北山造山带早泥盆世埃达克岩的发现及地质意义

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摘　要: 北山造山带位于中亚巨型造山带南缘,是剖析中亚造山带南缘增生构造过程的关键地区之一,古亚洲洋闭合时间存在较大争议,聚焦于泥盆纪古亚洲洋仍在俯冲还是已经闭合。作者在北山造山带南缘黑山头一带首次识别出具典型埃达克岩特征的中酸性侵入体,对其进行了岩石地球化学和锆石 U-Pb 年代学研究。黑山头岩体中花岗闪长岩 LA-ICP-MS 锆石 U-Pb 加权平均年龄为 407.7±1.6 Ma,形成于早泥盆世。地球化学数据表明,黑山头岩体为过铝质,属钙碱性系列,具典型埃达克岩特征:高硅(SiO_2 = 60.85% ~ 67.81%)、高铝(Al_2O_3 = 15.59% ~ 16.98%)、低镁(MgO = 0.55% ~ 1.53%, $Mg^{\#}$ = 0.36 ~ 0.46)、富钠贫钾(Na_2O = 2.65% ~ 3.54%, K_2O = 1.09% ~ 3.16%, Na_2O/K_2O = 0.96 ~ 2.44)、高 Sr($Sr = 253\times10^{-6} \sim 487\times10^{-6}$)、低 Y 和 Yb($Y = 5.65\times10^{-6} \sim 16.70\times10^{-6}$, $Yb = 0.37\times10^{-6} \sim 0.96\times10^{-6}$)、高 Sr/Y 值(25.75 ~ 73.58);轻稀土元素富集,轻重稀土元素分馏明显,样品不具明显的 Eu 异常(0.66 ~ 1.31,平均 0.92);微量元素富集大离子亲石元素 Rb、K、Th、U,亏损高场强元素 Nb、Ta、Ti、P。地球化学特征显示其为俯冲洋壳部分熔融形成的埃达克岩,残留相为石榴子石+金红石。结合前人研究认识,认为柳园洋(古亚洲洋)具有自西向东呈"剪刀式"闭合的特征,柳园洋(古亚洲洋)在早泥盆世仍处于俯冲碰撞阶段,早石炭世是北山地区古生代洋盆闭合时限上限。

关键词: 埃达克岩; 锆石 U-Pb 年龄; 岩石地球化学; 岩石成因; 北山造山带
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The discovery of Early Devonian adakites in Beishan orogenic belt and its geological significance

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Abstract: Located on the southern margin of the Central Asian giant orogenic belt, the Beishan orogenic belt is one of the key areas for dissecting the accretionary tectonic process of the southern margin of the Central Asian orogenic belt. Researchers have a great controversy about the closing time of the Paleo-Asian Ocean and focus on whether the Devonian ancient Asian Ocean was still subducting or closed. In this study, the authors firstly identified a pluton with typical adakite characteristics in Heishantou area on the southern margin of the Beishan orogenic belt. The

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geochemical characteristics and zircon U-Pb chronology of the pluton were studied to discuss its genesis and geodynamic significance. The Heishantou pluton is dominated by granodiorite and partially consist of tonalite. The weighted average age of granodiorite LA-ICP-MS zircon U-Pb is 407.7±1.6 Ma. Geochemical data show that the Heishantou pluton belong to peraluminous, calc-alkaline series, with typical adakite characteristics: high silicon (SiO_2 = 60.85% ~ 67.81%), high alumina (Al_2O_3 = 15.59% ~ 16.98%), low magnesium (MgO = 0.55% ~ 1.53%, $Mg^{\#}$ = 0.36~0.46), rich sodium and poor potassium (Na_2O = 2.65% ~ 3.54%, K_2O = 1.09% ~ 3.16%, Na_2O/K_2O = 0.96~2.44), high Sr (Sr = 253×10^{-6} ~ 487×10^{-6}) low Y and Yb (Y = 5.65×10^{-6} ~ 16.70×10^{-6}, Yb = 0.37×10^{-6} ~ 0.96×10^{-6}) compositions, with high Sr/Y ratio (25.75~73.58). Their light rare earth elements (LREE) are enriched, with obvious light and heavy rare earth fractionation. The samples do not have obvious Eu anomaly (0.66~1.31, averaging 0.92). Moreover, trace element composition is characterized by enrichment of LILEs such as Rb, K, Th and U, and depletion of high field strength elements HSFEs such as Nb, Ta, Ti and P. Geochemical characteristics show that these adakites were formed by partial melting of the subducting oceanic crust, and the residual minerals of the crust sources might have been garnet and rutile. Based on this study and regional geological data, the authors hold that the Liuyuan Ocean (Paleo-Asian Ocean) was still in the subduction and collision stage during the Early Devonian and had the characteristics of "scissoring" closure from west to east. The upper limit of the closing time of the Paleozoic ocean basin is Early Carboniferous in the Beishan area.

Key words: adakite; zircon U-Pb age; petrology and chemistry; petrogenesis; Beishan orogenic belt

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埃达克岩是具有一定地球化学特征的钙碱性中酸性岩石,具有高 SiO_2(≥56%)、高铝(Al_2O_3≥15%)、富钠($Na_2O>K_2O$)、高 Sr(>300×10^{-6})、低 Y(<20×10^{-6})和 Yb(<2×10^{-6})以及 Eu 异常不明显等地球化学特征(张旗, 2008; 张旗等, 2020),被认为是俯冲板片在部分熔融作用下的产物,可能代表了俯冲作用开始的记录(Defant and Drummond, 1990)。由于其特有的地球化学特征和特殊的成岩机理以及在恢复岩石形成的大地构造环境方面和认识陆壳增生方面的特殊意义(赵宏刚等, 2019),埃达克岩一经提出就受到了广泛关注(毛启贵等, 2010)。埃达克岩最早由美国学者 Defant 和 Drummond(1990)提出,他们将板片熔融形成的一套中酸性火山岩命名为 adakite,其概念于 2000 年被首次引入中国(王焰等, 2000)。近年来中国科学家围绕埃达克岩开展了大量研究,提出了不少学术观点(王焰等, 2000; 张旗等, 2001a, 2001b, 2003, 2020; 张旗, 2008, 2011, 2012; 毛启贵等, 2010; 许继峰等, 2014)。张旗(2011)根据埃达克岩中 Na 和 K 的含量的高低将其分为 O 型埃达克岩(板块熔融形成的埃达克岩)和 C 型埃达克岩(加厚下地壳部分熔融形成的埃达克岩);许继峰等(2014)将板片在俯冲环境下熔融形成且具上述地球化学特征的中酸性火成岩称为埃达克岩(adakite),将具有埃达克质地球化学特征但不是由板片熔融形成的中酸性火成岩称之为埃达克质岩(adakitic rock 或 adakite-like rock)。

北山造山带地处西伯利亚板块、塔里木板块和哈萨克斯坦板块的交汇部位,处于中亚巨型造山带南缘(图 1),是研究中亚造山带增生造山的关键地区之一,受到国内外学者的持续关注(刘雪亚等, 1995; 左国朝等, 1996, 2003; 汤中立等, 1997; 龚全胜等, 2003; 郑荣国等, 2012, 2016; 宋东方等, 2018; 田健等, 2020)。中亚造山带广泛发育埃达克岩,但多见报道于东天山地区,近年来随着北山地区花岗岩研究的深入,在柳园地区(毛启贵等, 2010)、金塔老虎山地区(王启航等, 2014)、公婆泉地区(余吉远等, 2017)、算井子一带(赵宏刚等, 2019)、红石山地区(黄增保等, 2005; 刘明强, 2007)、尖山和石板井地区(王鑫玉等, 2018)、东七一山地区(Zhang *et al.*, 2012)均有埃达克(质)岩的报道。针对北山南带,仅在柳园地区和金塔老虎山地区有零星埃达克岩被报道,其代表的柳园洋(古亚洲洋)在古生代俯冲碰撞的时限缺乏有力的依据。一些学者认为古亚洲洋在北山地区最终闭合时间为泥盆纪,在晚古生代转为陆内演化阶段(左国朝等, 2003; 李向民等, 2011; 牛亚卓等, 2014),也有学者提出泥盆

