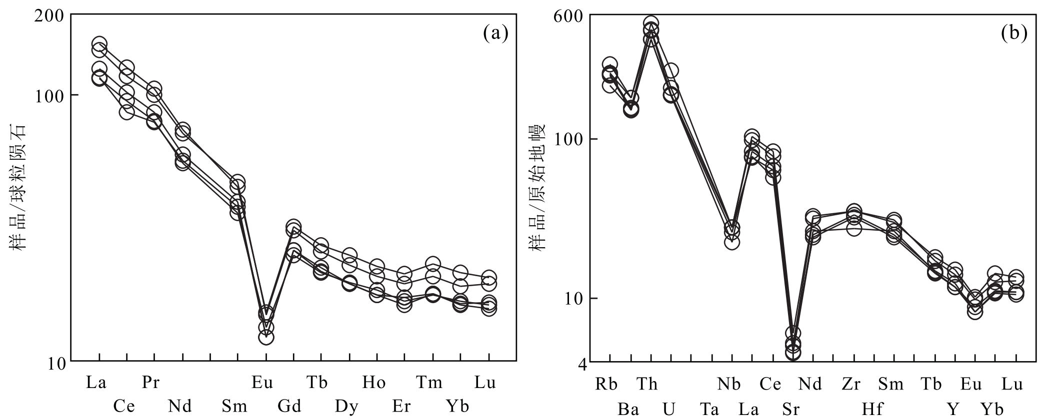

图 7 球粒陨石标准化稀土元素配分图(a)和原始地幔标准化微量元素蛛网图(b)

Fig.7 Chondrite-normalized REE patterns (a) and primitive-mantle normalized spider diagram for monzogranitic gneiss (b)

标准化值据 Taylor and McLemann(1985)

型花岗岩区.

稀土元素分析结果显示岩石样品的 ΣREE 总量为 213×10^{-6}～291×10^{-6},平均值为 246×10^{-6}.岩石各样品具有非常相似的稀土配分模式(图 7a),具有明显的 LREE 富集(LREE/HREE 比值为 3.88～4.65,$(La/Yb)_N$ 为 7.29～8.11,平均值为 7.71)和强烈 Eu 亏损(δEu 为 0.37～0.44)特征.曲线整体呈右倾的轻稀土富集、重稀土亏损的模式,具有

S型花岗岩稀土元素分配特点.

微量元素原始地幔标准化蛛网图(图7b)显示，岩石富集大离子亲石元素Rb、Th、K及La等，亏损Ba、Ta、Nb和Sr等.Th/U比值(7.0～8.9)稍高于上地壳平均值4.2，Zr/Hf比值为32.4～34.5，稍低于上地壳的Zr/Hf比值(～37)(Gao *et al.*，1998)，显示其源岩具有地壳沉积物的特征.

4　讨论

4.1　岩石成因和源岩特征

地球化学特征显示出高硅、富碱、低镁、过铝质的钙碱性花岗岩特征以及稀土配分曲线特征等，SiO_2与P_2O_5之间不具有负相关性(Li *et al.*，2007)(表2)，这些都显示出了S型花岗岩特征，反映其源岩可能含有较多的泥质沉积岩.但样品CaO/Na_2O较高，为0.7(均大于0.3)，暗示其源岩可能为陆壳沉积的砂质岩(Sylvester，1998).利用$CaO/(MgO+FeO)-Al_2O_3/(MgO+FeO)$图解(图8)进一步判别发现，样品均落于杂砂岩的部分熔融范围，靠近泥质岩部分熔融区域，与基性岩的部分熔融关系不大，这与其低的$Mg^{\#}$值(40.1～34.8，平均值为37)相一致.

锆石Hf同位素作为有力的示踪工具已广泛应用于岩石源区判别，已有研究成果表明，具有低的$^{176}Hf/^{177}Hf$以及$\varepsilon_{Hf}(t)$值表明花岗岩可能来源于古老地壳的深熔或重熔(Allègre and Othman，1980；Peter and Roland，2003)，具有较高的$^{176}Hf/^{177}Hf$以及$\varepsilon_{Hf}(t)$值表明花岗岩可能来源于新生地壳的再循环或大陆地壳中新生地幔物质的混入(Jahn *et al.*，2000；Zhu *et al.*，2009a，2009b).由表2可见，锆石$\varepsilon_{Hf}(t)$值为3.226 78～13.727 46，均为正值(13个点)，二阶段模式年龄主要集中在920～1 598 Ma(表2)，暗示了花岗岩很可能来源于古老的下地壳物质，而相对较高的$\varepsilon_{Hf}(t)$值显示了亏损地幔的特征，暗示可能有幔源镁铁质岩浆的加入，可能与镁铁质岩浆的底侵作用有关.在锆石$^{176}Hf/^{177}Hf-t$年龄图解中(图9)，投点均落于球粒陨石与亏损地幔演化线之间，也暗示了其母岩浆可能起源于亏损地幔源区.

