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东天山黑石墩基性岩地球化学、锆石年代学、Sr−Nd−Hf同位素特征及其俯冲岩浆作用

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提要:在东天山康古尔塔格南黑石墩一带新发现一套基性岩,岩性以辉长岩和橄榄辉长岩为主,岩石具有相对较低SiO_2(47.59%~50.79%)、富Na_2O(2.72%~4.42%)贫K_2O(0.26%~1.15%),低MgO(3.94%~12.55%),中等$Mg^\#$(47.6~66.64),高Al_2O_3(14.75%~19.65%),相对富集轻稀土($(La/Yb)_N$1.83~2.12),Eu弱正异常(1.00~1.25),富集LILE(Ba、U、Sr),亏损HFS(Ta、Nb、Th和Ti),并强烈富集Pb。锆石LA−ICP−MS U−Pb年龄((342.6 ±3.2)Ma) 表明该基性岩属于早石炭世岩浆活动的产物。岩石具有较低的$(^{87}Sr/^{86}Sr)_i$(0.703421~0.704551),正的$\varepsilon_{Nd}(t)$ (7.6~8.1)和$\varepsilon_{Hf}(t)$ (9.82~13.74)。地球化学特征和岩相学显示其来自亏损的岩石圈地幔源区,且源区在较低程度的部分熔融前受到俯冲板片中富含大离子亲石和轻稀土元素的海洋沉积物在俯冲过程中脱水熔融形成流体的交代作用影响,原始岩浆在侵位过程中发生程度不同的橄榄石、辉石和斜长石分离结晶作用,侵位过程中受到地壳物质混染的程度非常低。构造和动力学背景研究表明,黑石墩基性岩为北天山洋在早石炭世沿康古尔塔格—黄山大断裂向北俯冲阶段的产物。

关　键　词:黑石墩基性岩;锆石U−Pb年龄;Sr−Nd−Hf同位素;地球化学特征;东天山;地质调查工程

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Geochemistry, zircon chronology, Sr−Nd−Hf isotopic characteristics and subduction magmatism of Heishidun basic rocks in the East Tianshan

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Abstract: A new set of basic rocks was discovered in the Heishidun in South Kangurtag, Eastern Tianshan. Its lithology mainly consists of gabbro and olive gabbro. The rocks are characterized by relatively low contents of SiO_2 (47.59%−50.79%), K_2O (0.26%−

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1.15%) and MgO (3.94% − 12.55%), high contents of Na_2O (2.72% −4.42%) and Al_2O_3 (14.75% −19.65%), and moderate content of $Mg^{\#}$ (47.6−66.64). Light rare earth is enriched ($(La/Yb)_N$ of 1.83−2.12) with a bit of Eu positive anomaly (1.00−1.25). LILE (Ba, U, Sr) is enriched, while HFS (Ta, Nb, Th, and Ti) is depleted, and Pb is strongly enriched. LA−ICP−MS zircon U−Pb dating yields 342.6 ± 3.2 Ma, indicating that this basic rock is a product of Early Carboniferous magmatic activity. Rocks have lower Sr ratio ($(^{87}Sr/^{86}Sr)_i$ (0.703421−0.704551), positive $\varepsilon_{Nd}(t)$ (7.6−8.1) and $\varepsilon_{Hf}(t)$ (9.82−13.74). Geochemical characteristics and petrography show that it is originated from the lithospheric mantle source of the loss, and the source area was affected by the metamorphism of the dehydration and melting fluids resulted from the subduction of marine sediments rich in large ionic lithophile and light rare earth elements. The separation and crystallization of olivine, pyroxene and plagioclase took place during the emplacement of magma, the degree of contamination by the crustal material during the emplacement was very low. The structural and dynamic background shows that the Heishidun basic rock is the product of the Northern Tianshan Ocean's northward subduction along the Kangugtag−Huangshan fault in the Early Carboniferous.

Key words: Heishidun basic rock; zircon U−Pb age; Sr−Nd−Hf isotope; geochemistry; East Tianshan; geological survey engineering

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1 引 言

东天山是中亚地区东西走向的天山造山系的主要组成部分，在吐哈盆地南缘，不仅发育高钕低锶同位素初始比值的花岗岩（李锦轶等, 2006），而且从镜儿泉向西，经黄山、土墩、白鑫滩、海豹滩、红岭、康古尔塔格、恰特卡尔、路北，到色尔特能，出露100多个侵入到晚古生代地层的基性超基性岩（图1），构成了沿康古尔—黄山断裂长达数百千米的基性超基性岩带（李锦轶等, 2006），其产出受康古尔塔格—黄山大断裂及其次级断裂控制（毛亚晶等, 2014），且很多基性超基性岩有铜镍矿化，构成了恰特卡尔—黄山—镜儿泉铜镍成矿带，铜镍总储量达到百万吨，迄今这些含矿岩体中获得锆石U−Pb年龄为269~285 Ma(邓宇峰等, 2011) 。以往该地区基性超基性岩的研究多集中在该带东段含铜镍硫化物矿床的杂岩体(韩宝福等, 2004；Zhou et al., 2004；李锦轶，2006)。近年来，白鑫滩、路北和海豹滩等杂岩型铜镍矿的相继发现，将东天山沿康古尔—黄山大断裂分布的基性超基性杂岩型铜镍矿，由黄山经土墩向西过沙垄，经土屋延伸到石英滩东北，大大拓宽了东天山基性超基性杂岩型铜镍矿的找矿范围（杨万志等, 2017）。近年来虽然西段杂岩体研究成果明显增多，但集中于二叠纪基性超基性岩的研究，对石炭纪基性超基性岩文献报道较少，发现也很少。2014年新疆地质调查院承担的“新疆东天山成矿带中段1∶5万综合地质调查”项目在该地区新发现石炭纪黑石墩基性岩，并通过系统的岩相学、岩石地球化学、锆石U−Pb年代学和Sr−Nd−Hf同位素研究，为进一步探讨东天山地区的构造演化与成矿时代提供新的依据。

2 岩体地质背景及岩相学特征

2.1 地质背景

东天山处于西伯利亚、准噶尔—哈萨克斯坦和塔里木三大板块的接合处（Windley et al., 1990；肖序常等, 1992；何国琦等, 1994；Qin et al., 2003；何国琦和朱永峰, 2006；Zhu et al., 2007)，属中亚造山带的组成部分。区内蕴藏着丰富的矿产资源，是新疆乃至中国重要的铜、镍、金、铁、铅、锌等大型矿床集中区（王京彬等, 2006）。与铜镍矿相关的基性超基性岩石十分发育，且呈现含矿岩体以规模小、多阶段侵入、岩相分带清楚、成群成带出现的特点，小岩体成大矿是普遍的成矿现象，也是我国铜镍矿床的主要产出特点（顾连兴等, 2007；汤中立等, 2007；秦克章等, 2007；王玉往等, 2010）。对这些基性超基性杂岩的成因分歧较大：一是认为其归属蛇绿岩套的组成，其源区为软流圈地幔；二是认为形成于板块俯冲碰撞阶段，其源区为俯冲交代地幔；三是认为形成于碰撞造山后伸展环境，其源区为俯冲交代地幔或软流圈地幔；四是认为

