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塔里木西北缘瓦吉里塔格黑云母二长闪长岩年代学、地球化学特征及其地质意义

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摘要: 塔里木大火成岩省是塔里木克拉通地质演化历史中岩浆活动最为强烈, 影响范围最为广泛的一次构造热事件, 形成了包括瓦吉里塔格等赋存钽铌磁铁矿矿床的镁铁-超镁铁质层状岩体, 此次在瓦吉里塔格镁铁-超镁铁质层状岩体边部发现了偏中性的岩浆岩, 但前人对其关注较少, 这在一定程度上制约了对塔里木大火成岩省的岩浆演化过程及深部地球动力学机制的全面认识。笔者对瓦吉里塔格中性岩黑云母二长闪长岩进行了细致的岩相学、年代学及地球化学等研究。TIMA 面扫描结果显示该黑云母二长闪长岩主要由斜长石、正长石、黑云母、普通角闪石、普通辉石等组成。LA-ICP-MS 锆石 U-Pb 年龄为 $(277.9 \pm 1.5) \text{ Ma}$ ($\text{MSWD}=0.85$), 为早二叠世, 形成时代略晚于瓦吉里塔格镁铁-超镁铁质层状岩体。该岩石相对低硅 (SiO_2 值为 $52.14\% \sim 53.50\%$)、富碱 ($\text{Na}_2\text{O}+\text{K}_2\text{O}$ 值为 $7.26\% \sim 7.60\%$), 属钾玄岩系列, 球粒陨石标准化稀土配分模式显示为 LREE 富集、HREE 亏损的右倾模式, 富集大离子亲石元素 Ba, Pb 等, 高场强元素 Nb、Ta、Zr、Hf 等含量高, 无 Nb-Ta 负异常, 地球化学特征显示其源自 OIB 型富集地幔源区且上升过程中地壳混染较弱。轻微富集的锆石 Hf 同位素特征 ($\varepsilon_{\text{Hf}}(t)$ 值为 $-1.8 \sim -4.4$) 与塔里木大火成岩省大陆溢流玄武岩类似。在 TiO_2 - MnO - P_2O_5 及 Hf-Th-Ta 构造判别图中均显示其形成于板内环境。综合研究认为, 瓦吉里塔格黑云母二长闪长岩源自俯冲洋壳加入的富集岩石圈地幔部分熔融, 源区残留相为榴辉岩组分, 地幔柱与俯冲板片相互作用对岩石形成起重要作用。

关键词: 塔里木大火成岩省; 瓦吉里塔格; 锆石 U-Pb 年龄; 地球化学; 岩石成因

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Geochronological and Geochemical Characteristics of the Wajilitag Biotite Monzodiorite in the Northwestern Margin of Tarim Craton and Their Tectonic Implications

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Abstract: The Tarim Large Igneous Province constitutes the most significant tectono-thermal event in the evolution of the Tarim Craton, forming mafic-ultramafic layered intrusions (e.g., the Wajilitag complex) that host vanadium-titanium magnetite deposits. However, intermediate rocks identified at the margin of the Wajilitag intrusion have been largely overlooked. Thus, the magmatic evolution and deep-seated geodynamic processes of the Tarim Large Igneous Province have been incompletely understood. This study presents a comprehensive investigation of the Wajilitag biotite monzodiorite, integrating detailed petrographic, geochronological, and geochemical analyses. The biotite monzodiorite is primarily composed of plagioclase, orthoclase, biotite, hornblende and augite. LA-ICP-MS zircon U-Pb dating yields an age of 277.9 ± 1.5 Ma (MSWD = 0.85), constraining the emplacement of the biotite monzodiorite in the Early Permian. This age is slightly younger than that of the Wajilitag mafic-ultramafic layered intrusion. The biotite monzodiorite is characterized by relatively low silica (SiO_2 content is 52.14%–53.50%) and high alkali contents ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ content is 7.26%–7.60%), classifying it as shoshonitic series. The chondrite-normalized REE pattern displays a right-sloping trend with LREE enrichment and HREE depletion. It is enriched in large-ion lithophile elements (LILEs; e.g. Ba and Pb) and possesses high concentrations of high-field-strength elements (HFSEs; e.g. Nb, Ta, Zr, Hf), without Nb-Ta negative anomalies. These geochemical features are indicative of an OIB-like enriched mantle source, with negligible crustal contamination during ascent. The slightly enriched zircon Hf isotopic composition ($\varepsilon_{\text{Hf}}(t)$ value range from -1.8 to -4.4) of the Wajilitag biotite monzodiorite is similar to that of continental flood basalts from the Tarim Large Igneous Province. In the TiO_2 - MnO - P_2O_5 and Hf-Th-Ta tectonic discrimination diagrams, the rocks exhibit an affinity consistent with within-plate basalts. Integrated studies suggest that the Wajilitag biotite monzodiorite was derived from partial melting of an enriched lithospheric mantle that had been modified by subducted oceanic crust, with eclogite as the residual phase in the source. The interaction between a mantle plume and the subducted slab played a significant role in its formation.

Keywords: Tarim large igneous province; Wajilitag; Zircon U-Pb age; geochemistry; petrogenesis

大火成岩省作为地球历史上大规模的板内岩浆事件,以巨量岩浆的快速喷发为特征,其将地球内部巨大的物质与能量快速释放到地表,通常被认为与地幔柱活动有关,是新生地壳的重要形成区域,同时大火成岩省中往往发育众多具有经济价值的幔源岩浆矿床,如攀西地区峨眉山大火成岩省中的镁铁-超镁铁质层状岩体发育世界级的铁钛氧化物矿床(Coffin et al., 1994; Bryan et al., 2008; 夏林圻等, 2012; 宋谢炎等, 2018; 柏中杰等, 2024; 夏自辛等, 2025)。位于中国新疆的早二叠世塔里木大火成岩省,是欧亚大陆上继西伯利亚、峨眉山和 Panjal 之后,又一个备受关注的火成岩省,其以岩石组合复杂,持续时间长为特征(Tian et al., 2010; Zhang et al., 2010; Yang et al., 2013; Xu et al., 2014)。在塔里木大火成岩省内,目前已发现

并正在开采的瓦吉里塔格和普昌两处大型铁钛氧化物矿床。此外,近年来在瓦吉里塔格岩体北约 50 km 的小海子浅覆盖地区探获大型的钒钛磁铁矿,表明塔里木大火成岩省铁钛氧化物矿床资源潜力巨大(李立兴等, 2024; 薛胜超等, 2025)。

大火成岩省相关的中酸性岩浆成因多样,主要包括:①地幔柱产生大量镁铁质岩浆,在特定条件下通过 AFC 过程可分异出中酸性岩浆(Zhong et al., 2009; Shellnutt et al., 2010; Wei et al., 2014a);②地幔柱热烘烤并诱发先前被俯冲组分(沉积物/洋壳)富集过的岩石圈地幔发生部分熔融,进而形成中酸性岩浆(Xu et al., 2008);③镁铁质岩浆与酸性岩浆之间不同程度混合,也可形成一系列过渡类型的岩浆(Luo et al., 2007)。前人对塔里木西北缘瓦吉里塔格镁铁-超镁铁质岩的

成因及铁钛氧化物成矿过程进行了系统研究(Zhang et al., 2016; Cao et al., 2017; Zhu et al., 2021),但对于相关的中酸性岩的研究相对薄弱。因此,需要进一步加强对瓦吉里塔格中酸性岩的成因研究,其研究成果将有助于更全面地认识塔里木大火成岩省的岩浆演化过程及深部地球动力学机制。

1 区域地质背景

位于中国西北部的塔里木克拉通,其北部与天山造山带(中亚造山带的组成部分)接壤,南邻昆仑造山带和阿尔金造山带(属特提斯构造域)(图1)。塔里木克拉通主要由前寒武纪变质结晶基底和上覆的沉积盖层组成,具典型的双层结构(Han et al., 2011; Zhang et al., 2013; Wei et al., 2014b)。由于大部分地区被塔