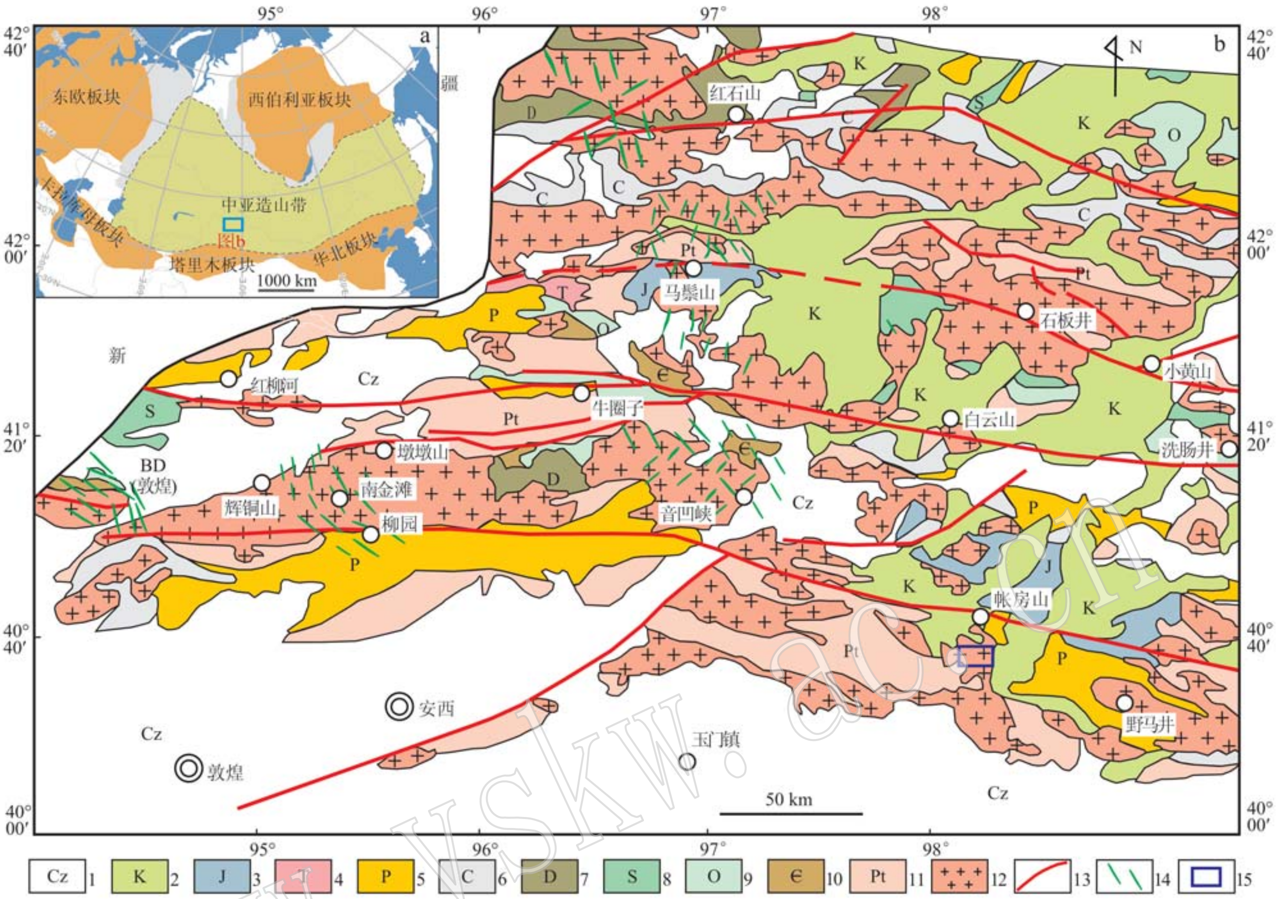

图 1　北山地区大地构造位置略图[a，据 Jahn(2002)]和地质简图[b，据王国强(2015)]

Fig. 1　Geotectonic map (a, after Jahn, 2002) and simplified regional geological map (b, after Wang Guoqiang, 2015) of the Beishan area

1—新生界；2—白垩系；3—侏罗系；4—三叠系；5—二叠系；6—石炭系；7—泥盆系；8—志留系；9—奥陶系；10—寒武系；11—元古界；12—花岗质岩类；13—断裂；14—基性岩墙；15—研究区位置

1—Cenozoic; 2—Cretaceous; 3—Jurassic; 4—Triassic; 5—Permian; 6—Carboniferous; 7—Devonian; 8—Silurian; 9—Ordovician; 10—Cambrian; 11—Proterozoic; 12—granites; 13—fault; 14—basic dike; 15—location of the study area

纪时古亚洲洋仍处于俯冲阶段，并列举了其在晚古生代活动陆缘的记录(Mao *et al.*, 2012; Guo *et al.*, 2012)。研究者对古亚洲洋闭合时间存在较大争议，聚焦点在于泥盆纪古亚洲洋仍在俯冲还是已经闭合。前人对研究区石炭纪、二叠纪、三叠纪岩浆活动进行了较为深入的研究，但对泥盆纪岩浆活动的研究略显薄弱，需进一步开展精准的年代学、岩石地球化学研究。

本文在大量野外和室内研究工作的基础上，通过 U-Pb 年代学和岩石地球化学研究，在北山造山带南缘黑山头一带发现了一套具典型埃达克岩地球化学特征的中酸性侵入岩，通过对黑山头花岗闪长岩成因和动力学背景研究，对古亚洲洋俯冲、闭合时限进行约束，对北山地区构造地质背景研究和大地构造单元划分提供了重要依据。

1　区域地质概况

北山造山带呈东西向展布，其西以星星峡断裂为界与东天山构造带相隔，北接蒙古南部增生系统，南邻敦煌地块，向东延入巴丹吉林沙漠(Xiao *et al.*, 2010, 2013；王疆涛等，2016；王鑫玉等，2018)。该造山带是由大量小的构造单元及构造块体，经过漫长而复杂的构造演化过程而形成的多旋回复合造山带(左国朝等，1990，2011；刘雪亚等，1995；何世平等，2002；龚全胜等，2003；杨合群等，2012)。在复杂的地质过程中，北山境内自北向南形成了红

石山-百合山、芨芨台子-小黄山、牛圈子-洗肠井、辉铜山-帐房山等 4 条蛇绿岩带,专家学者据此将北山地区划分至不同的构造单元(刘雪亚等, 1995; 左国朝等, 1996, 2003; 何世平等, 2002; 龚全胜等, 2003; 杨合群等, 2008, 2012)。

研究区位于辉铜山-帐房山蛇绿岩带南侧(图 2a)。最新资料表明,帐房山蛇绿岩带为一晚古生代蛇绿岩带(余吉远等,2012b)。区内侵入岩以花岗岩类为主,主要有三叠纪二长花岗岩、花岗闪长岩、似斑状花岗闪长岩,二叠纪石英二长闪长岩及泥盆纪花岗闪长岩、英云闪长岩。区内出露地层主要为长城系古硐井群、侏罗系水西沟群、白垩系新民堡群以及第四系等。古硐井群是一套浅变质碎屑岩及碳酸盐岩建造,为区内重要的含金、铅锌层位,水西沟群是一套含煤碎屑岩建造,新民堡群为一套杂色碎屑岩建造。区内构造发育,以 NW 向、NWW 向断裂构造为主(杨镇熙等, 2021)。

2 岩石学特征

黑山头中酸性侵入岩出露于甘肃省玉门市、北山缝合带黑山头一带,主体为花岗闪长岩(图 3a),局部见英云闪长岩,呈北西向展布,出露面积约 30 km^2,侵入长城系古硐井群,在黑山头一带被二叠纪石英二长闪长岩侵入(图 2b)。

本次工作选择黑山头花岗闪长岩体 6 件新鲜岩石样品进行了岩石地球化学研究,对其中 1 件样品进行了锆石 U-Pb 年龄测定。

花岗闪长岩,新鲜面浅灰-灰色,中细粒半自形粒状结构,块状构造。岩石主要由斜长石(35%~40%)、钾长石(15%±)、石英(20%±)、黑云母(15%~20%)、角闪石(10%±)和锆石、磷灰石、榍石等副矿物及高岭土、绢云母、绿泥石等少量次生矿物组成。斜长石呈半自形板状,粒度一般 0.2~2 mm,部分 2~4.5 mm,杂乱分布,具高岭土化、绢云母化等,环带构造较为发育,聚片双晶常见,与钾长石接触部位可见有交代蠕虫结构;钾长石呈半自形板状-它形粒状,粒度一般 0.2~2 mm,部分 2~3 mm,具轻高岭土化,少见格子双晶,局部交代斜长石;石英呈它形粒状,粒度一般 0.2~2 mm,部分<0.2 mm,填隙状分布,重结晶作用明显,粒内具波状消光现象;黑云母呈片状,片径一般 0.2~2.5 mm,少数<0.2 mm,杂乱