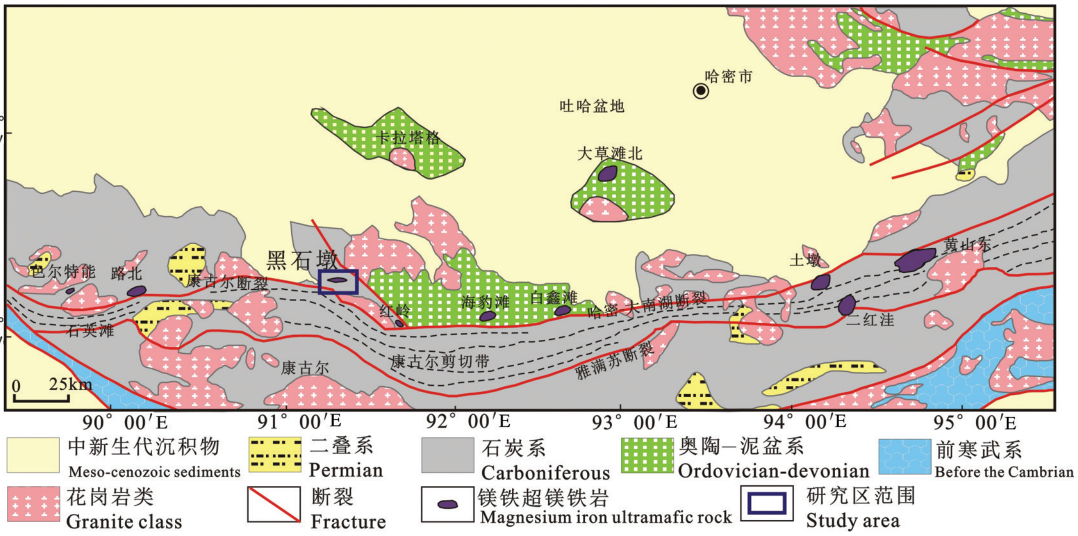

图1 北天山地区地质简图

Fig.1 Geologica map of Northern Tianshan

与塔里木地幔柱活动有关(邓宇峰等, 2011)。

黑石墩基性岩位于东天山中段鄯善县南侧,吐哈盆地南缘,恰特卡尔古火山机构东侧康古尔塔格一带,北距卡拉塔格约15 km,南距康古尔塔格—黄山大断裂约10 km,南邻康古尔韧性剪切带,构造位置属于小热泉子—大南湖岛弧带(舍建忠等, 2018),带内主要出露奥陶纪、志留纪、泥盆纪和石炭纪火山岩、火山沉积碎屑岩,也发育华力西中晚期岛弧型中酸性侵入岩。黑石墩基性岩地表被晚石炭世底坎尔组不整合覆盖,呈透镜体状出露,受断层控制,围岩无明显矿化蚀变。

2.2 岩相学特征

黑石墩基性岩岩性以辉长岩和橄榄辉长岩为主,有少量的辉石岩和辉绿岩分布。辉长岩均发生较强的蚀变。

辉长岩(图2a)主要矿物为斜长石、蛇纹石、普通辉石,极少量磁铁矿、钛铁矿,斜长石含量约74%,呈半自形—自形长板状杂乱分布,局部黝帘石化、绢云母化,蛇纹石含量约20%,呈鳞片状分布于斜长石间,部分蛇纹石集合体中可见辉石残留,普通辉石含量约为5%,呈半自形—他形柱粒状分布于斜长石间,部分为蚀变残留;橄榄辉长岩(图2b)主要矿物为普通辉石、斜长石、橄榄石,见少量钛铁矿和磁铁矿,普通辉石含量22%,呈半自形—他形柱粒状分布于斜长石间,粒径较大,部分粒径细小者包裹于粒径粗大者中,斜长石含量约60%,呈半

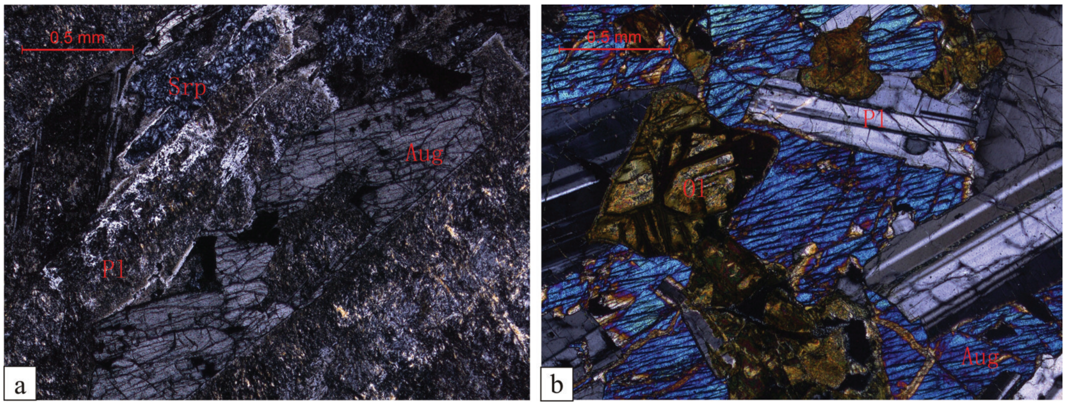

图2 黑石墩基性岩代表性岩石类型的显微照片

a—辉长岩;b—橄榄辉长岩;Pl—斜长石;Aug—普通辉石;Ol—橄榄石;Srp—蛇纹石

Fig.2 Microphotographs of the representative rocks in the Heishidun basic intrusive

a-Gabbro;b-Olivine gabbro;Pl-Plagioclase;Aug-Augite;Ol-Olivine;Srp-Serpentine

自形长板状、板状、粒状分布，表面干净，未见明显蚀变，橄榄石含量为15%，呈半自形—他形粒状，强蚀变，多已完全被蚀变矿物伊丁石、皂石所取代，保留其外形，分布于辉石中或斜长石间。

3 样品采集及分析方法

样品选取探槽里新鲜的岩石，硅酸盐、稀土-微量元素样品8件。测试单位为新疆维吾尔自治区矿产实验测试中心，主量元素使用X射线荧光光谱仪（XRF）进行测试，精度在0.1%以内；微量元素采用ICP-MS（ElementⅡ）（Agilent7500a）测试。

锆石U-Pb年龄样品岩性为辉长岩，锆石制靶由河北省区域地质矿产调查研究所完成，阴极发光显微照相由北京锆年领航科技有限公司完成，锆石U-Pb同位素测试由中国科学院广州地球化学研究所实验室完成，采用激光剥蚀电感耦合等离子质谱仪（LA-ICP-MS）分析，使用标准锆石91500作为外标加以校正，每测6个数值后进行一次91500标样测定，激光束斑直径为30 μm，使用^{29}Si作为内标测定锆石的U、Th、Pb含量。相关数据采用GLITTER和Isoplot软件进行数据处理。

锆石原位Hf同位素测试由中国地质调查局西安地质调查中心国土资源部岩浆作用成矿与找矿重点实验室完成，使用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，详细测试流程见侯可军等（2007）。测试束斑直径为44 μm。测试位置与测年点位相同或靠近。每分析10个样品测点插入一次标样测定（锆石标准GJ-1，GJ-1的测试精准度为0.282030±40（2SE））。

全岩Sr-Nd同位素化学前处理与质谱测定由南京聚谱检测科技有限公司完成。数据测试及处理流程详见Gao et al.（2004）。

4 分析结果

4.1 主、微量元素特征

样品的主量元素数据（表1）表明，黑石墩基性岩体SiO_2含量在47.59%~50.79%，相对富Na_2O（2.72%~4.42%，平均3.28%），贫K_2O（0.26%~1.15%，

表1 黑石墩基性岩岩石地球化学数据（含量单位：主量元素为%，微量元素为10^{-6}）

Table 1 Major elements (%) and trace elements(10^{-6}) data of the Heishidun basic rocks