克拉玛干大沙漠所覆盖,其前寒武纪结晶基底主要在盆地边缘的库鲁克塔格、敦煌、阿克苏、铁克里克、阿尔金等地区出露(Lu et al., 2008; 葛荣峰等, 2024)。塔里木克拉通基底主要由太古宙英云闪长质-奥长花岗质-花岗闪长质(TTG)片麻岩和角闪岩、古元古代晚期-新元古代早期海相火山岩-沉积岩以及新元古代晚期变质的火山碎屑岩及冰川沉积物组成,其上不整合覆盖寒武系到二叠系、新生界的碎屑岩、碳酸盐岩等沉积地层(Long et al., 2010; Tian et al., 2010; 杨树锋等, 2014; Sun et al., 2023)。

塔里木大火成岩省位于塔里木克拉通西北缘,被认为是塔里木克拉通地质历史中岩浆活动最为强烈,影响范围最为广泛的一期构造热事件(Zhang et al., 2010),主要由大面积的早二叠世大陆溢流玄武岩、镁铁-超镁铁质岩、正长岩、花岗岩及少量粗面岩和流

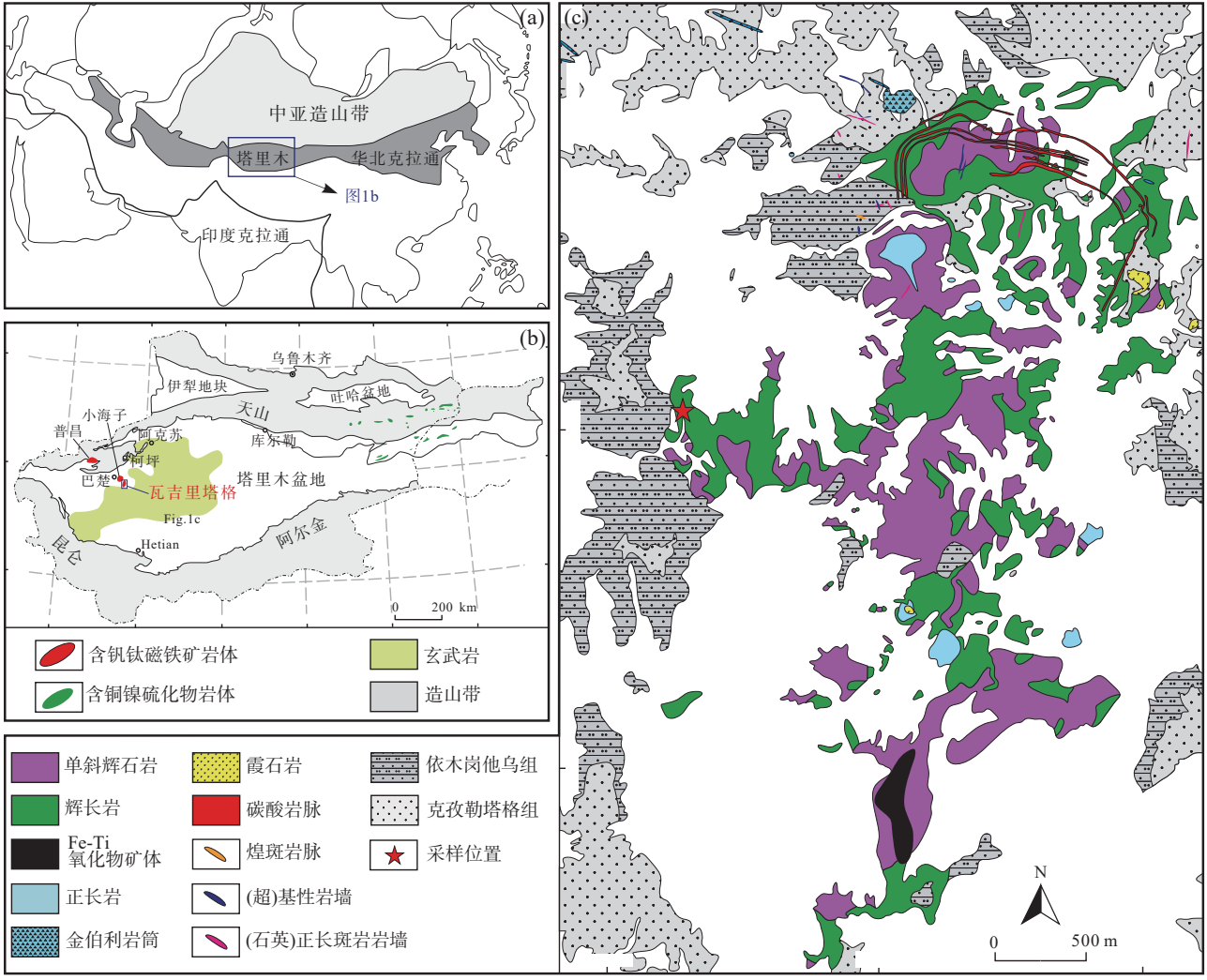


图1 塔里木克拉通西北缘瓦吉里塔格杂岩体地质简图(据 Zhu et al., 2021)

Fig. 1 Geological map of the Wajilitag intrusion in the northwestern margin of the Tarim Craton

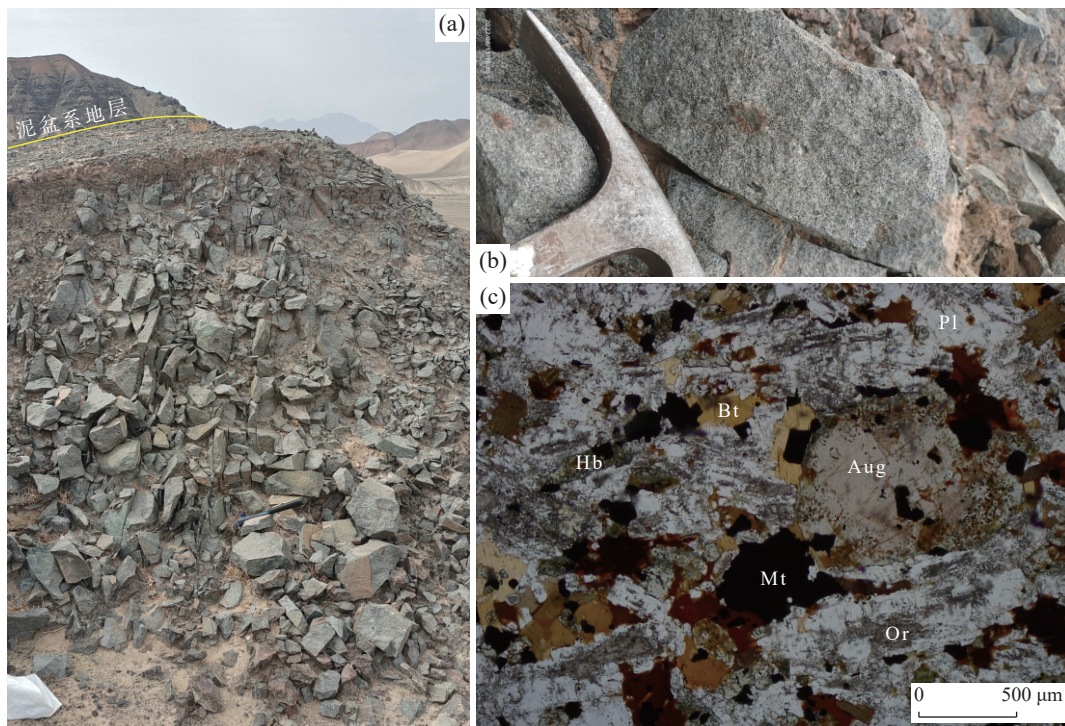
纹岩组成(陈汉林等, 1997; Xu et al., 2014; 杨树锋等, 2014; Wang et al., 2025)。塔里木大火成岩省具有多期次岩浆活动特征, 主要包括: ①约 300 Ma 的地幔柱活动最初响应期, 以金伯利岩(方解霞黄煌岩)为代表; ②约 290 Ma 主体形成期, 以大陆溢流玄武岩及少量长英质火山岩为代表; ③约 280 Ma 的晚期岩浆活动期, 以瓦吉里塔格、普昌、小海子等镁铁-超镁铁质岩体为代表(Xu et al., 2014; Cheng et al., 2017; 李立兴等, 2024)。根据野外露头、地震剖面及油田钻井资料显示, 塔里木大陆溢流玄武岩分布面积可达 30 万 km² 或更大, 累积厚度从数十米至千米以上(Tian et al., 2010; 杨树锋等, 2014), 全岩组分显示主体为碱性高钛玄武岩(Li et al., 2012)。