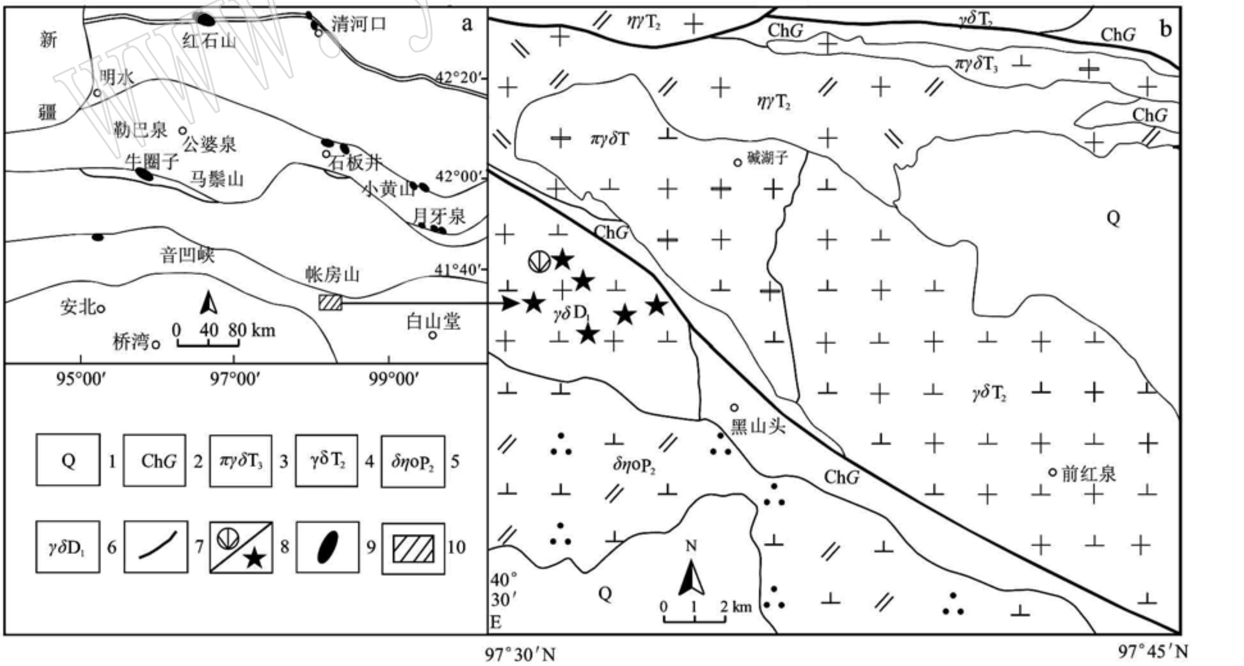

图 2 黑山头一带地质略图[a 据杨合群等(2010), b 据杨镇熙等(2021)]

Fig. 2 Geological map of Heishantou area (a after Yang Hequn *et al.*, 2010; b after Yang Zhenxi *et al.*, 2021)

1—第四系; 2—长城系古硐井群; 3—晚三叠世斑状花岗闪长岩; 4—中三叠世花岗闪长岩; 5—晚二叠世石英二长闪长岩; 6—早泥盆世花岗闪长岩; 7—断层; 8—锆石 U-Pb 年龄样/岩石全分析采样点; 9—蛇绿岩带; 10—研究区

1—Quaternary; 2—Gudongjing Group of Changcheng System; 3—Late Triassic porphyritic granodiorite; 4—Middle Triassic granodiorite; 5—Late Permian quartz monzodiorite; 6—Early Devonian granodiorite; 7—fault; 8—sampling site; 9—ophiolite belt; 10—study area

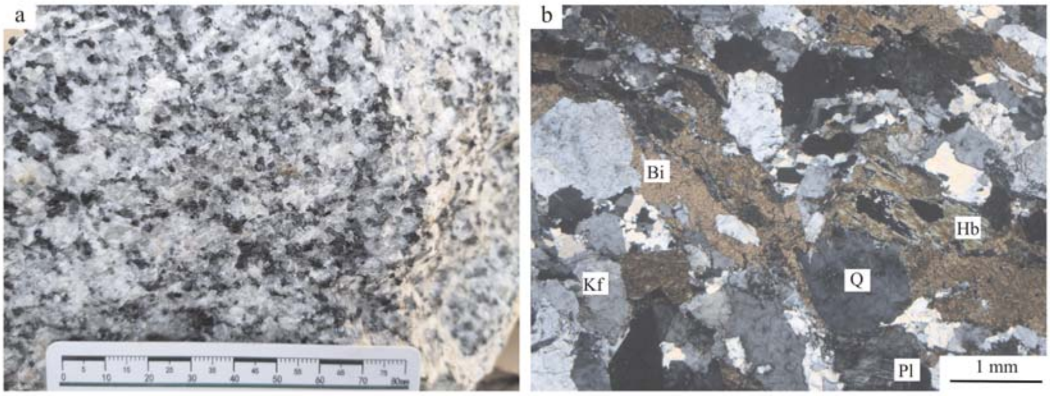

图 3　黑山头岩体花岗闪长岩野外(a)和显微特征(b，正交偏光)

Fig. 3　Field image (a) and microscopic characteristics (b, crossed nicols) of granodiorite in the Heishantou pluton

Kf—钾长石；Pl—斜长石；Q—石英；Hb—角闪石；Bi—黑云母

Kf—K-feldspar；Pl—plagioclase；Q—quartz；Hb—hornblende；Bi—biotite

分布,少具绿泥石化,多色性较明显;角闪石呈半自形-它形柱状、柱粒状,粒度一般 0.2~2.5 mm,杂乱分布,多色性较明显(图 3b)。

3　分析方法

主量、微量及稀土元素的分析测试由河北省区域地质矿产调查研究所实验室承担。首先将样品粗碎至 2~4 cm,采用 3%~5%的稀盐酸经超声波清除表面杂质,再细碎至 200 目备用。主量元素分析仪器为 Axiosmax X 射线荧光光谱仪(XRF),分析精度优于 2%,其中 FeO 测试采用氢氟酸、硫酸溶样和重铬酸钾滴定容量法;稀土、微量元素检测使用 XSeries2 型电感耦合等离子质谱仪(ICP-MS),精度和准确度优于 5%。

锆石制靶和阴极发光(CL)图像分析由廊坊诚信地质服务有限公司完成,首先将原样破碎至 60~80 μm 后分离出重砂,经磁选和电磁选后,在双目镜下选取晶形和透明度较好的代表性锆石,将锆石颗粒粘在双面胶上,用环氧树脂固定,并对其进行抛光,直到样品露出光洁的平面;然后拍摄锆石颗粒的透射光、反射光和阴极发光图像。

锆石年龄分析在中国地质调查局西安地质调查中心岩浆作用成矿与找矿重点实验室完成,分析仪器为 Agilent7700x 型激光剥蚀电感耦合等离子体质谱仪(LA-ICP-MS),采用国际标准锆石 91500 作为外标进行标准。应用 Glitter(4.0 版)程序计算锆石的表面年龄及标准偏差,并对测试过程中产生的元素分馏和质量歧视进行校正;应用 Isoplot(3.0 版)程序对锆石样品的 $^{206}Pb/^{238}U$ 年龄和 $^{207}Pb/^{235}U$ 年龄在谐和图上进行投图,并计算年龄谐和测点的加权平均值(李艳广等, 2015)。

4　锆石年龄测定结果

对花岗闪长岩进行了锆石 U-Pb 测年,结果见表 1。锆石多呈自形程度较好的柱状,部分为粒状,粒径 130~250 μm,长宽比变化于 1∶1~1∶3 之间,具有清晰、致密的岩浆结晶振荡环带,属典型的岩浆结晶锆石(吴元保等, 2004)。20 个锆石颗粒点 CL 图像及 U-Pb 年龄测定结果见图 4。LA-ICP-MS 锆石 U-Pb 年龄测定结果显示,20 个样品点的 U-Pb 年龄在误差范围内一致,$^{206}Pb/^{238}U$ 加权平均(26)年龄为 407.7±1.6 Ma(MSWD = 0.099)(图 5),表明黑山头花岗闪长岩体形成于早泥盆世。