测试项目	样号						测试项目	样号					
	H-44	H-45	H-264	H-265	H-266	H-267		H-44	H-45	H-264	H-265	H-266	H-267
SiO_2	47.88	50.79	47.59	50.14	50.64	50.35	Tm	0.36	0.43	0.31	0.39	0.46	0.31
TiO_2	1.21	1.37	1.07	1.14	1.29	0.99	Yb	2.33	2.79	2.05	2.44	2.94	2.04
Al_2O_3	16.81	18.08	14.75	18.84	19.65	19.34	Lu	0.36	0.41	0.31	0.37	0.44	0.32
CaO	9.74	9.44	7.45	9.75	8.35	10.40	Y	23.9	28.3	21.8	25.0	30.5	20.3
Fe_2O_3	3.21	3.32	3.42	3.29	2.17	3.53	ΣREE	57.15	65.59	50.89	58.42	74.19	47.29
FeO	5.59	6.29	8.12	5.65	5.78	4.75	LREE	41.69	47.81	37.39	42.46	54.95	34.11
K_2O	0.26	0.43	0.28	0.42	1.15	0.33	HREE	15.46	17.78	13.50	15.96	19.24	13.18
Na_2O	2.72	3.38	2.49	3.28	4.42	3.38	LREE/HREE	2.70	2.69	2.77	2.66	2.86	2.59
P_2O_5	0.16	0.19	0.15	0.16	0.22	0.12	La_N/Yb_N	1.97	1.90	2.06	1.91	2.12	1.83
MgO	6.78	6.01	12.55	6.10	3.94	5.83	δEu	1.12	1.00	1.05	1.10	1.09	1.25
MnO	0.16	0.16	0.18	0.15	0.14	0.13	δCe	1.02	1.03	1.04	1.06	1.04	1.05
LIO	6.01	1.12	2.4	1.51	2.7	1.26	Rb	4.10	7.50	6.00	7.90	23.30	4.10
Total	100.53	100.58	100.45	100.43	100.45	100.41	Ba	99.60	124.50	97.70	123.00	346.00	96.90
Mg$^{\#}$	58.77	53.59	66.64	55.81	47.60	56.73	Th	0.73	0.71	0.48	0.57	0.55	0.44
m/f	1.40	1.13	1.97	1.24	0.89	1.29	U	0.30	0.30	0.20	0.20	0.20	0.20
La	6.4	7.4	5.9	6.5	8.7	5.2	Ta	0.20	0.20	0.20	0.20	0.20	0.10
Ce	16.6	19.2	15.3	17.0	22.4	13.6	Nb	2.50	2.70	2.10	2.30	2.90	1.90
Pr	2.47	2.83	2.19	2.38	3.19	1.94	Pb	1.90	1.70	3.20	1.80	2.40	1.50
Nd	11.5	13.0	10.0	11.8	14.9	9.4	Sr	420.00	356.00	278.00	402.00	715.00	422.00
Sm	3.38	3.97	2.91	3.43	4.14	2.72	Zr	104.00	122.00	94.00	107.00	137.00	85.00
Eu	1.34	1.41	1.09	1.35	1.62	1.25	Hf	2.70	3.20	2.30	2.70	3.40	2.10
Gd	3.94	4.62	3.43	4.08	4.93	3.46	Ti	7180	8230	6340	6880	7900	6230
Tb	0.66	0.75	0.59	0.71	0.85	0.57	Cr	190	190	220	220	80	230
Dy	4.34	4.89	3.80	4.45	5.45	3.63	Ni	128.5	56.2	239	73.1	40.6	65.2
Ho	0.91	1.01	0.76	0.89	1.09	0.75	Co	35.6	32.6	60.6	32.3	21.8	30.4
Er	2.56	2.88	2.25	2.63	3.08	2.10							

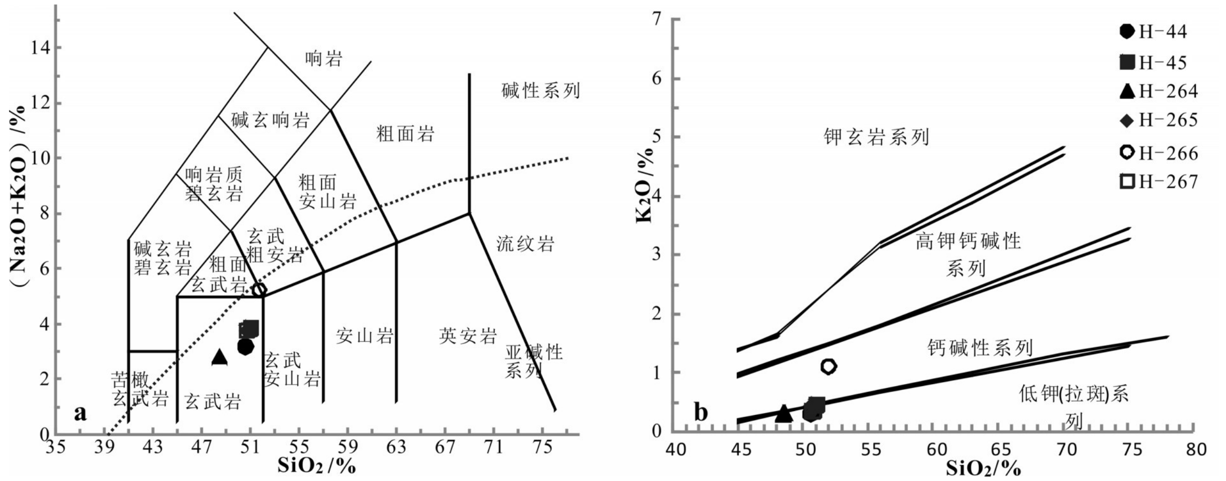

图3 黑石墩基性岩TAS图解(a)和SiO_2-K_2O图解(b)

Fig.3 TAS(a) and SiO_2 vs. K_2O (b)diagram of the Heishidun basic intrusive

平均0.48%)及Na_2O>K_2O的特征,在TAS图解中(图3a)除H-266外其余落在玄武岩区,在SiO_2-K_2O相关图解中(图3b)除H-266为钙碱性系列外,其余为低钾拉斑系列。MgO含量较低(3.94%~12.55%,平均6.87%),$Mg^{\#}$为47.6~66.64,m/f为0.89~1.966,Al_2O_3含量较高,为14.75%~19.65%。在Harker图中,MgO与SiO_2、Al_2O_3、CaO、P_2O_5、Na_2O、K_2O有明显的负相关性,与TiO_2具有弱负相关性(图4a、c~g),与T Fe_2O_3具有正相关关系(图4b)。

样品稀土总量偏低(∑REE在47.29×10^{-6}~74.19×10^{-6}),$(La/Yb)_N$介于1.83~2.12,说明轻重稀土元素之间分馏程度中等,LREE/HREE为2.59~2.86,轻微的Eu正异常(1.00~1.25),这是岩浆结晶分异成岩过程中,斜长石富集而造成的。在稀土元素球粒陨石标准化配分图中(图5a),所有样品曲线表现出一致的变化趋势,说明样品应该同源,并呈现出轻稀土略微富集的右倾特征,与E-MORB形态相似。微量元素原始地幔标准化蛛网图(图5b)中,所有样品都富集大离子亲石元素Ba、U、Sr,富集Pb,亏损高场强元素Ta、Nb、Th、Ti。

4.2 锆石U-Pb年龄

阴极发光图像显示锆石大多呈长柱状,自形晶,晶面整洁光滑,裂纹少,环带构造特征明显(图6a)。由表2可知,锆石Th含量为34.33×10^{-6}~753.69×10^{-6},U含量为51.59×10^{-6}~624.31×10^{-6},Th/U比值较高(0.56~1.21),多数在0.5~0.9,为岩浆锆石U、Th成分特征(吴元宝, 2004)。锆石年龄数据绝大多数落于谐和线上或其附近,个别数据落于谐和线右侧附近,说明有少量铅丢失,代表有后期热事件的干扰(张志诚等, 2009)。锆石$^{206}Pb/U^{238}$年龄加权平均值为(342.6 ±3.2)Ma(n=15,MSWD=0.54)(图6b),代表黑石墩岩体的形成时代为早石炭世。

4.3 锆石Hf同位素特征

本次对测年锆石进行了复位Lu-Hf同位素分析,所有测试位置与U-Pb测年点位相同或靠近。由表3可知锆石$^{176}Lu/^{177}Hf$比值最大值为0.000939,说明锆石形成后放射成因Hf的积累较少(杨进辉等, 2006b),因此所测定的$^{176}Hf/^{177}Hf$比值代表了其形成时体系的Hf同位素组成(吴福元等, 2007b)。$^{176}Hf/^{177}Hf$比值为0.282539~0.282950,$\varepsilon_{Hf}(t)$为正值(9.82~13.74),平均值为11.93,二阶段Hf模式年龄(t_{DM2})在473~724 Ma,平均值为587 Ma,与其形成年龄(342.6 ±3.2)Ma相差不大。