瓦吉里塔格杂岩体位于塔里木西北缘的巴楚隆起区, 岩体呈盆状, 长约为 5 km, 宽为 1.5~3 km, 厚为 0.11~0.27 km, 出露面积约为 12 km², 区内出露地层主要为泥盆纪依木岗他乌组和克孜勒塔格组。瓦吉里塔格杂岩体主要由金伯利岩筒(方解霞黄煌岩)、镁铁-超镁铁质层状岩体、碳酸岩脉、煌斑岩脉、霞石岩、正长岩等组成(图 1)。镁铁-超镁铁质层状岩体是瓦吉里塔格杂岩体的主体组成部分, 总体上岩体下部为

橄榄辉石岩相、中部为辉石岩相、顶部为辉长岩相, 钒钛磁铁矿主要赋存于辉石岩相中, 呈浸染状和极少量致密块状, 平均品位为约 20% FeO^t, 7% TiO₂, 0.14% V₂O₅, 达到大型规模(高玉山, 2007; Cao et al., 2014)。锆石 U-Pb 定年结果显示辉石岩与辉长岩的年龄在误差范围内一致, 为 284~280 Ma(Zhang et al., 2016; Zhu et al., 2021)。

2 岩石学特征

本次研究样品采集于瓦吉里塔格杂岩体边部, 其侵入至近水平产出的泥盆系依木岗他乌组砂岩内(图 2a)。岩石整体新鲜, 呈灰白色, 具块状构造、细粒结构(图 2b), 主要由斜长石(45%~55%)、正长石(5%~15%)、黑云母(10%~20%)、普通辉石(5%~15%)、普通角闪石(5%~15%)等组成(图 2c)。斜长石呈宽板状, 为自形晶-半自形晶, 薄片无色, 局部可见绢云母化, 正低突起, 干涉色 I 级灰白, 常见聚片双晶。正长石, 无色, 部分遭受蚀变表面浑浊, 显土灰色, 负低突起, I 级灰白干涉色, 可见卡斯巴双晶, 部分高岭土化。黑云母呈片状, 具有一组极完全解理, 单偏光



Pl.斜长石; Or.正长石; Aug.普通辉石; Hb.普通角闪石; Bt.黑云母; Mt.磁铁矿

图2 瓦吉里塔格黑云母二长闪长岩野外及镜下显微照片

Fig. 2 Field outcrop characteristics and microscopic photos of the Wajilitag biotite monzodiorite

下深褐-浅褐色显著多色性,包裹锆石、磷灰石的细小矿物包裹体。普通辉石,短柱状或粒状,自形晶,横切面呈近正方形或八边形,淡绿色,多色性不明显,正高突起,干涉色 II 级蓝绿。普通角闪石呈长柱状、浅绿色-浅黄色多色性,正中突起,干涉色为 II 级蓝绿。笔者对 WT-42 号样品采用自动矿物分析系统(TIMA)进行了面扫描,并精确确定了矿物含量(图 3),采用 QAP 图解综合确定该岩石为黑云母二长闪长岩。

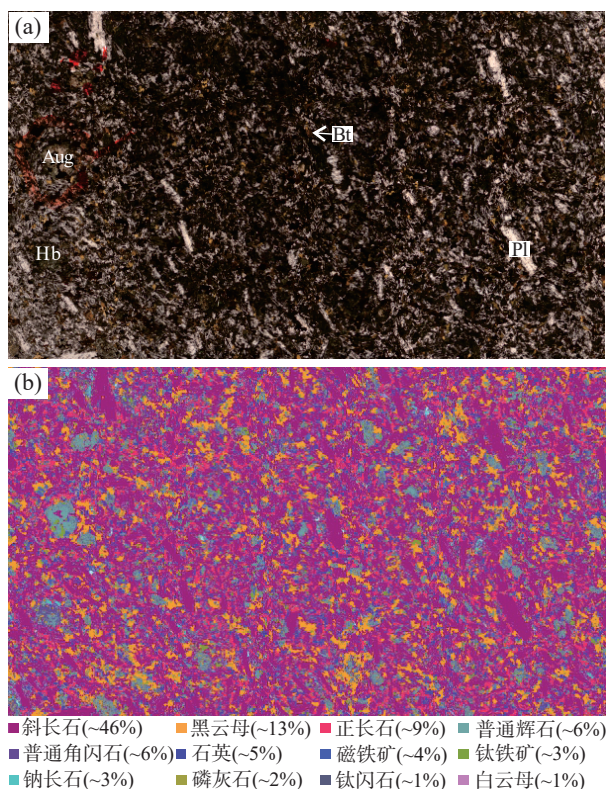


图3 瓦吉里塔格黑云母二长闪长岩(WT-42)TIMA 相图
(矿物代号同图 2)

Fig. 3 TIMA mineral phases map of the Wajilitag biotite monzonite (sample no. WT-42)

3 测试方法

岩相学分析在长安大学成矿作用及其动力学实验室的 TESCAN Integrated Mineral Analyzer (TIMA) 完成。首先对待测样品进行镀碳处理后置于 TESCAN MIRA3 场发射扫描电镜内完成扫描。实验条件:加速电压 25 kV, 电流 9 nA, 工作距离 15 mm。测试中采用的数据采集模式为点阵模式,分析模式为解离分析模式以获取 BSE 图和 EDS 能谱数据(陈倩等, 2021)。

全岩主、微量元素分析在长安大学成矿作用及其

动力学实验室完成。主量元素分析首先将适量粉末样品与无水四硼酸锂、氟化锂、硝酸铵混合均匀并烧制成碱熔玻璃片,然后使用 XRF-1800 型 X 射线荧光光谱仪对其进行分析,分析误差小于 5%(王建其等, 2016)。全岩微量及稀土元素分析时先将 50 mg 样品置于 Toflon 溶样弹中,加混合酸溶解后,使用美国热电 X-7 型电感耦合等离子体质谱仪(ICP-MS)分析完成,测试过程中使用 BHVO-1、BCR-2、AGV-1 等国际标准参考物质作为监控,分析误差小于 10%(Tan et al., 2020)。

锆石原位 U-Pb 测年在长安大学成矿作用及其动力学实验室完成。实验中使用 Agilent 7700X 四极杆等离子体质谱和 Photo Machines Analyte Excite 193 nm 激光,在激光频率为 5 Hz,束斑直径为 35 μm 条件下完成分析,用国际标准锆石 91500 和玻璃标准物质 NIST610 作为外标,进行同位素及微量元素校正,具体分析过程见栾燕等(2019)。数据处理采用 ICPMSDataCal 软件和 IsoplotR 完成(Liu et al., 2010; Vermeesch, 2018)。