5　岩石地球化学特征

5.1　主量元素

黑山头花岗闪长岩体具高硅(SiO_2 = 60.85%~67.81%)、高铝(Al_2O_3 = 15.59%~16.98%)、低镁(MgO = 0.55%~1.53%, $Mg^{\#}$ = 0.36~0.46)、富钠贫钾(Na_2O = 2.65%~3.54%, K_2O = 1.09%~3.16%, Na_2O/K_2O = 0.96~2.44)等特征, TiO_2 含量为 0.54%~0.91%, CaO 含量 3.71%~5.95%(表 2)。在TAS图解中大多数样品落入花岗闪长岩区,且均

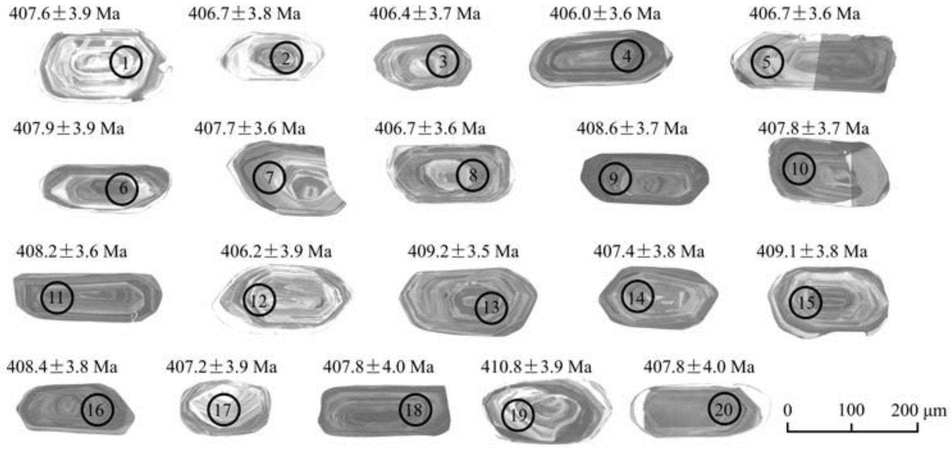

图 4 黑山头岩体锆石阴极发光(CL)图像及测试点

Fig. 4 Zircon cathodoluminescence (CL) images and test points of the Heishantou pluton

表 1 黑山头岩体锆石 U-Pb 同位素测年分析结果

Table 1 Zircon U-Pb isotopic analytical result of the Heishantou pluton

测点号	$w_B/10^{-6}$		$^{232}Th/^{238}U$	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	年龄/Ma					
	Th	U								$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ
1	2 787.31	27 698.24	0.10	0.055 59	0.001 29	0.500 43	0.011 06	0.065 27	0.000 64	412.0	7.5	407.6	3.9	435.8	50.4
2	3 053.88	35 213.76	0.09	0.063 79	0.001 29	0.572 90	0.010 96	0.065 12	0.000 62	459.9	7.1	406.7	3.8	734.8	42.3
3	5 007.75	38 255.65	0.13	0.059 35	0.001 07	0.532 55	0.009 03	0.065 07	0.000 60	433.5	6.0	406.4	3.7	579.9	38.8
4	9 322.21	74 202.13	0.13	0.057 21	0.000 99	0.512 92	0.008 30	0.065 01	0.000 60	420.4	5.6	406.0	3.6	499.0	37.6
5	4 578.57	62 195.70	0.07	0.062 78	0.001 06	0.563 82	0.008 88	0.065 12	0.000 60	454.0	5.8	406.7	3.6	700.9	35.6
6	3 842.95	30 680.86	0.13	0.057 22	0.001 35	0.515 53	0.011 63	0.065 33	0.000 65	422.2	7.8	407.9	3.9	499.5	51.8
7	3 492.96	42 547.14	0.08	0.055 49	0.000 99	0.499 68	0.008 40	0.065 29	0.000 60	411.5	5.7	407.7	3.6	431.8	39.0
8	5 944.83	80 343.38	0.07	0.055 85	0.000 87	0.501 58	0.007 24	0.065 12	0.000 59	412.8	4.9	406.7	3.6	446.1	33.9
9	3 092.64	54 243.05	0.06	0.068 35	0.001 19	0.616 83	0.010 04	0.065 43	0.000 61	487.9	6.3	408.6	3.7	879.2	35.7
10	8 623.14	64 140.89	0.13	0.056 33	0.001 04	0.507 41	0.008 83	0.065 31	0.000 61	416.7	6.0	407.8	3.7	464.6	40.8
11	4 557.61	50 480.28	0.09	0.055 23	0.000 92	0.497 94	0.007 71	0.065 36	0.000 59	410.3	5.2	408.2	3.6	421.5	36.5
12	3 848.11	34 979.76	0.11	0.054 88	0.001 27	0.492 28	0.010 86	0.065 03	0.000 64	406.5	7.4	406.2	3.9	407.3	50.6
13	10 106.86	101 027.30	0.10	0.055 14	0.000 81	0.498 42	0.006 70	0.065 54	0.000 58	410.6	4.5	409.2	3.5	417.7	32.2
14	3 068.24	28 129.87	0.11	0.054 74	0.001 14	0.492 60	0.009 75	0.065 24	0.000 62	406.7	6.6	407.4	3.8	401.7	45.7
15	2 907.78	39 825.54	0.07	0.053 86	0.001 19	0.486 75	0.010 22	0.065 52	0.000 63	402.7	7.0	409.1	3.8	365.1	49.0
16	3 634.12	30 056.59	0.12	0.055 58	0.001 23	0.501 39	0.010 54	0.065 40	0.000 63	412.6	7.1	408.4	3.8	435.3	48.1
17	3 638.53	30 152.36	0.12	0.055 75	0.001 31	0.501 42	0.011 21	0.065 21	0.000 64	412.7	7.6	407.2	3.9	442.0	51.0
18	2 554.71	23 956.16	0.11	0.054 97	0.001 39	0.496 24	0.012 00	0.065 45	0.000 66	409.2	8.1	408.7	4.0	410.8	54.8
19	3 886.66	31 920.05	0.12	0.055 08	0.001 27	0.499 91	0.011 02	0.065 80	0.000 64	411.6	7.5	410.8	3.9	415.2	50.1
20	4 746.12	35 502.41	0.13	0.055 42	0.001 45	0.499 19	0.012 52	0.065 30	0.000 66	411.2	8.5	407.8	4.0	428.9	56.9

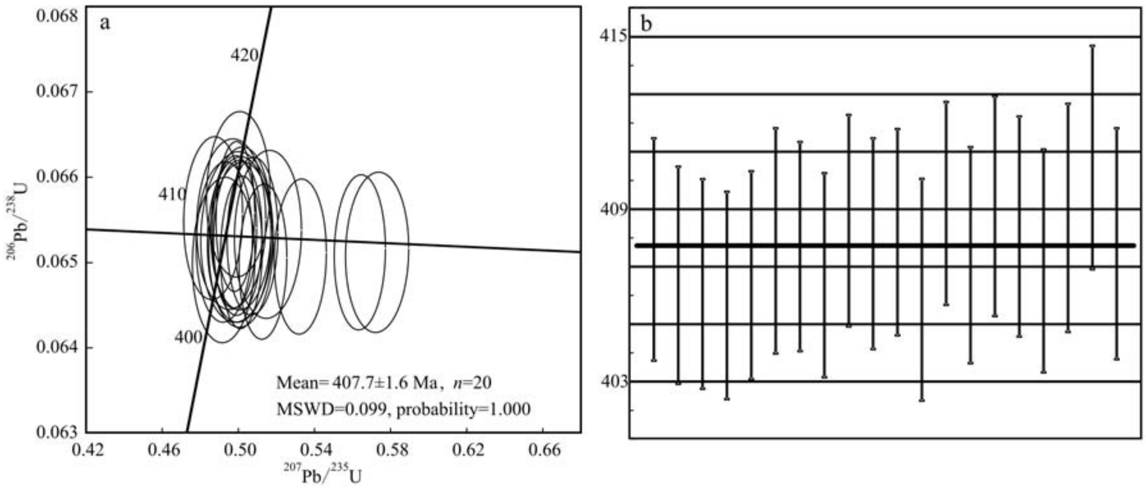

图 5 黑山头岩体锆石 U-Pb 谐和图(a)和加权平均年龄图(b)

Fig. 5 Zircon U-Pb concordia (a) and weighted average age (b) diagrams of the Heishantou pluton

表 2　黑山头岩体主量元素(w_B/%)和微量元素($w_B/10^{-6}$)分析结果

Table 2　Analytical results of major elements (w_B/%) and trace elements ($w_B/10^{-6}$) of the Heishantou pluton