4.4 Sr-Nd同位素特征

全岩Nd、Sr同位素按照t=342.6 Ma计算,由表4可知,全岩样品Nd、Sr同位素组成基本一致,$(^{87}Sr/^{86}Sr)_i$为0.703421~0.704551,比值较高且变化范围相对较大;$\varepsilon_{Nd}(t)$值则变化范围较小,在7.6~8.1;$^{147}Sm/^{144}Nd$比值较大(0.17564~0.18453);二阶段Nd模式年龄(t_{DM2})范围为436~480 Ma,平均值为461 Ma。

5 讨 论

5.1 岩浆演化(结晶分异)

原始岩浆从源区地幔源经部分熔融作用开始

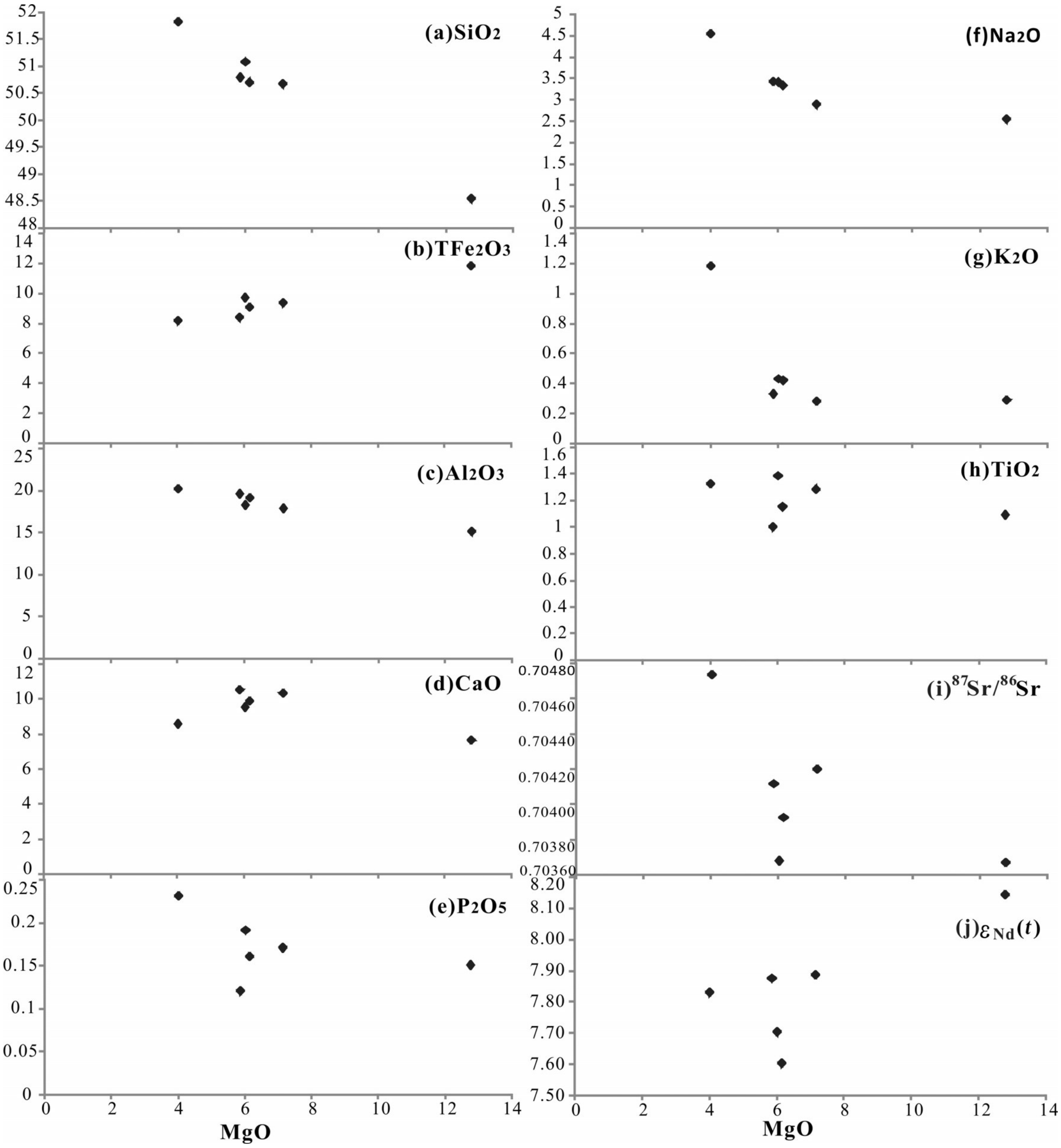

图4 黑石墩基性岩哈克图解(除$\varepsilon_{Nd}(t)$值外，其他单位均为%)

Fig.4 Harker diagrams of the Heishidun basic rocks(All the other units are % except the $\varepsilon_{Nd}(t)$ value)

发生、到迁移至岩浆房、再到最终喷出地表，是一个不断结晶分异、物质不断带出或带入、岩浆和矿物间平衡和再平衡的过程(张柳毅等, 2016)。黑石墩岩体与黄山东、黄山、香山等东天山典型含铜镍矿镁铁−超镁铁质岩体处于同一区域，但是这几处为高镁拉斑玄武质母岩浆(唐冬梅等, 2009;范亚洲等, 2014;尤敏鑫等, 2017)。黑石墩岩体锆石U−Pb测年所获得的年龄((342.6 ±3.2)Ma) 说明黑石墩岩体形成时间相对早。与黄山等典型含铜镍矿镁铁−超镁铁质岩体不同的是黑石墩基性岩具有较低的Mg(MgO=3.94%~12.55%，$Mg^{\#}$=47.6~66.74)以及较低的相溶元素Cr($80\times10^{-6}\sim220\times10^{-6}$)、Co($21.8\times10^{-6}\sim60.6\times10^{-6}$)和Ni($40.6\times10^{-6}\sim128.5\times10^{-6}$)含量，说明该岩体来源于分异程度相对较高的岩浆(Liu et al., 2008)。在Harker图解中(图4)，MgO与TFe_2O_3具有正相关性，说明岩浆在上升侵位过程中经历了橄榄石和斜方辉石的分离结晶作用，而MgO与TiO_2、P_2O_5、Al_2O_3以及CaO之间具有负相关性，暗示富含Ti矿物(金红石、钛铁矿和榍石)、磷灰石和单斜辉石不是主要的结晶相(冯光英等, 2011)。对

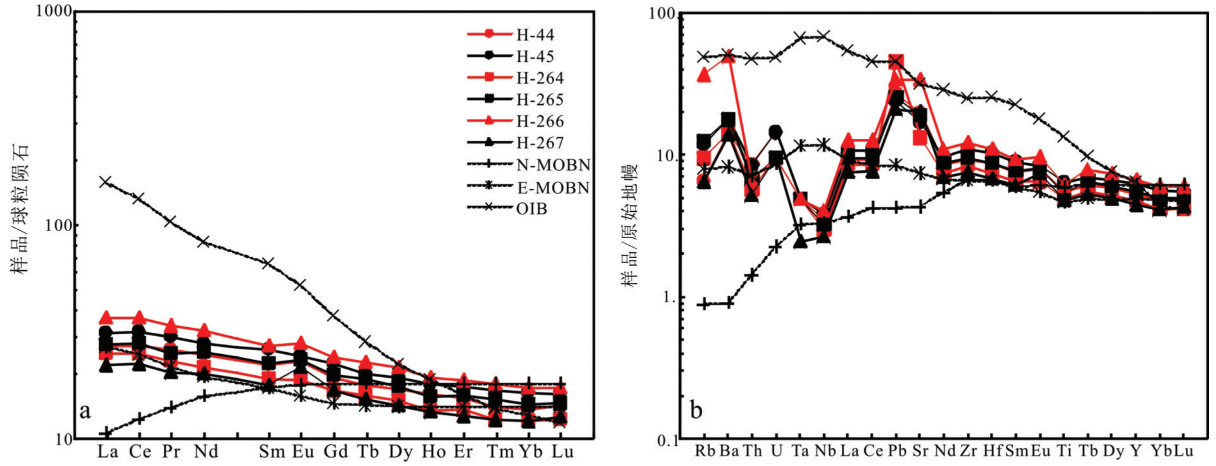

图5 黑石墩基性岩稀土元素球粒陨石标准化配分曲线(a)和微量元素原始地幔标准化蛛网图(b)(据Sun and McDonough, 1989)
Fig.5 Chondrite-normalized REE patterns(a)and Primitive mantle-normalized spidergrams(b)of Heishidun basic rocks(after Sun and McDonough, 1989)