锆石原位 Lu-Hf 同位素分析在西北大学大陆演化与早期生命全国重点实验室进行。实验使用 193 nm 准分子激光剥蚀系统(RESOLUTION M-50, ASI)和多接收等离子体质谱仪(Nu Plasma II MC-ICPMS)。在分析过程中,激光能量密度为 6 J/cm²,频率为 6 Hz,斑束为 53 μm ,高纯氦气为载气,以国际标准锆石样品 GJ-1 和 Mudtank 作为监控样品,详细的分析方法和仪器参数见 Yuan et al.(2008)和 Bao et al.(2023)。

4 分析结果

4.1 锆石 U-Pb 定年

本次对从瓦吉里塔格黑云母二长闪长岩样品(编号: WT-44)中挑选的 32 颗锆石进行了 LA-ICP-MS 锆石 U-Pb 定年测试(表 1)。黑云母二长闪长岩中锆石无色透明,呈自形-半自形,柱状,长 80~120 μm ,长宽比 2:1~3:1,无分带或弱分带,部分颗粒可见窄的增生边。锆石 Th 和 U 含量分别为 $200 \times 10^{-6} \sim 1281 \times 10^{-6}$ 和 $184 \times 10^{-6} \sim 601 \times 10^{-6}$, Th/U 为 0.92~2.18,显示岩浆锆石特征(Hoskin et al., 2003; 吴元保等, 2004)。31 颗锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄介于 270~286 Ma,加权平均年龄为 $(277.9 \pm 1.5) \text{ Ma}$ (MSWD=0.85; 图 4),该年龄代表黑云母二长闪长岩的形成时代。

表 1 瓦吉里塔格黑云母二长闪长岩锆石 U-Pb 同位素分析结果

Tab. 1 Analysis results of zircon U-Pb isotopic data for the Wajilitag biotite monzodiorite

样品号	元素含量 (10^{-6})		Th/U	同位素比值						年龄 (Ma)					
	Th	U		$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ
WT44-01	1 101	582	1.9	0.052 1	0.002 8	0.320 0	0.015 2	0.044 6	0.000 9	287.1	122.2	281.9	11.7	281.1	5.5
WT44-02	521	330	1.6	0.057 3	0.002 7	0.350 2	0.016 8	0.043 9	0.000 6	501.9	108.3	304.8	12.6	277.0	3.7
WT44-03	299	213	1.4	0.057 7	0.003 3	0.352 2	0.019 5	0.044 2	0.000 7	516.7	125.9	306.4	14.6	279.0	4.1
WT44-04	390	256	1.5	0.057 8	0.002 7	0.350 3	0.015 9	0.043 8	0.000 6	520.4	110.2	304.9	12.0	276.3	3.7
WT44-05	1 128	601	1.9	0.055 9	0.002 2	0.343 7	0.012 6	0.044 4	0.000 6	450.0	85.2	300.0	9.6	279.8	3.4
WT44-06	662	396	1.7	0.053 8	0.002 7	0.325 0	0.015 5	0.043 7	0.000 7	361.2	111.1	285.7	11.9	275.6	4.4
WT44-07	483	327	1.5	0.058 3	0.003 3	0.355 8	0.019 3	0.044 3	0.000 6	542.6	124.1	309.1	14.5	279.7	3.9
WT44-08	1 153	577	2.0	0.054 2	0.002 2	0.335 9	0.014 4	0.044 7	0.000 7	388.9	97.2	294.0	11.0	281.8	4.0
WT44-09	271	257	1.1	0.059 8	0.003 0	0.364 2	0.019 2	0.044 1	0.000 7	594.5	111.1	315.3	14.3	278.0	4.6
WT44-10	1 281	587	2.2	0.057 1	0.002 5	0.350 9	0.014 5	0.044 7	0.000 6	494.5	94.4	305.4	10.9	281.6	3.7
WT44-11	472	337	1.4	0.057 2	0.003 1	0.338 5	0.018 2	0.043 0	0.000 7	498.2	120.4	296.0	13.8	271.4	4.5
WT44-12	503	356	1.4	0.055 1	0.003 2	0.330 5	0.018 8	0.043 6	0.000 7	416.7	127.8	289.9	14.3	275.2	4.1
WT44-13	273	238	1.1	0.056 5	0.002 9	0.341 8	0.017 1	0.044 1	0.000 7	472.3	114.8	298.6	12.9	278.4	4.2
WT44-14	571	374	1.5	0.058 0	0.003 4	0.338 0	0.018 4	0.042 7	0.000 8	531.5	127.8	295.7	14.0	269.7	5.0
WT44-15	244	192	1.3	0.052 2	0.006 1	0.303 8	0.037 6	0.041 9	0.000 9	300.1	69.4	269.4	29.3	264.6	5.8
WT44-16	753	451	1.7	0.056 4	0.003 3	0.336 5	0.020 7	0.043 2	0.000 9	477.8	123.1	294.5	15.8	272.7	5.4
WT44-17	822	472	1.7	0.057 9	0.002 6	0.360 3	0.015 5	0.045 3	0.000 7	527.8	100.0	312.4	11.6	285.6	4.2
WT44-18	463	340	1.4	0.056 6	0.003 3	0.333 5	0.019 0	0.042 8	0.000 6	476.0	129.6	292.2	14.5	270.2	3.7
WT44-19	210	184	1.1	0.058 2	0.003 8	0.353 4	0.023 0	0.044 3	0.000 8	600.0	146.3	307.3	17.2	279.3	5.0
WT44-20	364	254	1.4	0.056 3	0.002 7	0.344 7	0.017 9	0.044 2	0.000 7	464.9	107.4	300.7	13.5	278.7	4.3
WT44-21	504	351	1.4	0.053 6	0.002 1	0.325 2	0.013 8	0.043 9	0.000 7	353.8	88.9	285.9	10.5	276.8	4.6
WT44-22	558	371	1.5	0.050 9	0.002 3	0.302 6	0.012 2	0.043 4	0.000 6	239.0	103.7	268.5	9.5	274.1	3.9
WT44-23	1 074	583	1.8	0.056 7	0.002 4	0.351 6	0.016 1	0.044 6	0.000 6	479.7	94.4	305.9	12.1	281.3	3.9
WT44-24	854	463	1.8	0.055 1	0.002 5	0.344 6	0.016 2	0.045 2	0.000 8	416.7	103.7	300.6	12.2	284.9	5.2
WT44-25	886	496	1.8	0.054 1	0.004 3	0.328 4	0.024 4	0.044 1	0.001 1	376.0	179.6	288.4	18.6	278.2	6.8
WT44-26	314	234	1.3	0.056 2	0.004 0	0.346 4	0.026 0	0.044 1	0.000 8	461.2	156.5	302.0	19.6	278.0	4.8
WT44-27	350	248	1.4	0.053 3	0.003 7	0.317 3	0.021 5	0.043 2	0.000 8	342.7	155.5	279.8	16.6	272.6	4.9
WT44-28	200	219	0.9	0.065 5	0.005 7	0.394 0	0.032 9	0.043 7	0.000 9	790.7	184.1	337.3	23.9	275.5	5.4
WT44-29	421	279	1.5	0.058 0	0.005 6	0.350 7	0.033 8	0.044 1	0.000 9	527.8	212.9	305.2	25.4	278.1	5.6
WT44-30	762	417	1.8	0.059 0	0.002 7	0.370 4	0.017 0	0.045 0	0.000 7	568.6	100.0	320.0	12.6	284.0	4.3
WT44-31	505	336	1.5	0.052 5	0.003 3	0.321 7	0.020 3	0.043 8	0.000 8	309.3	147.2	283.2	15.6	276.0	5.2
WT44-32	723	457	1.6	0.062 3	0.004 1	0.386 8	0.024 8	0.044 8	0.000 9	687.1	140.7	332.0	18.2	282.6	5.6