样号	9YQ-2	9YQ-21	9YQ-41	9YQ-42	9YQ-44	9YQ-45
SiO_2	60.85	67.81	67.70	67.67	64.23	63.29
TiO_2	0.91	0.58	0.61	0.54	0.74	0.88
Al_2O_3	16.98	15.59	15.73	16.23	16.80	16.59
Fe_2O_3	1.09	0.57	0.85	0.91	0.89	1.41
FeO	4.73	2.89	2.74	2.38	3.28	3.55
MnO	0.06	0.06	0.04	0.05	0.05	0.08
MgO	2.75	1.19	1.08	1.08	1.83	2.19
CaO	5.95	4.26	3.71	3.72	5.03	5.95
Na_2O	2.79	3.10	3.04	3.54	3.05	2.65
K_2O	1.75	1.85	3.16	2.71	1.89	1.09
P_2O_5	0.24	0.17	0.16	0.15	0.16	0.18
H_2O^+	1.19	1.36	0.37	0.32	1.07	1.57
H_2O^-	0.21	0.21	0.12	0.11	0.11	0.18
烧失量	1.74	1.77	0.74	0.60	1.53	1.62
总量	99.83	99.84	99.87	99.85	99.83	99.87
Na_2O+K_2O	4.50	3.04	4.24	3.80	3.72	3.28
Na_2O/K_2O	0.64	1.55	2.92	2.50	1.03	0.50
A/NK	2.62	2.20	1.87	1.85	2.38	3.00
A/CNK	0.98	1.05	1.04	1.05	1.04	1.01
AR	1.49	1.66	1.94	1.91	1.59	1.40
$Mg^{\#}$	0.46	0.39	0.36	0.38	0.45	0.45
Li	18.4	21.9	11.9	23.1	10.8	10.9
Be	2.27	3.73	3.00	4.08	2.62	2.40
Sc	28.5	5.13	6.10	4.81	10.10	15.20
V	72.1	29.2	30.6	19.6	60.8	71.9
Cr	9.93	11.40	9.49	14.00	17.80	19.40
Co	10.80	6.17	4.36	4.28	8.06	9.34
Ni	4.46	2.74	4.02	3.70	5.24	3.88
Cu	5.32	4.80	7.51	6.52	12.60	13.80
Zn	117.0	108.0	86.4	130.0	89.4	91.4
Ga	24.7	27.1	23.5	28.5	23.5	22.9
Ge	1.23	1.51	1.27	1.29	1.20	1.25
Rb	83.4	81.0	105.0	120.0	76.2	44.1
Sr	418	430	253	388	487	415
Zr	242	262	220	304	363	213
Nb	16.1	25.8	21.8	31.1	15.2	22.0
Ta	0.66	0.69	0.49	1.22	0.48	0.93
Mo	0.14	0.10	0.41	0.25	0.16	0.21
Cs	2.42	2.17	3.96	4.22	1.87	2.28
Ba	597	711	524	531	647	395
Hf	6.54	7.17	5.79	7.77	8.88	5.10
W	0.06	0.22	0.43	0.12	0.27	0.20
Pb	6.23	29.60	18.00	23.20	10.30	10.70
Th	18.50	19.70	10.80	20.30	15.20	6.42
U	0.78	2.29	0.91	1.82	0.85	0.66
Te	0.010	0.008	0.014	0.016	0.017	0.017
La	59.99	53.27	34.50	62.68	50.94	28.15
Ce	118.00	106.00	63.39	107.31	93.35	50.91
Pr	13.40	12.10	7.49	12.26	10.85	6.22

续表 2

Continued Table 2

样号	9YQ-2	9YQ-21	9YQ-41	9YQ-42	9YQ-44	9YQ-45
Nd	48.80	44.30	27.26	42.17	38.51	22.89
Sm	8.62	8.10	4.65	6.66	6.14	3.92
Eu	1.64	2.10	1.40	1.55	1.47	1.52
Gd	6.75	6.38	3.67	5.19	4.72	3.19
Tb	0.84	0.82	0.42	0.57	0.55	0.36
Dy	3.20	3.40	1.56	2.18	2.24	1.52
Ho	0.45	0.51	0.22	0.31	0.34	0.23
Er	1.05	1.27	0.53	0.79	0.84	0.51
Tm	0.12	0.18	0.06	0.09	0.11	0.06
Yb	0.64	0.96	0.37	0.55	0.64	0.37
Lu	0.09	0.13	0.06	0.08	0.11	0.06
Y	13.25	16.69	5.72	8.25	8.55	5.65
ΣREE	263.51	239.21	145.60	242.40	210.79	119.92
LREE	250.37	225.56	138.69	232.63	201.26	113.61
HREE	13.14	13.64	6.91	9.77	9.54	6.30
LREE/HREE	19.05	16.53	20.08	23.80	21.10	18.02
$(La/Yb)_N$	63.47	37.36	62.47	76.60	54.08	51.28
δEu	0.66	0.89	1.04	0.81	0.83	1.31

注：$Mg^{\#} = 100\ Mg^{2+}/(Mg^{2+}+Fe^{2+})$；$A/CNK = Al_2O_3/(CaO+Na_2O+K_2O)$；$A/NK = Al_2O_3/(Na_2O+K_2O)$；$\delta Eu = 2\ Eu_N/(Sm_N+Gd_N)$，N 表示球粒陨石化标准化。

归属于亚碱性岩石(图 6a)；在 SiO_2－AR 图解上，全部落入钙碱性区域(图 6b)；在 K_2O－SiO_2 图解上(图 6c)，除 1 个样品外，其余均落入钙碱性系列；铝饱和指数 A/CNK 值为 0.98～1.05，A/NK 值为 1.85～3.00，显示其属于过铝质岩石系列(图 6d)。

5.2　稀土和微量元素

从稀土元素分析结果表(表 2)中可以看出，黑山头花岗闪长岩稀土元素总量变化范围较大，介于 119.92×10^{-6}～263.51×10^{-6} 之间，轻、重稀土元素明显分馏，LREE/HREE 值平均为 19.77，$(La/Yb)_N$ 值变化于 37.36～76.60 之间，平均为 57.54，具有明显右倾的稀土元素配分型式(图 7a)。样品均显示不明显的 Eu 异常(δEu＝0.66～1.31，平均 0.92)。

从微量元素蛛网图(图 7b)及微量分析结果表(表 2)中可以看出，黑山头花岗闪长岩体明显富集大离子亲石元素 Rb、K、Th、U，亏损高场强元素 Nb、Ta、Ti、P，显示出岛弧岩浆岩的成分特征。

6　讨论

6.1　黑山头花岗闪长岩体成因类型

花岗岩是陆壳最主要的组成部分，前人将成因类型划分为 I 型、S 型、A 型及 M 型(Chappell, 1999;