综合样品岩石地球化学特征和同位素数据，大白石头南片麻状花岗岩的岩浆源区应为古老的下地壳杂砂岩和泥质岩，因此，地球化学特征显示出S型花岗岩特征，但花岗岩形成过程中还有幔源物质的加入，使锆石Hf同位素示踪显示出了亏损地幔源区特征.

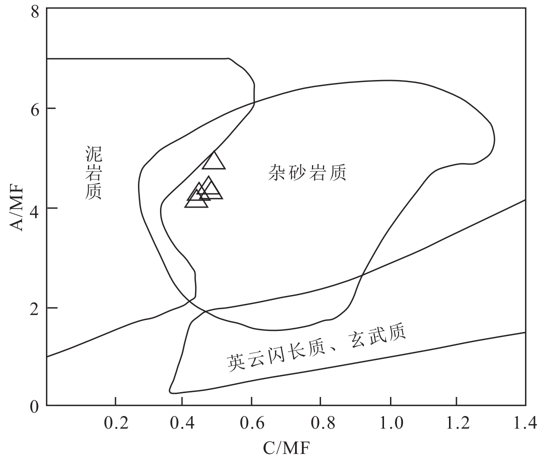

图8　岩石A/MF－C/MF成因图解

Fig.8　Petrogenesis A/FM－C/MF diagram

据Altherr *et al.*(2000)

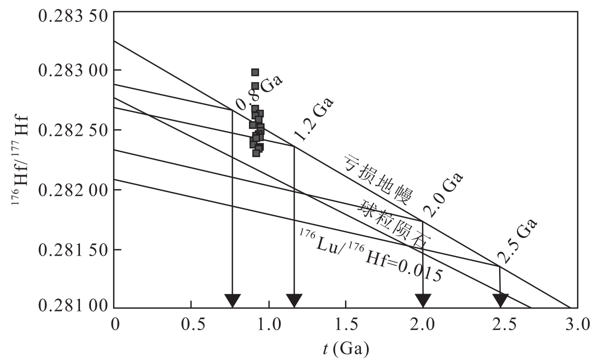

图9　片麻状花岗岩的锆石$^{176}Hf/^{177}Hf-t$年龄图解

Fig.9　Zircons $^{176}Hf/^{177}Hf-t$ diagram of the gneissic granite

4.2　构造环境分析

岩石微量元素Nb和Ta含量分别为12.5×10^{-6}～15.6×10^{-6}和0.94×10^{-6}～1.39×10^{-6}，类似于陆－陆碰撞型花岗岩6×10^{-6}～16×10^{-6}和0.6×10^{-6}～2.6×10^{-6}(Pearce *et al.*，1984).在Rb－(Ta＋Yb)判别图中(图10a)，样品均落在同碰撞花岗岩区域，在Rb－(Nb＋Yb)判别图中(图10b)，样品落在板内和火山弧花岗岩之间，但是，在微量元素蛛网图中样品具有明显的Ba、Nb和Sr负异常，与板内形成的A型花岗岩的特征明显不同.综合分析认为它们形成的构造环境可能是与大陆边缘的构造岩浆活动有关.

4.3　地质意义探讨

在整个天山地区已有部分0.9 Ga左右花岗岩的报道(表4).黄博涛等(2014)对阿拉塔格地区花岗片麻岩进行了LA-ICP-MS锆石U-Pb研究，获得两个新元古代花岗片麻岩年龄为945±6 Ma和942±

6 Ma;Chen *et al*.(2000)对独库公路南段拉尔敦达坂的北段出露的片麻状花岗岩进行了锆石 U-Pb 年龄分析,确定该套岩体成岩年龄应该在 882 Ma;陈新跃等(2009)获得了巴仑台北片麻状花岗岩的精确锆石 SHRIMP U-Pb 年龄为 926±8 Ma;李婷等(2015)获得伊犁地块达根别里花岗岩锆石 U-Pb 年龄为 942.5±2.6 Ma;胡霭琴等(2006)对西天山赛里木湖以东的片麻状花岗岩进行研究,认为其形成时代为 930 Ma;胡霭琴等(2008)获得了东天山星星峡和西天山温泉地区片麻状花岗岩的锆石 SHRIMP U-Pb 年龄分别为 924±7 Ma 和 919±6 Ma,认为这些新元古代花岗岩形成于大陆边缘构造环境,由古元古代地壳重熔并经历了高度的结晶分异作用而形成,并结合塔里木盆地周边古老地块年龄的研究结果,推断在早新元古代时期塔里木周边和天山的古老地块可能曾是组成 Rodinia 超大陆的一部分(郭召杰等,2000;胡霭琴等,2001;陆松年等,2004;Wang *et al*.,2013,2015;王洪浩等,2015).除此之外,新元古代早期岩浆活动在一些早古生代的岩浆岩中仍然残留有该时代的锆石(龙灵利等,2006;胡霭琴等,2006,2008),这进一步说明天山地区新元古代早期岩浆岩是广泛分布的.