4.2 岩石地球化学

4.2.1 主量元素

瓦吉里塔格黑云母二长闪长岩样品的 SiO_2 含量

较低, 为 52.14%~53.50%, 位于基性岩与中性岩 SiO_2 含量分界线附近; CaO 含量为 6.87%~7.24%; Al_2O_3 含量为 15.56%~15.83%; Na_2O 含量为 4.37%~4.64%,

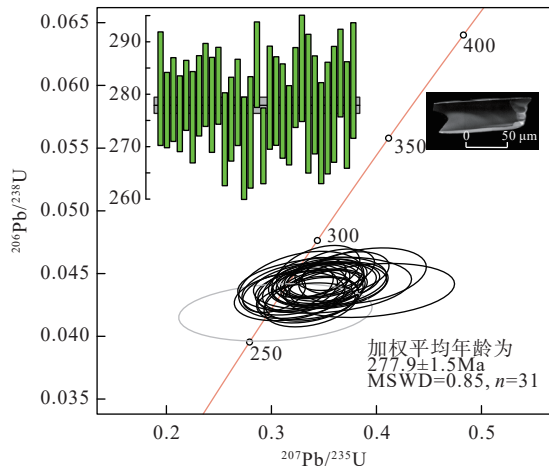


图4 瓦吉里塔格黑云母二长闪长岩(WT-44)代表性锆石阴极发光及 U-Pb 年龄谐和图

Fig. 4 Representative zircon cathodoluminescence image and U-Pb concordia diagram for the Wajilitag biotite monzodiorite (sample no. WT-44)

K₂O 含量为 2.75%~3.04%, Na₂O+K₂O 含量为 7.26%~7.60%; Mg[#] 值为 39~40(表 2)。在 TAS 图解中, 所有样品均落入二长闪长岩区域(图 5a); 在 SiO₂-K₂O 图解

中, 落在钾玄岩系列(图 5b)。

4.2.2 微量及稀土元素

瓦吉里塔格黑云母二长闪长岩样品稀土总量(ΣREEs)较高, 为 339×10⁻⁶~367×10⁻⁶(表 2)。球粒陨石标准化稀土配分图解显示显著的轻稀土富集, 重稀土亏损模式(图 6a), (La/Yb)_N 值为 17.10~18.45, 轻、重稀土内部也具有一定的分馏, (La/Sm)_N 值为 2.98~3.16, (Gd/Yb)_N 值为 2.67~2.77; 弱的 Eu 正异常, δEu 值为 1.10~1.18(表 2)。

在原始地幔标准化微量元素蛛网图中, 瓦吉里塔格黑云母二长闪长岩富集大离子亲石元素 Ba、Pb 等, 高场强元素 Nb, Ta, Zr, Hf 等含量高, 无 Nb、Ta 负异常(图 6b), 显示与 OIB 一致的地球化学特征。

4.3 锆石 Hf 同位素

此次在瓦吉里塔格黑云母二长闪长岩锆石 U-Pb 定年的位置或其附近同时测定锆石 Hf 同位素组成。锆石 Hf 同位素组成显示初始 ¹⁷⁶Hf/¹⁷⁷Hf 值为 0.282 463~0.282 548, 相应的 ε_{Hf}(t) 值为 -1.8~-4.4(表 3, 图 7), 单阶段和两阶段模式年龄分别为 992~1 130 Ma 和 1 414~1 605 Ma。

表 2 瓦吉里塔格黑云母二长闪长岩主(%)、微量元素(10⁻⁶)分析结果

Tab. 2 Analysis results of major (%) and trace (10⁻⁶) elements composition for the Wajilitag biotite monzodiorite

样品号	WT-38	WT-39	WT-40	WT-41	WT-42	WT-43
SiO ₂	53.08	52.14	52.59	53.50	52.38	52.16
TiO ₂	2.32	2.30	2.31	2.25	2.31	2.25
Al ₂ O ₃	15.69	15.78	15.68	15.83	15.68	15.56
Fe ₂ O ₃ ^T	10.22	10.49	10.14	9.99	10.44	10.21
MnO	0.17	0.17	0.17	0.16	0.17	0.16
MgO	3.36	3.40	3.39	3.26	3.41	3.36
CaO	6.87	7.24	7.03	6.93	7.22	7.12
Na ₂ O	4.37	4.64	4.56	4.47	4.47	4.60
K ₂ O	2.89	2.75	3.04	2.87	2.92	2.91
P ₂ O ₅	0.89	0.91	0.91	0.89	0.92	0.90
LOI	0.26	0.08	0.22	0.07	0.04	0.07
TOTAL	100.12	99.90	100.04	100.22	99.96	99.30
Mg [#]	40	39	40	39	40	40
Na ₂ O+K ₂ O	7.26	7.39	7.60	7.34	7.39	7.51
Li	8.40	7.42	7.90	7.15	7.12	7.17
Be	2.71	2.35	2.63	2.58	2.45	2.58
Sc	8.41	8.14	7.52	7.78	7.51	9.75
V	141	138	134	135	134	140
Cr	6.73	4.84	4.25	4.73	4.10	5.04
Co	51.5	46.6	49.2	71.0	45.3	52.1
Ni	6.82	6.92	4.33	4.97	4.72	4.91

续表 2

样品号	WT-38	WT-39	WT-40	WT-41	WT-42	WT-43
Cu	13.1	13.5	9.01	6.02	7.37	7.18
Zn	147	142	143	140	138	150
Ga	24.3	24.1	23.1	23.1	23.1	25.7
Rb	30.0	22.6	29.6	27.2	32.4	34.3
Sr	935	970	885	900	911	951
Y	42.2	41.2	39.6	41.7	37.7	41.5
Zr	451	409	388	402	411	428
Nb	73.3	69.4	70.7	71.6	70.6	75.6
Mo	3.33	2.86	3.01	2.99	2.87	2.99
Sn	3.24	3.32	3.15	3.58	3.60	3.40
Ba	1 007	1 094	921	887	941	983
La	69.1	68.4	66.0	66.2	67.1	72.8
Ce	146	141	140	140	142	151
Pr	17.4	17.1	16.4	16.6	16.8	17.9
Nd	77.0	75.9	72.7	74.2	74.5	78.4
Sm	14.6	14.6	14.0	14.4	14.3	14.9
Eu	4.25	4.43	4.14	4.16	4.05	4.28
Gd	9.16	9.11	8.96	9.00	8.89	9.36
Tb	1.64	1.60	1.56	1.60	1.56	1.65
Dy	8.18	8.07	7.76	8.07	7.82	8.18
Ho	1.48	1.46	1.40	1.45	1.40	1.49
Er	3.53	3.46	3.38	3.52	3.35	3.57
Tm	0.47	0.45	0.45	0.46	0.44	0.47
Yb	2.84	2.72	2.69	2.78	2.68	2.83
Lu	0.38	0.36	0.36	0.36	0.35	0.37
Hf	9.72	8.53	8.58	8.68	8.97	9.49
Ta	4.34	3.83	4.21	4.55	4.09	4.52
Pb	9.81	8.86	9.16	8.51	8.87	8.94
Th	10.2	7.61	9.89	9.51	7.14	9.83
U	1.71	1.56	1.80	1.69	1.63	1.80
Σ REEs	356	349	339	343	345	367
δ Eu	1.12	1.18	1.13	1.12	1.10	1.11
(La/Yb) _N	17.46	18.03	17.61	17.10	17.97	18.45
(La/Sm) _N	3.05	3.03	3.05	2.98	3.02	3.16
(Gd/Yb) _N	2.67	2.77	2.76	2.68	2.75	2.74

5 讨论

5.1 岩石成因

稀土元素(REE)及铌(Nb)、钽(Ta)、锆(Zr)、铪(Hf)等高场强元素的化学性质稳定,且不易受蚀变和变质作用改造,可作为指示源区性质和岩石成因的有效示踪剂(Depaolo, 1981; Dupuy et al., 1992; 李永生等,