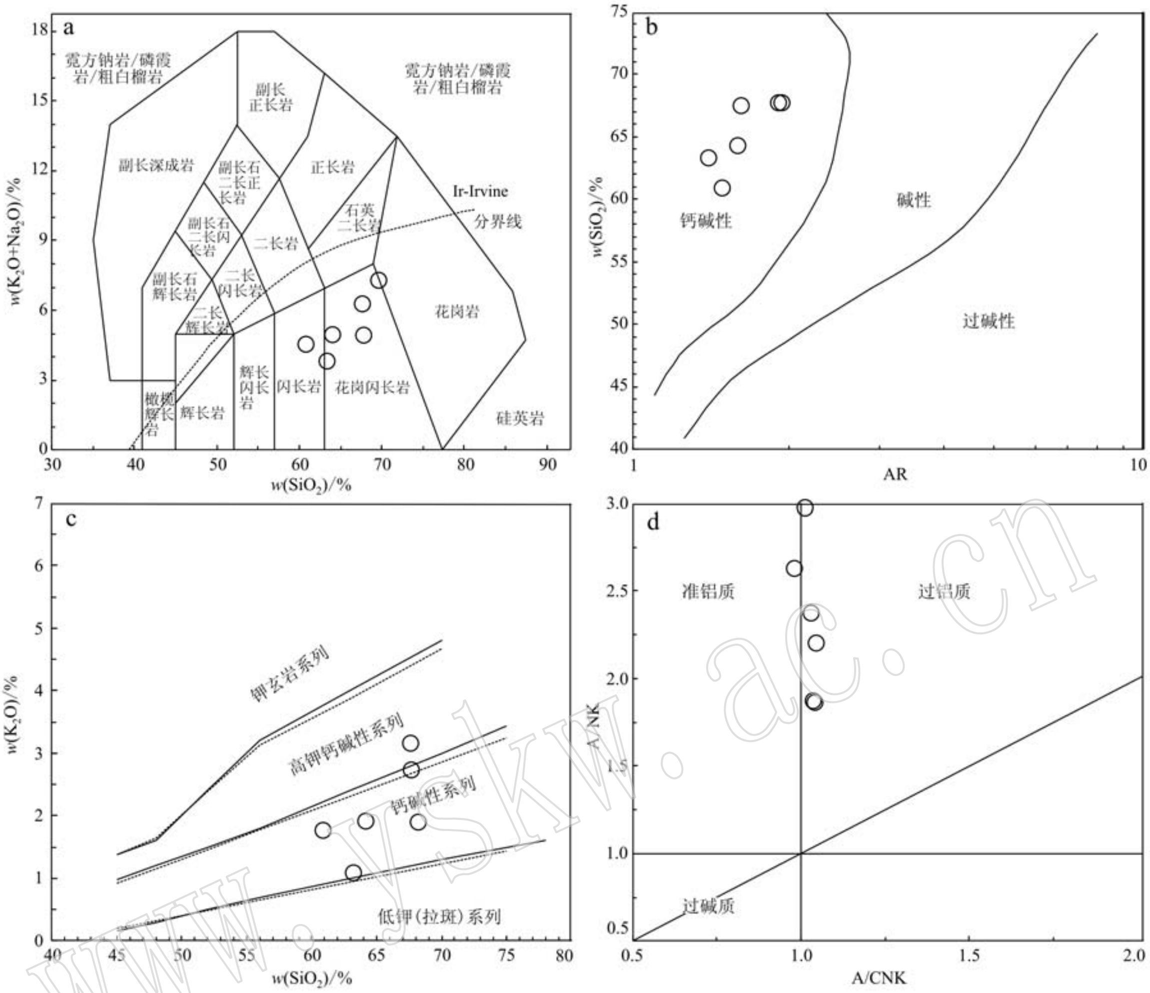

图 6　黑山头岩体主量元素地球化学图解

Fig. 6　Geochemical diagrams of principal elements of the Heishantou pluton

a—TAS 图解(底图据 Middlemost, 1994); b—SiO_2-AR 图解(底图据 Wright, 1969); c—K_2O-SiO_2 图解(底图据 Middlemost, 1985); d—A/NK-A/CNK 图解(底图据 Maniar and Piccoli, 1989)

a—TAS diagram (Middlemost, 1984); b—SiO_2-AR diagram (Wright, 1969); c—K_2O-SiO_2 diagram (Middlemost, 1985); d—A/NK-A/CNK diagram (Maniar and Piccoli, 1989)

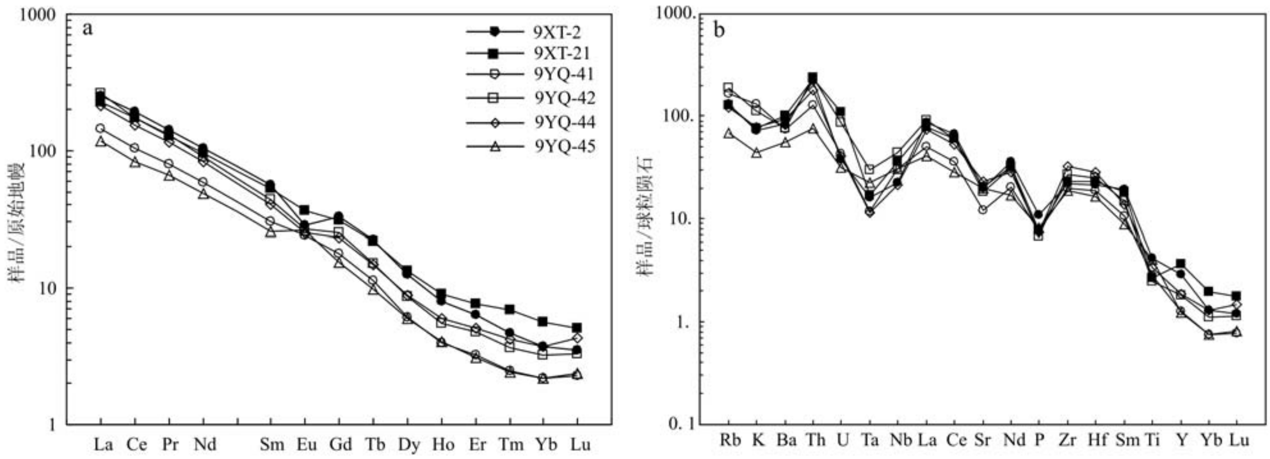

图 7　稀土元素球粒陨石标准化图解(a)和微量元素原始地幔标准化图解(b)(标准化值据 Sun and McDonough, 1989)

Fig. 7　Chondrite-normalized REE patterns (a) and trace element spider diagram (b) (normalization value after Sun and McDonoug, 1989)

Bonin, 2007)。自然界中由幔源岩浆衍生的 M 型花岗岩极少,黑山头岩体空间上缺乏共生的蛇绿岩及基性岩,可排除 M 型花岗岩的可能。A 型花岗岩与源区无关,是形成于拉张环境中的高温无水花岗岩(张旗等, 2012),多数学者认为研究区泥盆纪并非处于拉张的大地构造环境,故排除 A 型花岗岩的可能。一般情况下,I 型花岗岩中 P_2O_5 随 SiO_2 含量增加而降低,而 S 型花岗岩中 P_2O_5 随 SiO_2 含量增加而升高或者基本不变(Chappell, 1999),黑山头花岗闪长岩体岩石的 P_2O_5 与 SiO_2 呈明显负相关关系,与Ⅰ型花岗岩特征一致。吴福元等(2007)曾提出岩石中堇青石、角闪石及碱性铁镁矿物可作为判断Ⅰ型、S 型和 A 型花岗岩的重要且有效的矿物学标志,通过 CIPW 标准矿物计算黑山头花岗闪长岩的刚玉分子 AC<1%(除 9YQ-45 为 1.03),同时不含有石榴子石、堇青石、原生白云母等特征富铝矿物,这与 S 型花岗岩的特征(Sylvester, 1998; 李献华等, 2007)明显不符,故其不是 S 型花岗岩。据野外及镜下观察,黑山头岩体花岗闪长岩暗色矿物主要是角闪石和黑云母,而角闪石被认为是Ⅰ型花岗岩的标志矿物,具有Ⅰ型花岗岩的成分特征。岩石的 10^4 Ga/Al 值较低,介于 2.00~2.49 之间,平均值为 2.27,低于 A 型花岗岩下限值(2.6, Whalen *et al.*, 1987);岩石的 Zr+Nb+Ce+Y 含量在 108.16×10^{-6} ~ 249.33×10^{-6} 之间,平均值为 166.52×10^{-6},远低于 A 型花岗岩的下限值(350×10^{-6}, Whalen *et al.*, 1987)。在相关的岩石成因类型判别图解(图 8, Whalen *et al.*, 1987)中,样品全部投入未分异的Ⅰ型花岗岩区域。综合分析表明黑山头花岗闪长岩为未分异的Ⅰ型花岗岩。

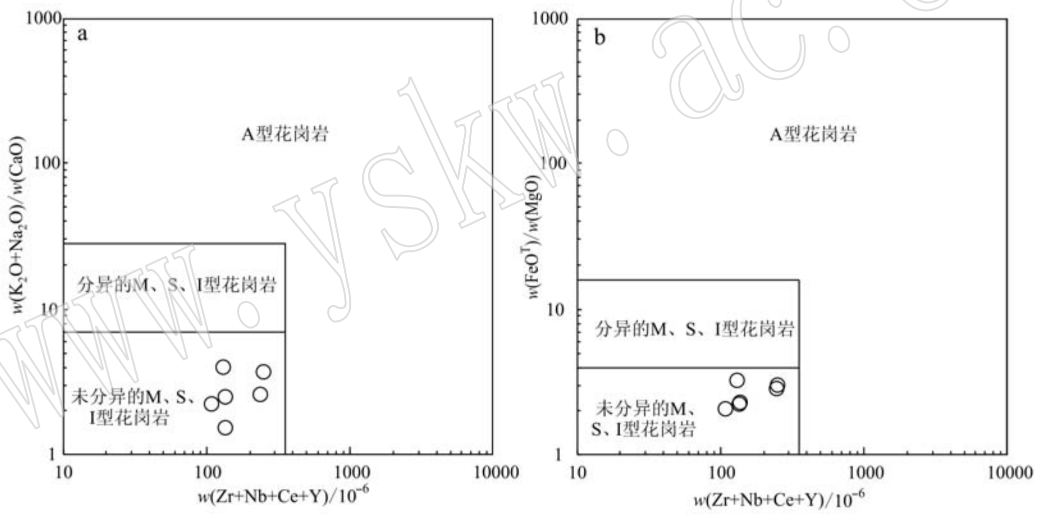

图 8　黑山头岩体成因类型判别图解(据 Whalen *et al.*, 1987)