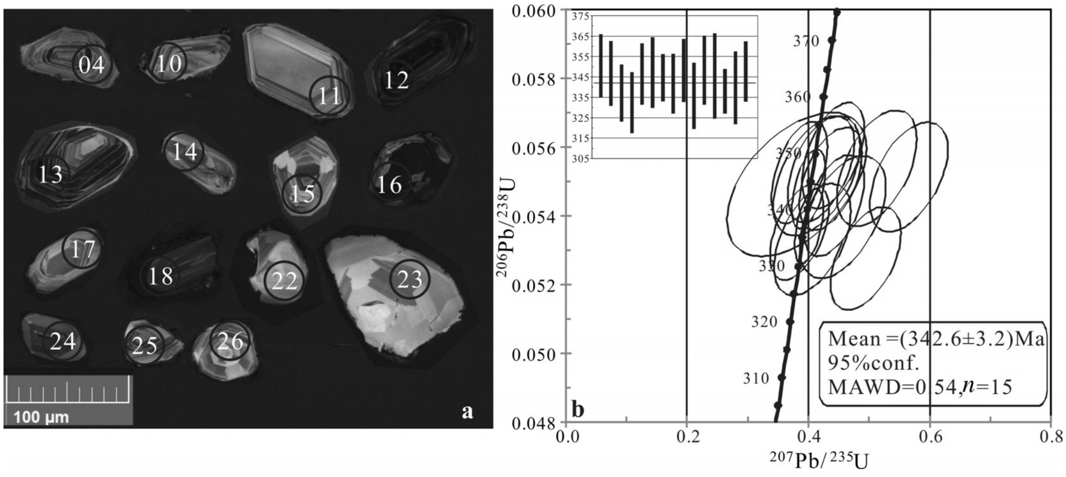

图6 黑石墩辉长岩锆石阴极发光图像及测点点号图(a)和U-Pb谐和图(b)
Fig.6 CL images and test point number (a) and U-Pb concordia plots(b) of zircons from Heishidun gabbro

表2 黑石墩辉长岩LA-ICP-MS锆石U-Pb同位素数据
Table 2 LA-ICP-MS zircon U-Pb dating results of Heishidun gabbro

测试点	Pb/10^{-6}	Th/10^{-6}	U/10^{-6}	Th/U	同位素比值				年龄/Ma			
					^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ
126CD04	4.09	45.54	63.06	0.72	0.4404	0.0419	0.0558	0.0013	370.50	29.50	349.70	7.72
135CD10	4.17	47.18	68.67	0.69	0.5656	0.0525	0.0551	0.0013	455.20	34.04	345.90	7.91
136CD11	3.21	40.75	56.96	0.72	0.3848	0.0396	0.0535	0.0011	330.60	29.05	336.20	6.97
137CD12	3.46	34.33	61.19	0.56	0.4946	0.0477	0.0528	0.0012	408.00	32.39	331.40	7.47
139CD13	8.67	91.09	132.68	0.69	0.4364	0.0424	0.0551	0.0012	367.70	30.00	345.60	7.48
140CD14	6.23	83.27	95.31	0.87	0.4132	0.0587	0.0552	0.0014	351.20	42.16	346.20	8.65
141CD15	4.67	64.85	79.65	0.81	0.4004	0.0228	0.0548	0.0009	341.90	16.56	343.70	5.75
142CD16	42.45	753.69	624.31	1.21	0.4419	0.0410	0.0543	0.0012	371.60	28.84	340.80	7.32
143CD17	6.33	92.91	106.63	0.87	0.4207	0.0449	0.0554	0.0013	356.60	32.12	347.30	7.70
144CD18	5.41	80.18	90.99	0.88	0.4065	0.0520	0.0533	0.0013	346.30	37.56	334.80	8.13
151CD22	3.28	37.81	54.92	0.69	0.5128	0.0538	0.0554	0.0014	420.30	36.08	347.50	8.44
152CD23	4.22	51.76	64.34	0.80	0.3806	0.0942	0.0549	0.0017	327.40	69.28	344.60	10.47
153CD24	10.89	131.52	168.51	0.78	0.4009	0.0194	0.0537	0.0009	342.30	14.07	337.10	5.46
155CD25	5.44	72.58	84.58	0.86	0.4564	0.0579	0.0540	0.0015	381.80	40.37	338.80	8.90
156CD26	3.55	40.89	51.59	0.79	0.3853	0.0379	0.0553	0.0012	330.90	27.79	346.80	7.40

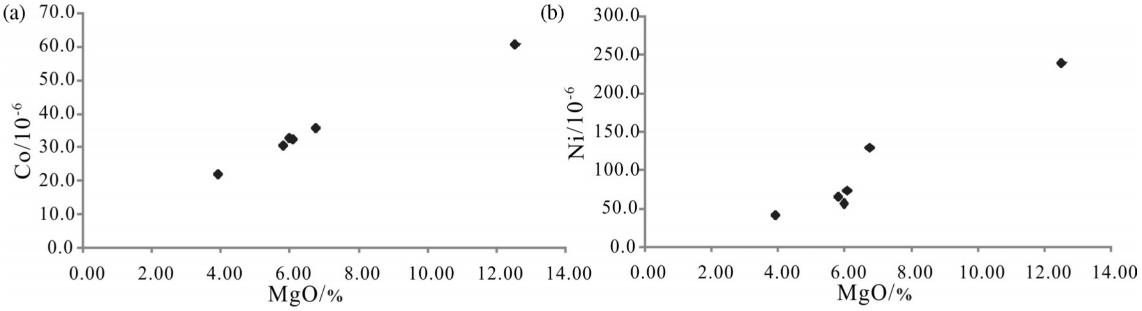

图7 黑石墩基性岩MgO−Co图解（a）和MgO−Ni图解（b）
Fig.7 MgO−Co diagram（a）and MgO−Ni diagram（b）of the Heishidun basic rocks

于橄榄石和辉石而言，Mg与Co、Ni是相溶元素，该岩体Co、Ni与MgO呈正相关性（图7a、b），说明该岩体发生过橄榄石、辉石的结晶作用。综上所述，黑石墩基性岩在岩浆演化过程中经历了橄榄石、辉石和斜长石的分离结晶作用，这与岩相学特征一致。

5.2 源区特征及部分熔融程度

黑石墩基性岩具有较低的Sr同位素初始比值（0.703421～0.704551），正的$\varepsilon_{\mathrm{Nd}}(t)$值（7.6～8.1），以及模式年龄与岩石形成年龄相近，说明岩体来源于亏损地幔。其Sr同位素显示为亏损，说明该亏损地幔可能为新生，但随后经历了一定程度的不相容元素富集作用（Wu et al., 2004;冯光英等, 2011）。从稀土元素球粒陨石标准化配分图解中和原始地幔标准化微量元素蛛网图（图5）可以看出，黑石墩基性岩微量元素组成特征与N−MORB和OIB有明显的差异，与E−MORB较相似。