2011; Kirchenbaur et al., 2015)。瓦吉里塔格黑云母二长闪长岩的 Nb/Ta 值为 15.76~18.15, 平均值为 16.93, 与 OIB(Nb/Ta=17.8)类似, 而与大陆地壳(Nb/Ta=11)明显不同(Green, 1995; 吴福元等, 2017)。Nb/U、Nb/La 值可作为判别地壳混染的标志(Taylor et al., 1985)。瓦吉里塔格黑云母二长闪长岩的 Nb/La 值为 1.01~1.08, 平均值 1.05, 显著高于地壳的平均值 0.5; 黑云母二长闪长岩的 Nb/U 值为 39.40~44.58, 平均值为 42.44,

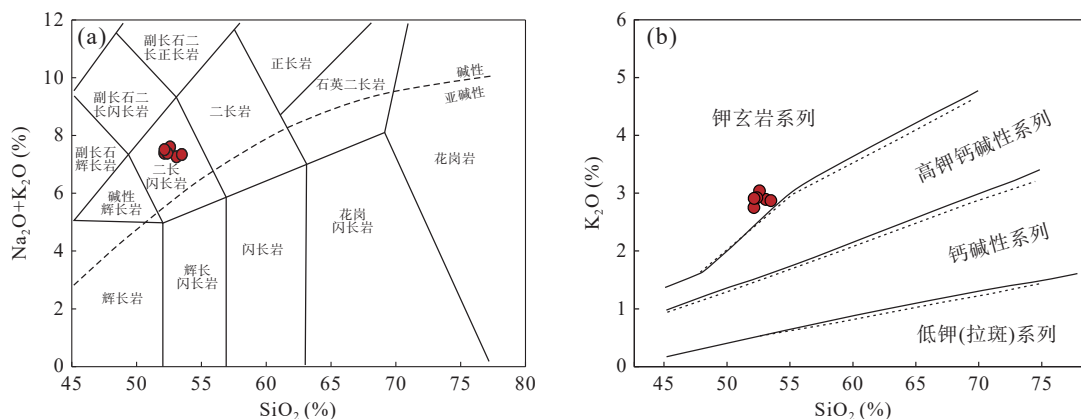


图5 TAS 岩石分类命名图(a)(底图据 Irvine et al., 1971; Middlemost, 1994)及 SiO_2 - K_2O 图(b)(底图据 Middlemost, 1994)

Fig. 5 Diagrams of (a) TAS and (b) SiO_2 - K_2O

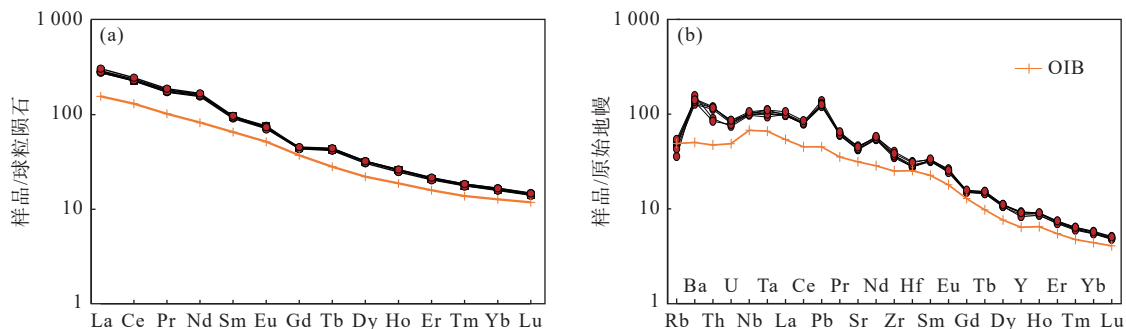
略低于洋中脊玄武岩和洋岛玄武岩 Nb/U 值(47 ± 10), 而显著高于大陆地壳值(8.93)。此外, 黑云母二长闪长岩的 Ba/Nb 值为 12.4~15.8, 平均值为 13.5, 略高于地幔平均值(9.0), 而显著低于地壳标准值(54.0); 黑云母二长闪长岩的 Th/Nb 值为 0.10~0.14, 平均值为 0.13, 也类似 OIB(0.08), 而显著低于大陆地壳(0.7; Sun et al., 1989)。综上所述, 地球化学数据表明瓦吉里塔格黑云母二长闪长岩的母岩浆来自地幔且在上升过程中未受到地壳污染或地壳混染弱。

稀土元素 Dy/Yb 是判断源区特征的重要地球化学指标, 如果部分熔融发生在石榴子石稳定区, 其熔体的 Dy/Yb 值大于 2.5, 如果熔融作用发生在尖晶石稳定区, 其熔体的 Dy/Yb 值小于 1.5(Jiang et al., 2013)。瓦吉里塔格黑云母二长闪长岩的 Dy/Yb 值为 2.88~2.96, 平均值为 2.91, 高的 Dy/Yb 值指示部分熔融发生在石榴子石稳定区。此外, 由于重稀土元素在石榴子石中分配系数大, 而中稀土元素在角闪石中分配系数大, 当源区残留石榴子石时, 形成的熔体 HREE 配分

模式为右倾型, Y/Yb 值明显大于 10, 甚至接近 20; 而当源区残留角闪石时, 形成的熔体 HREE 配分模式为平坦型, Y/Yb 值接近 10(Sisson, 1994; 葛小月等, 2002)。瓦吉里塔格黑云母二长闪长岩 HRRE 内部分馏显著, 呈右倾型, Y/Yb 值为 14.07~15.13, 平均值为 14.75, 显著大于 10, 也指示源区石榴子石残留。由于具有高的单斜辉石/石榴子石值的富单斜辉石岩源区能够产生相对恒定的 Sm/Sr 值的熔体(Ren et al., 2004; 曹俊等, 2025), 瓦吉里塔格黑云母二长闪长岩 Sm/Sr 值为 0.015~0.016, 稳定的 Sm/Sr 值指示地幔源区残留矿物相主要为单斜辉石和石榴子石。此外, 瓦吉里塔格黑云母二长闪长岩的稀土配分模式显示弱的正 Eu 异常, 指示源区无明显的斜长石残留。因此, 根据源区富含单斜辉石、石榴子石, 而无斜长石的矿物组合特点, 综合推测源区残留相应为榴辉岩组分。

5.2 与塔里木溢流玄武岩的联系

大火成岩省中镁铁-超镁铁质侵入岩与大陆溢流玄武岩之间往往存在成因上的联系, 相同或相似的年



球粒陨石和原始地幔数据引自 Sun et al. (1989)

图6 球粒陨石标准化稀土配分模式图(a)和原始地幔标准化微量元素蛛网图(b)

Fig. 6 (a) Chondrite-normalized REE pattern and (b) primitive mantle-normalized trace element spider diagrams

表 3 瓦吉里塔格黑云母二长闪长岩锆石 Hf 同位素分析结果

Tab. 3 Analysis results of zircon Hf isotope composition for the Wajilitag biotite monzodiorite