该期花岗岩不仅在天山地区广泛分布,在扬子地块、塔里木周缘、柴北缘、北山、中祁连、昆中等地区均有发现,并且与全球该期岩浆活动也可以对比.比如我国扬子地块南缘的西袭和桃红岩体,英云闪长岩和花岗闪长岩的 SHRIMP U-Pb 年龄分别为 913±15 Ma 和 905±14 Ma(Ye *et al*.,2007);塔里木盆地北缘辛格尔南托格拉克布拉克太古宙杂岩中斜长角闪岩的角闪石激光熔样 $^{40}Ar/^{39}Ar$ 等时线年龄为 866±6 Ma(胡蔼琴等,2006);杨鑫等(2017)通过对塔北隆起区钻井取样,获得二云斜长片麻岩锆石 U-Pb 年龄为 822±7 Ma;兴地断裂南阔克苏地区的石英闪长岩锆石 U-Pb 年龄为 828 Ma;库尔勒至阿克苏公路北侧 16 km 处的片麻状花岗岩锆石 U-Pb年龄为 970 Ma、944 Ma 和 884 Ma(胡蔼琴等,1997);塔里木盆地东南缘阿尔金山地区环形山二长花岗片麻岩 LA-ICP-MS 锆石 U-Pb 年龄为 928±9 Ma(王立社等,2015);柴北缘沙柳河、鱼卡河、六五沟一线花岗片麻岩时代介于 1.0~0.8 Ga,以 0.9 Ga左右为主(Yu *et al*.,1999);柴北缘锡铁山花岗质片麻岩独居石电子探针原位 U-Th-Pb 定年年龄为 886±18 Ma(张聪等,2016);甘肃北山柳园西古堡泉花岗片麻岩锆石 U-Pb 年龄为 880±31 Ma(梅华林等,1999);中祁连山东段响河花岗岩锆石 U-Pb 年龄为 917±12 Ma(郭进京等,1999);昆中断裂带两侧花岗片麻岩体 4 组锆石 U-Pb 年龄在 900 Ma左右(陆松年,2002).另外,与印度的 Eastern Ghats Belt、南极洲东部的 Rayner 省和非洲北部的 Rahaba-Absol 地体等均可对比.目前,主流观点认为该期构造热事件与 Rodinia 超大陆的聚合事件有关(李曰俊等,2005;Li *et al*.,2008;Lei *et al*.,2011;Shu *et al*.,2011;Ma *et al*.,2012b;Zhang *et al*.,2012).

在甘肃北山、柴北缘均发现榴辉岩-含柯石英榴辉岩,呈构造透镜体状分布在花岗质片麻岩中,被作为地块汇聚碰撞带的标志之一(于海峰等,1999),因此,该期花岗片麻岩显示的构造岩浆事件说明塔里