前人研究认为REE的含量主要受地幔组成和部分熔融程度的控制，地幔橄榄岩熔融过程中Yb

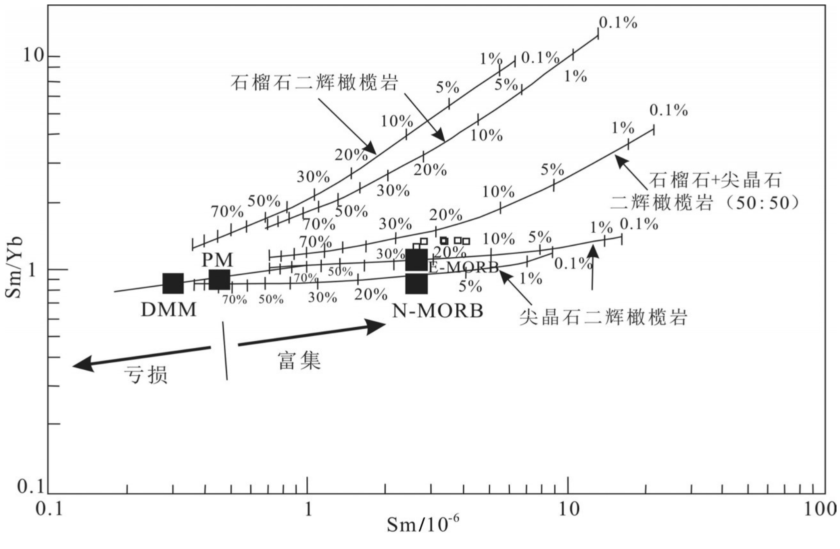

图8 黑石墩基性岩Sm/Yb−Sm相关图解

熔融曲线为尖晶石二辉橄榄岩(模式及熔体模式:ol 0.530+opx 0.270+cpx 0.170+spo.030 and ol 0.060+opx 0.280+ cpx 0.670+sp 0.110)(据Kinzler, 1997)和石榴子石二辉橄榄岩(模式及熔体模式:ol 0.600+opx 0.200+cpx 0.100+gt 0.100 and ol 0.030+opx 0.160+cpx0.880+gt 0.090)(据Walter, 1998);矿物/基质分配系数以及DMM引自Mc Kenzie and O'Nions (1991, 1995);PM, N−MORB和E−MORB组成引自Sun and Mc Donough (1989);每条曲线上的数字对应于给定地幔源区的部分熔融程度

Fig.8 Sm/Yb vs.Sm diagram of the Heishidun basic rocks

Melt curves are drawn for spinel−lherzolite(with mode and melt mode of ol 0.530 + opx 0.270 + cpx 0.170 + sp 0.030 and ol 0.060+opx0.280+cpx0.670+ sp 0.110, respectively;after Kinzler, 1997)and for garnet−lherzolite(with mode and melt mode of ol 0.600+opx 0.200+cpx0.100+gt 0.100and ol 0.030+opx0.160+cpx 0.880+gt 0.090, respectively;after Walter, 1998);Mineral/matrix partition coefficients and DMM arefrom the compilation of Mc Kenzie and O'Nions(1991, 1995);PM, N−MORB and E−MORB compositions are from Sun and Mc Donough(1989);Tickmarks on each curve(or line)correspond to degrees of partial melting for a given mantle source

元素来源于残留石榴石,所以,含有石榴石残留的地幔橄榄岩部分熔融熔体具有Yb元素含量低，La/Yb和Sm/ Yb比值高的特征（Pearce and Peate, 1995; Johnson, 1998;Münker, 2000;Zhao and Zhou, 2007; Liu et al., 2010b;冯光英等, 2011）。在Sm/Yb-Sm图解中(图8),黑石墩基性岩的Sm/Yb比值分布于尖晶石二辉橄榄岩和石榴石+尖晶石二辉橄榄岩熔融曲线之间,且接近E-MORB,显示为较低程度的部分熔融(15%～25%)的产物。较低程度的部分熔融会导致La/Sm和La/Yb的强烈分异,且地幔橄榄岩熔融过程中铁优先进入熔体,随着熔融程度的升高,岩浆中的镁含量随之升高(冯光英等, 2011)。而黑石墩基性岩具有较高的La/Sm (1.87～2.1)和$(La/Yb)_N$ (2.65～2.96)比值,较低的MgO含量和$Mg^{\#}$值(47.6～66.64)、较高的稀土含量(∑REE=47.29×10^{-6}～74.19×10^{-6}),都暗示原始岩浆经过了较低程度的部分熔融。

5.3 地壳混染

幔源岩浆在上升或者侵位过程中一般都会受到不同程度地壳混染(Mohr, 1987),黑石墩基性岩亏损高场强元素Ta、Nb、Th和Ti,富集LILE和LREE,且Ta / La比值(0.019～0.034)低于原始地幔(Ta/La=0.06,Wood et al., 1979),说明在上升或者侵位过程中可能存在壳源物质的混染(冯光英等, 2011)。地壳中富集Zr和Hf元素,地壳混染会导致Zr和Hf元素含量显著增高(舍建忠等, 2017),而样品中Zr和Hf元素没有明显异常(图5b),其较低的含量指示壳源物质的混染程度较低。一般来说地壳混染也会导致MgO和$\varepsilon_{Nd}(t)$之间具有正相关性,MgO和$(^{87}Sr/^{86}Sr)_i$之间具有负相关性(Liu et al., 2010b),表1、表4、图4说明黑石墩基性岩不存在这种相关性,故笔者认为黑石墩基性岩原始岩浆在上升或侵位过程中地壳物质的混染程度较低。此外样品具有较低的$(^{87}Sr/^{86}Sr)_i$(0.703421～0.704551)，正的$\varepsilon_{Nd}(t)$ (7.6～8.1)和$\varepsilon_{Hf}(t)$(9.82～13.74)(表3,表4),同样原始岩浆在上升或侵位过程中地壳混染的程度不大。通常情况下可以用亏损地幔与上地壳作为两端元、亏损地幔与下地壳作为两端元混合计算方式来检验是否存在地壳混染及混染程度（冯光英等, 2011）,由图9可知,黑石墩基性岩成岩过程中几乎没有受到下地壳物质的混染,上地壳物质的混染也不明显(混染程度为1%左右)。所以黑石墩基性岩的地球化学特征可能主要呈现源区岩浆的特征。另外,因为锆石具有封闭温度高、Hf含量高和Lu/Hf比值低等特征,常用于测年、指示岩浆源区性质以及混合过程(Griffin et al., 2002;Kemp and Hawkesworth, 2006;Yang et al., 2006a; 吴福元, 2007b;胡芳芳等, 2007 ;Liu et al., 2010a)。黑石墩基性岩体锆石$\varepsilon_{Nd}(t)$值较高且变化不大(表3),也说明原始源区岩浆比较单一。

5.4 流体交代

黑石墩基性岩Sr元素含量较高(278×10^{-6}～715×10^{-6},平均值为432×10^{-6}),明显高于地幔Sr元素含量(17.8×10^{-6})（Taylor and Mc Lennan, 1985）。Sr元素含量增高可能受围岩混染或者俯冲板片流体交代作用的影响 (Mc Culloch and Gamble, 1991;

表3 黑石墩基性岩锆石Lu-Hf同位素组成

Table 3 Zircn Lu-Hf isotopic composition of Heishidun basic rocks

测点号	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$f_{Lu/Hf}$	Age/Ma	$(^{176}Hf/^{177}Hf)_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	2σ	t_{DM1}/Ma	t_{DM2}/Ma
1	0.027745	0.000732	0.282930	0.000020	-0.98	349.7	0.282926	5.60	13.12	0.71	453	515
2	0.026017	0.000743	0.282930	0.000018	-0.98	347.5	0.282925	5.58	13.06	0.64	454	518
3	0.027734	0.000794	0.282950	0.000018	-0.98	345.9	0.282945	6.31	13.74	0.63	425	473
4	0.019209	0.000653	0.282878	0.000018	-0.98	336.2	0.282873	3.73	10.98	0.62	526	642
5	0.016462	0.000479	0.282869	0.000017	-0.99	331.4	0.282866	3.43	10.62	0.61	536	661
6	0.034073	0.000939	0.282903	0.000017	-0.97	345.6	0.282897	4.62	12.01	0.61	495	583
7	0.025676	0.000741	0.282903	0.000018	-0.98	346.2	0.282899	4.65	12.09	0.62	491	579
8	0.014325	0.000485	0.282837	0.000019	-0.99	347.3	0.282834	2.30	9.82	0.65	581	724