分析点	¹⁷⁶ Yb/ ¹⁷⁷ Hf	¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Hf/ ¹⁷⁷ Hf	2σ	(¹⁷⁶ Hf/ ¹⁷⁷ Hf) _i	εHf(0)	εHf(<i>t</i>)	T _{DM1} (Ma)	T _{DM2} (Ma)	f _(Lu/Hf)
WT44@02	0.057 012	0.001 606	0.282 556	0.000 048	0.282 548	-7.6	-1.8	1 000	1 414	-0.95
WT44@04	0.049 228	0.001 402	0.282 551	0.000 036	0.282 543	-7.8	-2.0	1 003	1 425	-0.96
WT44@06	0.063 764	0.001 700	0.282 514	0.000 040	0.282 505	-9.1	-3.3	1 064	1 511	-0.95
WT44@07	0.047 553	0.001 369	0.282 493	0.000 033	0.282 486	-9.9	-4.0	1 084	1 554	-0.96
WT44@08	0.072 806	0.002 035	0.282 513	0.000 033	0.282 502	-9.2	-3.4	1 075	1 517	-0.94
WT44@10	0.094 815	0.002 627	0.282 488	0.000 048	0.282 475	-10.0	-4.4	1 128	1 578	-0.92
WT44@11	0.035 918	0.001 093	0.282 553	0.000 044	0.282 547	-7.8	-1.9	992	1 417	-0.97
WT44@12	0.052 176	0.001 404	0.282 542	0.000 039	0.282 535	-8.1	-2.3	1 015	1 443	-0.96
WT44@13	0.044 007	0.001 085	0.282 537	0.000 035	0.282 531	-8.3	-2.4	1 014	1 451	-0.97
WT44@16	0.046 647	0.001 325	0.282 517	0.000 041	0.282 510	-9.0	-3.1	1 048	1 499	-0.96
WT44@17	0.088 488	0.002 242	0.282 518	0.000 035	0.282 506	-9.0	-3.3	1 074	1 508	-0.93
WT44@19	0.039 230	0.001 173	0.282 525	0.000 032	0.282 519	-8.7	-2.8	1 033	1 479	-0.96
WT44@20	0.049 804	0.001 272	0.282 527	0.000 028	0.282 520	-8.7	-2.8	1 034	1 477	-0.96
WT44@21	0.038 142	0.001 072	0.282 547	0.000 030	0.282 541	-8.0	-2.0	999	1 429	-0.97
WT44@23	0.082 554	0.001 937	0.282 473	0.000 032	0.282 463	-10.6	-4.8	1 130	1 605	-0.94
WT44@24	0.064 567	0.001 796	0.282 484	0.000 031	0.282 475	-10.2	-4.4	1 109	1 577	-0.95

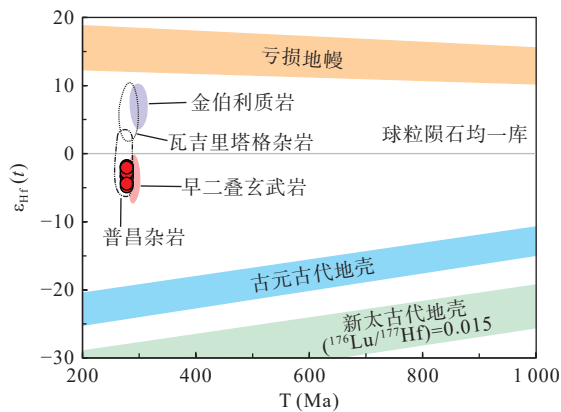


图7 瓦吉里塔格黑云母二长闪长岩(WT-44)锆石 Hf 同位素图解(底图据 Zhang et al., 2016)

Fig. 7 Zircon $\epsilon_{\text{Hf}}(t)$ versus U-Pb age diagram for the Wajilitag biotite monzodiorite (sample no. WT-44)

代学及地球化学特征, 指示其来自地幔柱相关的共同地幔源区, 如攀西的峨眉山玄武岩被认为是下部成矿岩浆房结晶并卸载铁钛氧化物后喷出地表的残余岩浆(Bai et al., 2012; 宋谢炎等, 2018; 柏中杰等, 2024)。塔里木溢流玄武岩主要出露于盆地边缘, 以柯坪玄武岩为代表, 其形成年代峰期为约 290 Ma(Yu et al., 2011; Wei et al., 2014b); 而瓦吉里塔格镁铁-超镁铁质岩年龄(284~280 Ma; 曹俊, 2015; Zhang et al., 2016; Zhu et

al., 2021)及二长闪长岩年龄(277.5±1.5 Ma, 本文), 明显晚于塔里木溢流玄武岩, 因此瓦吉里塔格镁铁-超镁铁质层状岩体与塔里木溢流玄武岩, 虽然二者均与塔里木地幔柱有关, 但二者不可能为同一岩浆系统的演化产物。前人系统的 Sr-Nd-Hf 同位素地球化学研究显示瓦吉里塔格镁铁-超镁铁质岩源自亏损地幔源区, 而塔里木溢流玄武岩显示源自富集地幔源区, 二者是不同地幔源区的产物(张东阳, 2014; Zhang et al., 2016)。

本次研究的黑云母二长闪长岩位于瓦吉里塔格杂岩体的边部, 侵入围岩泥盆系地层内, 其形成年龄与瓦吉里塔格镁铁-超镁铁质层状的形成时代类似, 二者是否具有成因联系? 瓦吉里塔格黑云母二长闪长岩的锆石 Hf 单阶段模式年龄 992~1 130 Ma, 明显老于成岩年龄, 指示岩浆起源于富集的地幔源区或受到地壳物质混染(吴福元等, 2007)。前已述及, 瓦吉里塔格黑云母二长闪长岩受到的地壳混染较弱, 因此推测其源自富集地幔源区。瓦吉里塔格黑云母二长闪长岩具有与塔里木溢流玄武岩类似的锆石 Hf 同位素组成特征(图 7)。此外, 前人研究认为塔里木溢流玄武岩为碳酸盐化榴辉岩释放的熔体与地幔橄榄岩反应后部分熔融形成的母岩浆演化而成(程浩, 2024),

而瓦吉里塔格黑云母二长闪长岩源区残留相也显示为榴辉岩组分。因此,综合推测瓦吉里塔格黑云母二长闪长岩源自与塔里木溢流玄武岩一致的富集地幔源区,其与瓦吉里塔格镁铁-超镁铁质层状岩体虽年龄相近,但并不是同一母岩浆分异而成。

5.3 对塔里木大火成岩省深部过程的指示

塔里木克拉通北缘经历了新元古代 Rodinia 洋和早古生代南天山洋两期俯冲事件(Ge et al., 2012; Zhang et al., 2016; Wang et al., 2025; 曹俊等, 2025)。此外,塔里木克拉通南缘在早古生代晚期至中生代早期持续受到原特提斯洋和古特提斯洋的北向俯冲影响(Wang et

al., 2020; 曹俊等, 2025; 魏博等, 2025)。塔里木克拉通周缘广泛的洋壳俯冲可对地幔组成产生显著影响,且这些俯冲板片可能发生榴辉岩相变质及随后的熔体上升(Qu et al., 2011)。在 $(\text{Th}/\text{Nb})_{\text{PM}}-(\text{Nb}/\text{Zr})_{\text{PM}}$ 和 $(\text{Th}/\text{Nb})_{\text{PM}}-(\text{La}/\text{Zr})_{\text{PM}}$ 关系图中,瓦吉里塔格黑云母二长闪长岩主要落入 EMI 区域(图 8), 指示其母岩浆源区有近期俯冲再循环的海洋沉积物或洋壳物质加入。此外,瓦吉里塔格黑云母二长闪长岩具有相对低的 Th/Zr (0.017~0.026) 和高的 Nb/Zr (0.16~0.18) 值, 在 $\text{Th}/\text{Zr}-\text{Nb}/\text{Zr}$ 图解中(图 9), 显示其源区受到俯冲板片熔体的交代作用。