Fig. 8　Diagrammatic diagram of genetic types of the Heishantou pluton (after Whalen*et al.*, 1987)

6.2　岩石成因及源区性质

黑山头岩体 SiO_2 含量为 60.85% ~ 67.81% (≥ 56%), Al_2O_3 含量为 15.59% ~ 16.98% (≥ 15%), MgO 含量为 1.08% ~ 2.75% (< 3%), Na_2O 含量为 2.65% ~ 3.54%, K_2O 含量为 1.09% ~ 3.16%, Na_2O/K_2O 值为 0.96 ~ 2.44(除 1 个样品外, $Na_2O>K_2O>2$), Y 含量为 5.65×10^{-6} ~ 16.70×10^{-6} ($<20\times10^{-6}$), Yb 含量为 0.37×10^{-6} ~ 0.96×10^{-6} ($<2\times10^{-6}$), Sr 含量为 253×10^{-6} ~ 487×10^{-6} (除 9YQ-41 外,其余均大于 300×10^{-6}), Sr/Y 值为 25.75 ~ 73.58 (>20),显示其具有高硅、高铝、富钠、贫钾、低 $Mg^{\#}$、低 Y、低 Yb、高 Sr/Y 值的特征。岩体轻稀土元素高度富集,重稀土元素亏损,不具明显的 Eu 异常(δEu = 0.66 ~ 1.31, 平均 0.92),微量元素富集大离子亲石元素 Th、U、Rb、K,亏损高场强元素 Nb、Ta、Ti、P,这些都揭示黑山头岩体属典型的埃达克岩(Defant and Drummond, 1990; Defant *et al.*, 2002; 毛启贵等, 2010; Zheng *et al.*, 2018),在 Sr/Y − Y 和 $(La/Yb)_N - Yb_N$ 判别图解(图 9)上,样品全部落入埃达克岩区域。

前人根据不同的成因机制对埃达克(质)岩进行了分类,总结起来主要有以下 5 种成因模式: ① 俯冲洋壳的部分熔融形成埃达克岩(Defant and Drummond, 1990; Kay *et al.*, 1993; Defant *et al.*, 2002; Martin *et al.*, 2005; Wang *et al.*, 2007, 2008a; Tang *et al.*, 2010; 毛启贵等, 2010; 许继峰等, 2014; Zheng

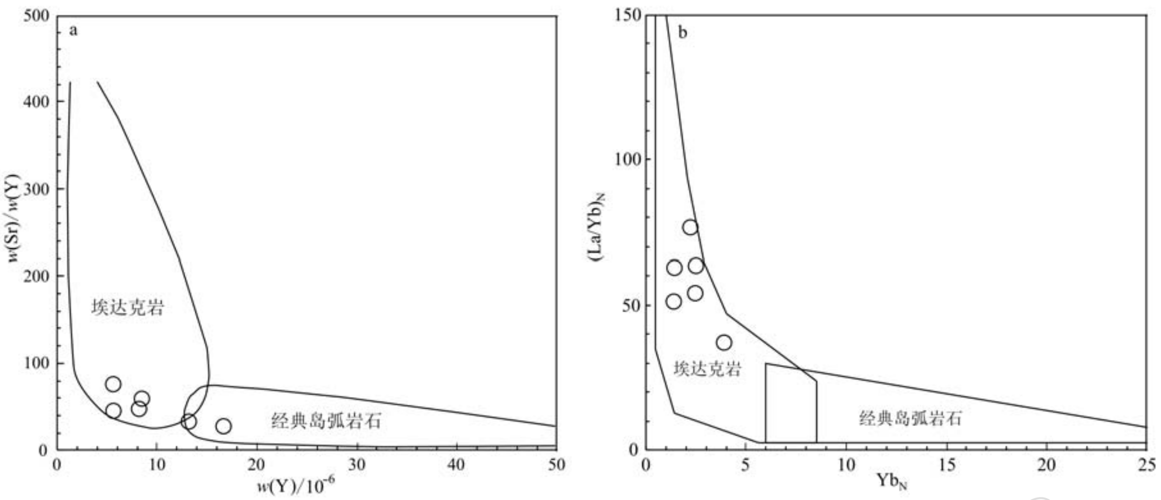

图 9 黑山头岩体 Sr/Y－Y 和$(La/Yb)_N-Yb_N$判别图(底图据 Defant and Drummond, 1990)

Fig. 9 Sr/Y－Y and$(La/Yb)_N-Yb_N$ discriminant diagrams of granodiorites (after Defant and Drummond, 1990)

et al., 2018; 王鑫玉等, 2018; 樊新祥等, 2020); ② 受玄武质岩浆底侵作用或陆内俯冲的上地壳脱水作用产生的流体诱发的增厚下地壳熔融形成埃达克岩(Wang *et al*., 2008b; Lai and Qin, 2013; 唐卓等, 2018; 樊新祥等, 2020); ③ 拆沉下地壳部分熔融产生的流体和地幔楔物质发生作用形成高 $Mg^{\#}$埃达克岩 (Rudnick *et al*., 1995; Gao *et al*., 2004; Wang *et al*., 2006; 朱涛等, 2014; 王楠等, 2016; 唐卓等, 2018; 樊新祥等, 2020); ④ 含水玄武质岩浆高压分异形成埃达克岩(Castillo *et al*., 1999; Macpherson *et al*., 2006; Castillo, 2012; 许继峰等, 2014; 赵宏刚等, 2019; 樊新祥等, 2020); ⑤ 混合成因的埃达克岩(许继峰等, 2014)。

黑山头岩体地球化学特征表明其为高 Al 富 Na 贫 K 的钙碱性岩浆,与俯冲洋壳熔融形成的埃达克岩特征一致(Defant *et al*., 2002; 樊新祥等, 2020),与增厚下地壳部分熔融形成的低 Al、富碱、富 K 特征的埃达克岩存在明显差异,在 $MgO-SiO_2$ 图解中样品全部投入俯冲洋壳形成的埃达克岩区域(图10)。岩体 $Mg^{\#}$值为 0.36~0.46(平均 0.41),属典型的 MORB 部分熔融的产物($Mg^{\#}<0.45$; Rapp, 1997)。拆沉下地壳部分熔融过程中不可避免地与地幔橄榄岩发生反应导致 $Mg^{\#}$值明显增高,同时该类型埃达克岩多见有壳源继承锆石,研究区样品中未见有继承性锆石且 $Mg^{\#}$值较低,故其应不是拆沉下地壳部分熔融形成的埃达克岩。许继峰等(2014)认为,含水玄武质岩浆在高压条件下发生结晶分异形成的埃达克岩通常与一系列有成因联系的中基性岩石密切共生,研究区未发现与黑山头岩体共生的中基性岩石,黑山头岩体也不属于玄武质岩浆结晶分异形成的埃达克岩。混合成因的埃达克岩应该保留有基性岩浆和酸性岩浆混合作用的证据。因此,黑山头岩体是典型的由俯冲洋壳部分熔融形成的埃达克岩。

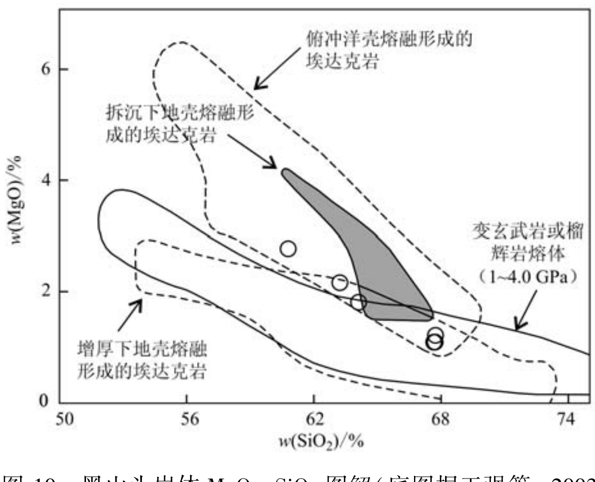

图 10 黑山头岩体 $MgO-SiO_2$ 图解(底图据王强等, 2003)