注：$\varepsilon_{Hf(0)}=((^{176}Hf/^{177}Hf)_s/(^{176}Hf/^{177}Hf)_{CHUR,\ 0}-1)\times10000$; $f_{Lu/Hf}=(^{176}Lu/^{177}Hf)_s/(^{176}Lu/^{177}Hf)_{CHUR}-1$; $\varepsilon_{Hf}(t)=((^{176}Hf/^{177}Hf)_s-(^{176}Lu/^{177}Hf)_s\times(e^{\lambda t}-1)/((^{176}Hf/^{177}Hf)_{CHUR,0}-(^{176}Lu/^{177}Hf)_{chur}\times(e^{\lambda t}-1))-1)\times10000$;$t_{DM1}=1/\lambda\times(1+(^{176}Hf/^{177}Hf)_s-(^{176}Hf/^{177}Hf)_{DM}/((^{176}Lu/^{177}Hf)_s-(^{176}Lu/^{177}Hf)_{DM}))$; $t_{DM2}=t_{DM1}(Hf)-(t_{DM1}(Hf)-t)((f_{cc}-f_s)/(f_{cc}-f_{DM}))$.where, $(^{176}Hf/^{177}Hf)_s$and$(^{176}Lu/^{177}Hf)_s$ are the measured values of samples;$(^{176}Lu/^{177}Hf)_{CHUR}=0.0332and(^{176}Hf/^{177}Hf)_{CHUR,\ 0}=0.282772$(Blichert- Toft and Albarede, 1997);$(^{176}Lu/^{177}Hf)_{DM}=0.0384and(^{176}Hf/^{177}Hf)_{DM}=0.28325$(Griffin et al., 2000); $f_{cc}=-0.548$(average continentalcrust),$f_{DM}=0.16$, t=crystallization time of zrrcon, $\lambda=1.865\times10^{-11}a^{-1}$(Soderlund et al., 2004) are used in calculation

表4 黑石墩基性岩的全岩Sr−Nd同位素组成

Table 4 Whole−rock Sr−Nd isotopic compositions of Heishidun basic rocks

样品号	H-44	H-45	H-264	H-265	H-266	H-267
^{87}Rb/^{86}Sr	0.02497	0.05258	0.04901	0.03339	0.03733	0.01641
^{87}Sr/^{86}Sr	0.704199	0.703678	0.703667	0.703923	0.704734	0.704117
^{147}Sm/^{144}Nd	0.17760	0.18453	0.17584	0.17564	0.16789	0.17485
^{143}Nd/^{144}Nd	0.512999	0.513005	0.513008	0.512980	0.512974	0.512992
$(^{87}Sr/^{86}Sr)_i$	0.704077	0.703421	0.703427	0.703759	0.704551	0.704037
$\varepsilon_{Nd}(0)$	7.04	7.16	7.21	6.67	6.56	6.91
$\varepsilon_{Nd}(t)$	7.9	7.7	8.1	7.6	7.8	7.9
$(^{143}Nd/^{144}Nd)_i$	0.512599	0.512590	0.512612	0.512585	0.512596	0.512599
$f_{Sm/Nd}$	-0.65	-0.64	-0.66	-0.66	-0.67	-0.66
t_{DM1}/Ma	645	765	578	687	590	626
t_{DM2}/Ma	457	472	436	480	462	458

Hawkesworth et al., 1993;熊富浩等, 2011)，而根据前述,黑石墩基性岩受围岩混染程度非常低,那么造成Sr元素含量高的原因可能是受到俯冲板片流体交代作用的影响。

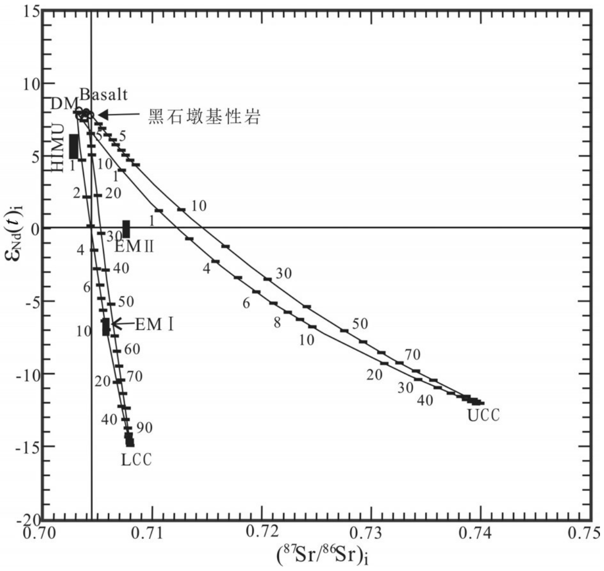

图9 黑石墩基性岩$(^{87}Sr/^{86}Sr)_i$−$\varepsilon_{Nd(t)}$图解

其中数字表示地壳物质参与的比例,计算采用的参数Nd(10^{-6})、$\varepsilon_{Nd}(t)$、Sr(10^{-6})和$(^{87}Sr/^{86}Sr)_i$值如下:软流圈地幔(DM)分别为1.2、+8、20和0.703;玄武岩分别为15、+8、200和0.704; 上地壳(UCC)分别为30、−12、250和0.740(据Jahn et al., 1999);下地壳(LCC)分别为20、−15、230和0.708(据Wu et al., 2000)

Fig.9 $(^{87}Sr/^{86}Sr)_i$vs. $\varepsilon_{Nd}(t)$diagram of the Heishidun basic rocks

The numbers indicate the percentages of participation of the crustal materials. The calculated parameters of Nd(10^{-6}), $\varepsilon_{Nd}(t)$, Sr(10^{-6})and $(^{87}Sr/^{86}Sr)_i$are1.2、+8、20、and 0.703 for asthenospheric mantle(DM); 15、+8、200and 0.704 for basalt;30、−12、250and 0. 740 for upper continental crust(UCC) (after Jahn et al., 1999); 20、−15、230、0.708 for lower continental crust(LCC). All data derive from Wu et al. (2000a)

前人研究认为地幔流体交代作用主要有深部地幔上升过程中的流体、俯冲板片中富含大离子亲石元素和轻稀土元素的深海沉积物在俯冲深部脱水熔融产生的流体和俯冲板片熔融生成的流体等3种形式(Meen et al., 1989; Maury et al., 1992; Hawkesworth et al., 1993; Elliott et al., 1997; Ishikawa and Tera, 1999;熊富浩等, 2011)。深部地幔源区的岩浆一般具有洋岛构造环境背景的岩石地球化学特征(熊富浩等, 2011),而俯冲板片中富含大离子亲石元素和轻稀土元素的深海沉积物在俯冲深部脱水熔融产生的流体一般则与地幔交代从而形成富含钾和高场强元素的岩浆(Sajona et al., 2000;Defant and Kepezhinskas, 2001; 熊富浩等, 2011),俯冲板片熔融生成的流体则会影响亲湿岩浆元素的含量,高场强元素又因在水中的溶解度较小呈现出相对亏损(Regelous, 1997;Johnson and Plank, 1999;冯光英, 2011)。而黑石墩基性岩具有中等的Mg$^{\#}$、相对富集Ba、U、Sr等大离子亲石元素和轻稀土元素,强烈富集Pb元素,亏损Ta、Nb、Th、Ti等高场强元素。因此,笔者认为研究区地幔流体交代作用主要是通过俯冲板片中富含LILE和LREE的海洋沉积物脱水形成的流体完成的。