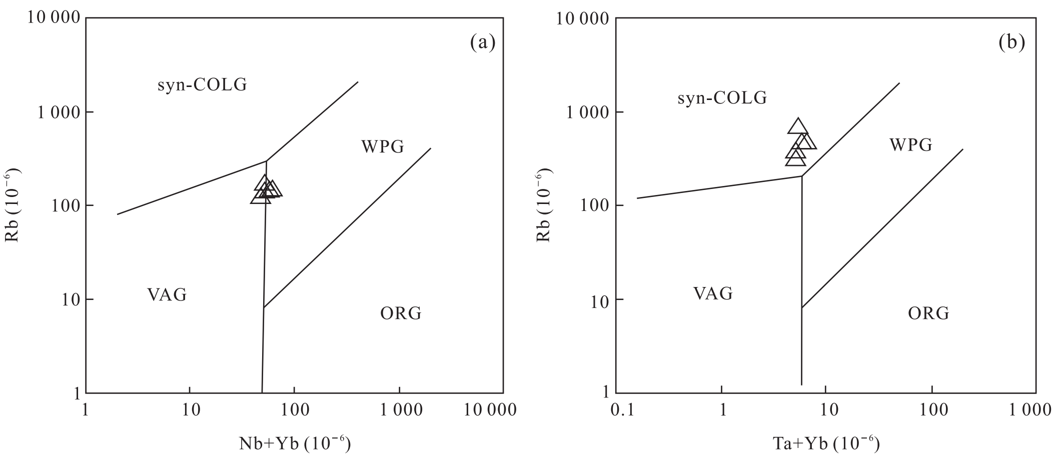

图 10 岩石 Rb-(Ta+Yb)(a)和 Rb-(Nb+Yb)(b)图解

Fig.10 Rb-(Ta+Yb)(a) and Rb-(Nb+Yb)(b) diagrams for samples

syn-COLG.同碰撞花岗岩;WPG.板内花岗岩;VAG.火山弧花岗岩;ORG.洋脊花岗岩.据 Pearce *et al*.(1984)

表4　天山及西北邻区部分新元古代花岗岩年龄统计

Table 4　Some ages of Neoproterozoic granite in the Tianshan and Northwest China area

位置	样品名称	年代学方法	年龄	备注
阿拉塔格	花岗片麻岩	LA-ICP-MS锆石U-Pb	945±6 Ma，942±6 Ma	黄博涛等，2014
拉尔敦达坂北	片麻状花岗岩	LA-ICP-MS锆石U-Pb	882±33 Ma	Chen *et al.*，2000
东天山星星峡	片麻状花岗岩	SHRIMP锆石U-Pb	942±7 Ma	胡霭琴等，2008
西天山温泉	片麻状花岗岩	SHRIMP锆石U-Pb	919±6 Ma	
西天山赛里木湖以东	片麻状花岗岩	SHRIMP锆石U-Pb	930 Ma	胡霭琴等，2006
巴仑台北	片麻状花岗岩	SHRIMP锆石U-Pb	926±8 Ma	陈新跃等，2009
伊犁地块达根别里	花岗岩	LA-ICP-MS锆石U-Pb	942.5±2.6 Ma	李婷等，2015
塔里木盆地北缘	二云斜长片麻岩	LA-ICP-MS锆石U-Pb	822±7 Ma	杨鑫等，2017
塔里木盆地北缘辛格尔南托格拉克布拉克	斜长角闪岩	角闪石激光熔样 $^{40}Ar/^{39}Ar$ 等时线年龄	866±6 Ma	胡蔼琴等，2006
兴地断裂南阔克苏	石英闪长岩	锆石U-Pb	828 Ma	胡蔼琴等，1997
库尔勒至阿克苏	片麻状花岗岩	锆石U-Pb	970 Ma，944 Ma，884 Ma	
阿尔金环形山	二长花岗片麻岩	LA-ICP-MS锆石U-Pb	928±9 Ma	王立社等，2015
柴北缘锡铁山	花岗质片麻岩	独居石电子探针原位U-Th-Pb定年	886±18 Ma	张聪等，2016
北山柳园西古堡泉	花岗片麻岩	单颗粒锆石U-Pb	880±31 Ma	梅华林等，1999
中祁连山东段响河	花岗岩	单颗粒锆石U-Pb	917±12 Ma	郭进京等，1999
昆中断裂带两侧	花岗片麻岩	锆石U-Pb	900 Ma±	陆松年，2002

木、柴达木和阿尔金造山带在新元古代早期曾经存在板块的汇聚碰撞作用，天山地区出露的该期构造岩浆事件应处于同样的构造作用应力背景之下，可能对应于新元古代的罗迪尼亚（Rodinia）超大陆汇聚事件.

5　结论

（1）东天山大白石头南新元古代灰色片麻状花岗岩形成于新元古代早期的青白口纪，锆石 $^{206}Pb/^{238}U$ 加权平均年龄为922.7±7.9 Ma.

（2）片麻状花岗岩为高硅、富碱、低镁、强过铝质的钙碱性岩石，岩石地球化学特征显示其为S型花岗岩.结合锆石Hf同位素分析，花岗岩的岩浆源区应为古老的下地壳物质，并含有幔源物质的混入.

（3）岩石成因及年代学研究表明，新元古代早期中天山发生了板块的汇聚碰撞作用，这与塔里木、柴达木和祁连等微板块新元古代早期所处的构造背景是一致的，可能对应于新元古代的罗迪尼亚（Rodinia）超大陆汇聚事件.

致谢：岩矿鉴定得到叶芳老师的指导；锆石U-Pb测试分析得到中国地质调查局西安地质调查中心自然资源部岩浆作用成矿与找矿重点实验室靳梦琪的帮助；编辑和审稿专家认真细致地审阅文本，提出了宝贵的修改建议；在此一并深表感谢！

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