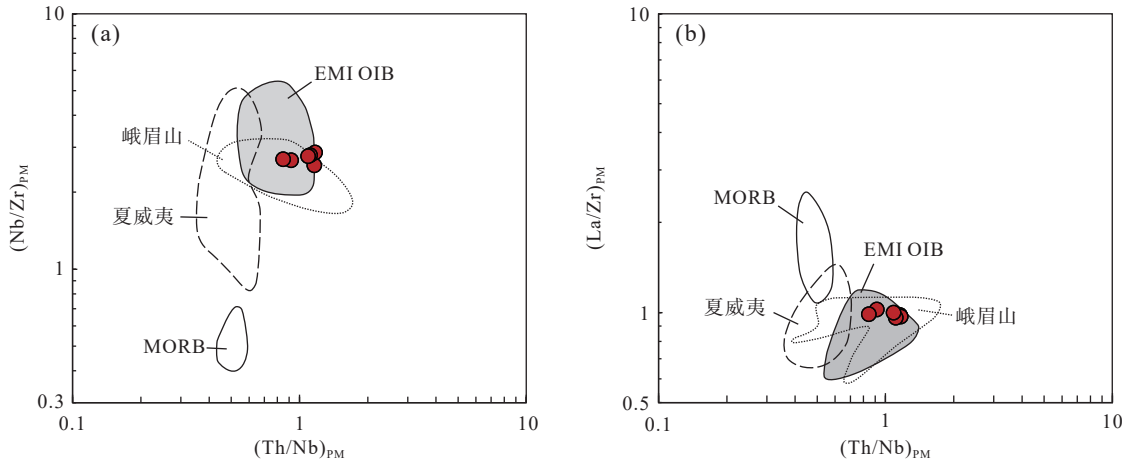


图8 瓦吉里塔格黑云母二长闪长岩的 $(\text{Th}/\text{Nb})_{\text{PM}}-(\text{Nb}/\text{Zr})_{\text{PM}}$ (a)和 $(\text{Th}/\text{Nb})_{\text{PM}}-(\text{La}/\text{Zr})_{\text{PM}}$ (b)关系图(底图据 Wei et al., 2014)

Fig. 8 (a) $(\text{Th}/\text{Nb})_{\text{PM}}-(\text{Nb}/\text{Zr})_{\text{PM}}$ and (b) $(\text{Th}/\text{Nb})_{\text{PM}}-(\text{La}/\text{Zr})_{\text{PM}}$ diagrams for the Wajilitag biotite monzodiorite

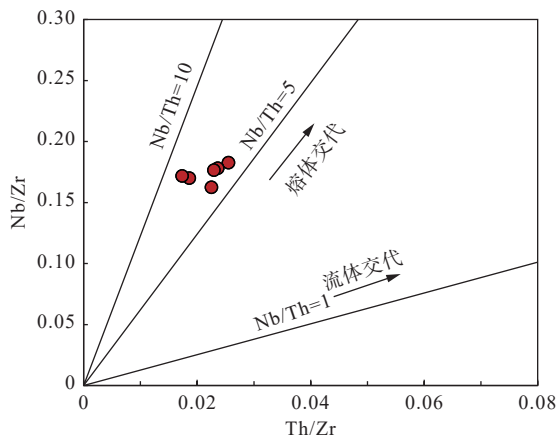


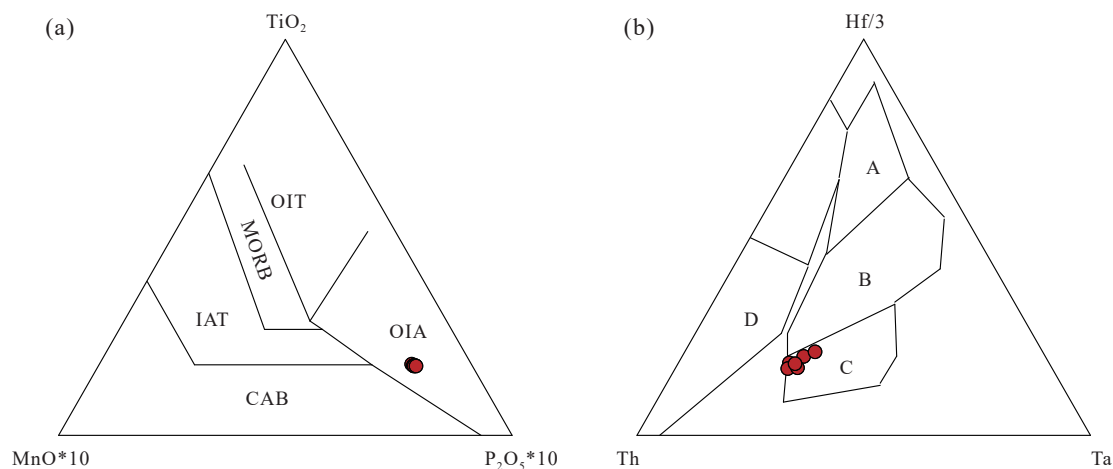
图9 瓦吉里塔格黑云母二长闪长岩的 $\text{Th}/\text{Zr}-\text{Nb}/\text{Zr}$ 图解(底图据 Zhao et al., 2007)

Fig. 9 $\text{Th}/\text{Zr}-\text{Nb}/\text{Zr}$ diagram of Wajilitag biotite monzodiorite

瓦吉里塔格黑云母二长闪长岩右倾的稀土配分模式,及无 Nb-Ta 负异常,低的 Ba/Nb(平均值为 13.5)、

高的 Nb/U 值(平均值为 42.44),以及轻微富集的锆石 Hf 同位素组成($\epsilon\text{Hf}(t)=-1.8\sim-4.4$)等地球化学特征,指示其起源于 OIB 型富集地幔源区,且未受到明显的地壳混染。在 $\text{MnO}-\text{TiO}_2-\text{P}_2\text{O}_5$ 构造环境判别图中瓦吉里塔格黑云母二长闪长岩样品主要落入板内玄武岩区域(图 10a); 在 $\text{Hf}-\text{Th}-\text{Ta}$ 三角图中,也全部落入板内碱性玄武岩区域(图 10b),均指示其形成于板内环境。结合区域地质背景,推测与塔里木地幔柱有关。

综合研究认为,塔里木克拉通周缘的俯冲事件使洋壳物质加入克拉通边缘的软流圈地幔,并且俯冲作用使洋壳发生高压相变形成榴辉岩,在二叠纪板内环境,塔里木地幔柱将其捕获并带入大陆岩石圈底部,这种榴辉岩组分参与的富集岩石圈地幔部分熔融形成瓦吉里塔格黑云母二长闪长岩组分,这表明俯冲板片与地幔柱相互作用对该类岩石形成具有重要控制作用。



A.N-type MORB; B.E-type MORB+板内拉斑玄武岩; C.板内碱性玄武岩; D.岛弧玄武岩

图10 瓦吉里塔格黑云母二长闪长岩的 $\text{MnO-TiO}_2\text{-P}_2\text{O}_5$ (a) (底图据 Mullen, 1983)和 Hf-Th-Ta (b) (底图据 Wood et al., 1979)构造环境判别图

Fig. 10 (a) $\text{MnO-TiO}_2\text{-P}_2\text{O}_5$ and (b) Hf-Th-Ta discrimination diagrams for the Wajilitag biotite monzodiorite

6 结论

(1) LA-ICP-MS 锆石 U-Pb 定年结果显示瓦吉里塔格黑云母二长闪长岩形成时代为 $(277.5 \pm 1.5)\text{Ma}$, 为早二叠世。

(2) 瓦吉里塔格黑云母二长闪长岩属钾玄武岩系列, 具有与 OIB 类似的地球化学特征, 指示其形成于板内环境。

(3) 瓦吉里塔格黑云母二长闪长岩锆石 Hf 同位素组成与塔里木大火成岩省溢流玄武岩类似, 推测为源自俯冲洋壳加入的富集岩石圈地幔部分熔融形成。

致谢: 本次研究在野外工作中得到了新疆维吾尔自治区地质局哈密地质大队刘振远工程师及长安大学地球科学与资源学院胡俊杰、袁宏典等研究生的帮助; 在测试过程中得到长安大学成矿作用及其动力学实验室王柱命、杜金花老师, 以及西北大学大陆演化与早期生命全国重点实验室包志安老师的指导; 两位匿名审稿人对文章提出诸多建设性的意见建议, 在此一并表示衷心感谢!

利益冲突声明 (Conflict of Interests):

所有作者声明不存在利益冲突。

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