Fig. 10 $MgO-SiO_2$ diagram of the Heishantou pluton (after Wang Qiang *et al*., 2003)

黑山头岩体亏损高场强元素 Nb、Ta、Ti、P 和 HREE,具不明显的 Eu 异常,说明源区角闪石或石榴子石是主要的残留相。前人研究成果表明岩浆源区中角闪石或石榴子石的残留体对岩浆熔体的 HREE 配分模式和 Y/Yb 值有明显影响(张新远等, 2020),

即当岩浆源区中以角闪石为残留相时,熔体的 Y/Yb 值一般接近 10,且具轻微上凹的 HREE 配分模式;当源区中以石榴子石为残留相时,熔体的 Y/Yb 值明显大于 10 且具有倾斜的 HREE 配分模式(Rollinson, 1993; 高永丰等, 2003; 赵宏刚等, 2019; 樊新祥等, 2020)。黑山头岩体 Y/Yb 值为 13.44~20.74(平均 16.16),远大于 10 且稀土元素配分曲线(图 7a)显示其为向右倾斜的 HREE 配分模式,表明岩浆岩区残留相以石榴子石为主。

目前关于 Nb、Ta、Ti 的负异常主要有以下 3 种解读: ① 俯冲背景下,地幔楔物质与大陆地壳发生混染(赵振华, 2005; 赵志雄等, 2018); ② 源区为早先存在的火山弧或地壳(赵泽辉等, 2007); ③ 源区有金红石残留,岩浆来源较深(Xiong *et al.*, 2005)。黑山头岩体位于帐房山蛇绿岩带南侧,塔里木板块和哈萨克斯坦板块的俯冲带上(何世平等, 2005; 杨合群等, 2012),处于火山弧的构造环境(图 11)。因此,黑山头花岗闪长岩 Nb、Ta、Ti 的负异常表明其形成于与岛弧有关的俯冲环境,源区可能有金红石残留。

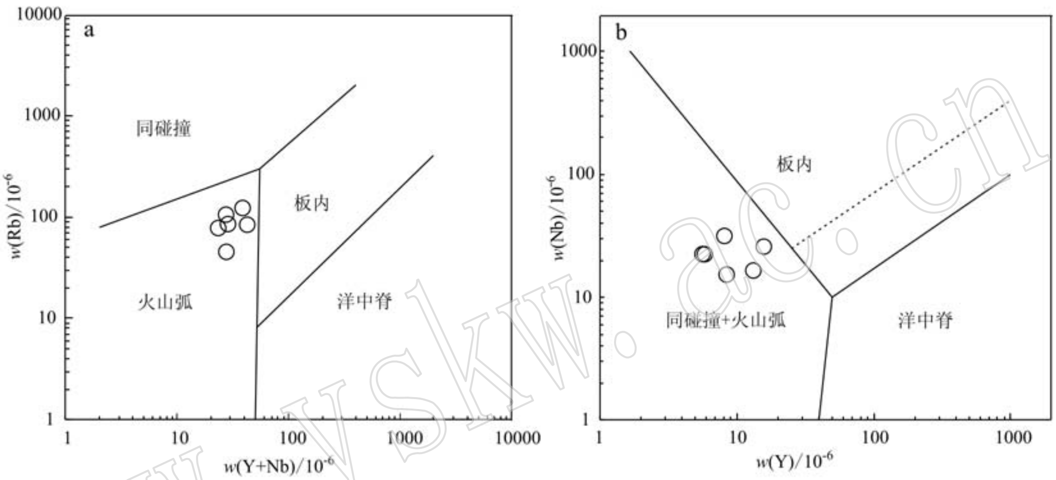

图 11　黑山头岩体 Rb-(Y+Nb)图解(a)和 Nb-Y 图解(b)(Pearce *et al.*, 1984)

Fig. 11　Rb-(Y+Nb) diagram and Nb-Y diagram of the Heishantou pluton (after Pearce *et al.*, 1984)

6.3　地球动力学意义

北山造山带位于中亚巨型造山带南缘,是剖析中亚造山带南缘增生大地构造过程的重要区域之一(宋东方等, 2018)。北山造山带具复杂造山和增生演化的特征,近年来已成为国内外研究的热点和前沿地区。研究者对北山造山带构造演化提出了不同的观点,对于古亚洲洋闭合的时限存在泥盆纪、石炭纪和二叠纪 3 种不同的认识(刘雪亚等, 1995; 左国朝等, 1996, 2003; 何世平等, 2002; 聂风军等, 2002; 龚全胜等, 2002, 2003; 毛启贵等, 2008; 杨合群等, 2012)。余吉远等(2012a)依据中泥盆统三个井组和寒武系、奥陶系为不整合接触关系,提出早泥盆世是北山地区古生代洋盆闭合时限的上限;田健等(2020)通过对北山中部地区上泥盆统墩墩山群火山岩研究认为,北山造山带中部晚泥盆世处于陆缘弧的构造环境,柳园洋(古亚洲洋)的演化持续到早石炭世之后;基于大量沉积学、构造变形和年代学研究,部分学者提出北山地区俯冲-增生造山作用可能一直持续到二叠纪甚至早中三叠世(Xiao *et al.*, 2010; Guo *et al.*, 2012; Tian *et al.*, 2015; Song *et al.*, 2016)。

田健等(2020)认为,北山造山带中部晚泥盆世酸性火山岩的源区包括了俯冲洋壳+地幔楔、弧增生物(变质玄武岩为主),晚泥盆世柳园洋仍在向北俯冲。余吉远等(2012b)通过同位素年代学研究,获得辉铜山蛇绿岩带中辉长岩的年龄为 446.1±3.0 Ma,相当于晚奥陶世;帐房山蛇绿岩带中辉长岩的年龄为 362.6±4.0 Ma,相当于晚泥盆世。帐房山蛇绿岩带中斜长花岗岩的年龄为 350.6±2.0 Ma(未发表数据,引自田健等, 2020),相当于早石炭世。由此可见,柳园洋(古亚洲洋)闭合时间在 351 Ma 之后,早石炭世是北山地区古生代洋盆闭合时限上限。埃达克岩代表俯冲作用开始的记录,柳园地区发现有 465 Ma 的榴辉岩(Liu *et al.*, 2011)、451 Ma 的富 Nb 玄武岩(Mao *et al.*, 2012)及 424 Ma 的埃达克岩(毛启贵等, 2010),说明北山南部地区在中奥陶世已经发

生洋壳的俯冲消减作用(李小菲等, 2015)。黑山头早泥盆世埃达克岩的发现,证实其所代表的柳园洋(古亚洲洋)在早泥盆世仍处于俯冲/碰撞阶段,柳园洋在早泥盆世尚未闭合,这为研究古亚洲洋俯冲碰撞过程提供了较丰富的岩石学证据和时间约束。

前人研究认为,中亚造山带所代表的的亚洲洋具有自西向东呈“剪刀式”闭合的特征,即西段闭合时间相对较早,东段闭合时间相对较晚(何世平等, 2002; 龚全胜等, 2002; 苗来成等, 2014)。北山造山带南部柳园地区埃达克岩年龄为424 Ma,金塔老虎沟一带埃达克岩年龄为407.8~391.0 Ma,本文在玉门黑山头一带发现的花岗闪长体具有埃达克岩成分特征,成岩年龄为407.7 Ma,北山缝合带埃达克质岩石的成岩年龄表现出自西向东逐渐年轻的趋势,佐证了柳园洋(古亚洲洋)具有自西向东呈“剪刀式”闭合的特征。

7 结论

(1) 黑山头花岗闪长岩体为未分异的过铝质、钙碱性I型花岗岩,具有高硅、高铝、富钠、贫钾、低$Mg^{\#}$、低Y、低Yb、高Sr/Y值和低HREE等典型埃达克岩的成分特征。

(2) 黑山头岩体花岗闪长岩中锆石LA-ICP-MS U-Pb加权平均年龄为407.7±1.6 Ma,显示其形成于早泥盆世。

(3) 综合前人研究成果,认为柳园洋(古亚洲洋)具有自西向东呈“剪刀式”闭合的特征,柳园洋(古亚洲洋)在早泥盆世仍处于俯冲/碰撞阶段。

致谢 甘肃省地矿局四勘院赵青虎、张增馨、郭峰、魏万疆、成锐、陈世明、康维良、杜红伟、雷自强等人参与了部分野外工作,胡金凤女士在图件绘制中给予了帮助,多位审稿人共同审阅了全文并提出了宝贵的意见和建议,在此一并谨致谢忱。

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