5.5 构造意义

分析表明黑石墩基性岩岩浆源区受到俯冲作用影响。高场强元素Nb、Ta、Zr和Hf在岩石蚀变和变质等过程中一般具有很好的稳定性,可以作为岩石成因和源区性质的示踪剂,并且一般岛弧玄武岩和部分亏损型洋中脊玄武岩(N−MORB)的Ta、Nb丰度分别不大于0.7×10^{-6}和12×10^{-6},Nb/La<1,Hf/

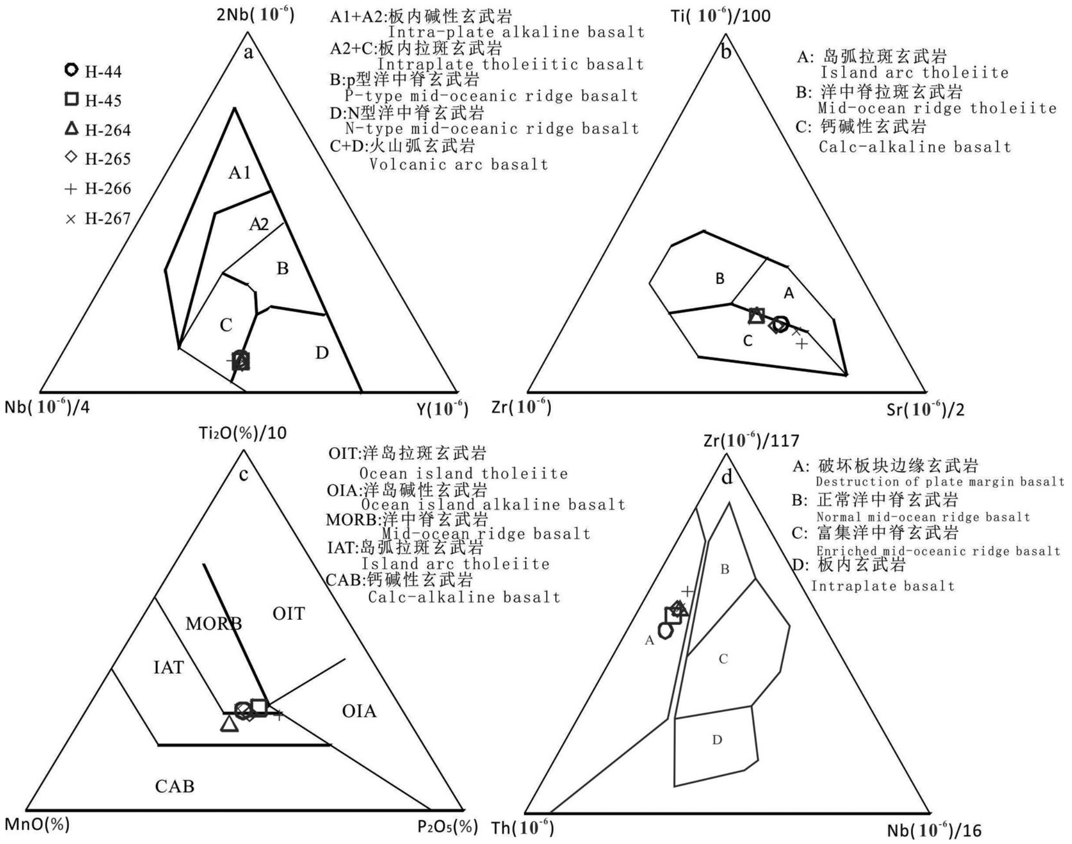

图10 主量及微量元素构造环境判别图解(a, 据Meschede, 1986;b, 据Pearce and Cann，1973;c, 据Mullen, 1983;d, 据Wood et al., 1979)

Fig.10 Tectonic discriminative diagrams by major−and trace−elements (a, after Meschede, 1986;b, after Pearce and Cann, 1973;c, after Mullen, 1983;d, after Wood et al., 1979)

Ta>5, La/Ta>15,板内玄武岩(WPB)、过渡型洋中脊玄武岩(T−MORB)和富集型洋中脊玄武岩(E−MORB)则正好相反(Condie et al., 1989)。黑石墩样品中玄武岩的Ta元素含量(平均0.18×10^{-6})和Nb元素含量(平均2.4×10^{-6})较低,Nb/La比值为0.36,Hf/Ta比值15.17,La/Ta比值37.22,表明该玄武岩形成环境与WPB、T−MORB、E−MORB构造环境无关,类似于岛弧玄武岩或N−MORB的构造环境。笔者采用不同构造环境判别图来进一步分析黑石墩岩体形成的环境,在2Nb− Nb /4−Y构造判别图解中(图10a),样品投影点落入火山弧玄武岩区;在Ti−Zr−Sr构造判别图解中(图10b),样品投影点落入岛弧拉斑玄武岩区和钙碱性玄武岩区界线上;在TiO_2−MnO−P_2O_5构造判别图解中(图10c),样品投影点落入洋中脊玄武岩区和岛弧拉斑玄武岩区界线上;在Zr/117−Th−Nb构造判别图解中(图10d),样品投影点落入破坏板块边缘玄武岩区。投图样品具有与俯冲有关的环境特征。

长期以来对东天山造山带内觉罗塔格地区的大地构造背景及演化存在争议,归纳起来主要有3种认识:一是为晚古生代裂陷槽(肖序常等, 1992;成守德等, 2001;冯益民等, 2002;秦克章等, 2002;潘桂棠等, 2009);二是为晚古生代被动大陆边缘(何国琦等, 1994;侯广顺等, 2006);三是为塔里木板块和哈萨克斯他—准噶尔板块的缝合带(姬金生等, 1994;李锦轶等, 2004;肖文交等, 2006;左国超等, 2006;舍建忠等, 2018)。笔者同意第三种认识,综合该地区岩浆岩地球化学特征,认为北天山洋从奥陶纪开始沿康古尔塔格—黄山大断裂向北俯冲(李锦轶等, 2004;舍建忠等, 2018),并在志留纪显示出洋盆闭合的特征(舍建忠等, 2017),在早石炭世开始双向俯冲(舍建忠等, 2018),在晚石炭世晚期闭合(李锦轶等, 2004;舍建忠等, 2018)。

综合岩石地球化学、矿物学、同位素等方面的

研究，笔者认为黑石墩基性岩岩浆为北天山洋在早石炭世沿康古尔塔格—黄山大断裂向北俯冲，富含大离子亲石元素和轻稀土元素的海洋沉积物在俯冲过程中脱水形成的流体，改造先存亏损的岩石圈地幔发生较低程度部分熔融形成原始岩浆，且上升或者侵位过程中经历了程度不同的橄榄石、辉石和斜长石分离结晶作用，最后形成了研究区早石炭世基性岩。

6 结 论

(1)锆石U−Pb年龄表明黑石墩基性岩形成于（342.6 ±3.2）Ma（n=15，MSWD=0.54）（图6b），代表其结晶年龄为早石炭世，佐证东天山秋格明塔什—黄山断裂带不仅有二叠纪基性超基性杂岩，还有华里西中期基性岩浆活动。

(2)黑石墩基性岩主体属于低钾拉斑系列，具有中等的Mg$^{\#}$值、大离子亲石元素富集，轻稀土元素相对富集，Pb元素强烈富集，高场强元素亏损，具有较低的$(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$，正的$\varepsilon_{\mathrm{Nd}}(t)$和$\varepsilon_{\mathrm{Hf}}(t)$，为亏损地幔较低程度的部分熔融(15%～25%)的产物。

(3)岩石具有俯冲环境特征，结合区域构造演化特征，认为黑石墩基性岩岩浆为北天山洋在早石炭世沿康古尔塔格—黄山大断裂向北俯冲，造成俯冲板片流体，交代亏损地幔发生较低程度部分熔融形成原始岩浆，在上升或者侵位过程中经历了程度不同的橄榄石、辉石和斜长石分离结晶作用。

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