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北祁连东段早古生代洋壳俯冲作用记录

——来自晚奥陶世高镁埃达克岩的证据

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摘要: 具有特殊成因机制的埃达克质岩石是探究深部岩浆动力学过程与区域构造演化的重要岩石探针之一。本文对北祁连造山带东段宁夏南华山地区出露的石洼里花岗岩进行了系统的锆石 U-Pb 年龄、主量-微量元素及锆石原位 Hf 同位素分析,以探讨其岩石成因及地球动力学意义。LA-ICP-MS 锆石 U-Pb 定年结果表明石洼里花岗岩侵位年龄为 452 ± 4 Ma, 为晚奥陶世岩浆活动的产物。岩石具有较高的 SiO_2 (68.60%~71.42%)、 Al_2O_3 (14.95%~15.75%) 和 Na_2O (5.06%~5.79%) 含量,较低的 K_2O (2.23%~3.10%)、 MgO (0.91%~1.73%) 含量和较高的 $\text{Mg}^\#$ 值 (55~59), 属弱过铝质钙碱性系列岩石; 岩石具有高 Ba (1.025×10^{-6} ~ 1.250×10^{-6})、Sr (324×10^{-6} ~ 577×10^{-6}) 和低 Y (6.99×10^{-6} ~ 7.69×10^{-6})、Yb (0.65×10^{-6} ~ 0.71×10^{-6}) 含量,较高的 Sr/Y (45~79) 和 (La/Yb)_N (17~31) 值,且无明显 Eu 负异常。锆石 $\varepsilon_{\text{Hf}}(t)$ 值相对较高,变化范围为 +0.5~+15.5。主量-微量元素及同位素分析结果表明石洼里花岗岩具有高镁埃达克岩的典型特征,可能是在 30~40 km 深度的岛弧基性下地壳部分熔融的产物,其源区中可能存在早古生代的新生地壳。结合区内蛇绿岩、高压变质岩、弧岩浆岩的研究成果,笔者认为受北祁连原特提斯洋北向俯冲影响,石洼里高镁埃达克岩形成于老虎山弧后盆地洋壳在晚奥陶世的南向俯冲过程中。

关键词: 高镁埃达克岩; 晚奥陶世; 洋壳俯冲; 原特提斯洋; 南华山; 石洼里花岗岩; 北祁连

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A record of Early Paleozoic subduction of oceanic crust in the eastern part of the North Qilian Mountains: Evidence from the Late Ordovician high-Mg adakites

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Abstract: With special genetic mechanisms, adakitic rock is one of the important rock probes for exploring the deep magmatic dynamic process and regional tectonic evolution. In this paper, zircon U-Pb age, major and trace elements

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and zircon in-situ Hf isotopes of the Shiwal granite from the eastern part of the North Qilian orogenic belt were systematically analyzed to explore its petrogenesis and geodynamics significance. LA-ICP-MS zircon U-Pb dating yields an emplacement age of 452 ± 4 Ma for the Shiwal granite, indicating a product of Late Ordovician magmatic activity. Bulk-rock analyses show that these rocks contain high SiO_2 (68.60% ~ 71.42%), Al_2O_3 (14.95% ~ 15.75%) and Na_2O (5.06% ~ 5.79%) contents, with low K_2O (2.23% ~ 3.10%) and MgO (0.91% ~ 1.73%) contents, and resultant high $\text{Mg}^\#$ value (55 ~ 59), belonging to the weak peraluminous and calc-alkaline series of rocks. These rocks have high concentrations of Ba (1.025×10^{-6} ~ 1.250×10^{-6}), Sr (324×10^{-6} ~ 577×10^{-6}) and low Y (6.99×10^{-6} ~ 7.69×10^{-6}), Yb (0.65×10^{-6} ~ 0.71×10^{-6}) contents, with high Sr/Y (45 ~ 79) and $(\text{La}/\text{Yb})_N$ (17 ~ 31) values, and no significant negative Eu anomalies. The $\varepsilon\text{Hf}(t)$ values of zircons are relatively high, with a range of +0.5 to +15.5. The geochemical and zircon Hf isotopic compositions of the Shiwal granites are similar to that of high-Mg adakites, which may be the product of partial melting of the basic lower crust of the island arc at a depth of 30 ~ 40 km, and there may be Early Paleozoic juvenile crust in the source area. Combined with the research results of ophiolites, high-pressure metamorphic rocks and arc magmatic rocks in the study area, we suggest that the Shiwal high-Mg adakitic granites might be generated during the southward subduction of the oceanic crust in the Laohushan back-arc basin in the Late Ordovician, which affected by the northward subduction of the North Qilian Proto-Tethys ocean.

Key words: high-Mg adakite; Late Ordovician; oceanic crust subduction; Proto-Tethys ocean; Nanhushan; Shiwal granite; North Qilian

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位于青藏高原东北缘的北祁连造山带被认为是原特提斯构造域最北部的构造拼合体,其经历了早古生代洋壳俯冲及之后的陆-陆碰撞,是一个具有典型“沟-弧-盆”体系的增生型造山带(许志琴等, 1994; 张建新等, 1997; 张招崇等, 1997; Song *et al.*, 2009; Xia *et al.*, 2016; Yu *et al.*, 2021)。前人对该带内出露的蛇绿岩、高压变质岩和花岗岩类的大量研究已取得了一系列重要成果,但北祁连原特提斯洋的俯冲极性和最终闭合过程仍是长期争论的问题。从现今的构造格局来看,北祁连造山带从南向北依次发育早古生代洋中脊蛇绿岩、高压变质岩、弧岩浆岩和弧后盆地蛇绿岩(图 1a),据此多数研究者倾向于认为北祁连洋在奥陶纪向北俯冲(许志琴等, 1994; 夏林圻等, 1996; Wang *et al.*, 2005; Song *et al.*, 2013; Xia *et al.*, 2016),且普遍认为至少在 440 Ma 时大洋已经闭合。值得注意的是,这些研究主要集中在北祁连造山带西段和中段,而对于原特提斯洋所在的北祁连东段,尤其是最东端的宁夏南华山地区的演化过程研究相对薄弱。近年来的研究表明,北祁连造山带东段发育大量的早古生代埃达克质花岗岩类,从西至东分布于雷公山-老虎山-宝积山-屈吴山一带,形成时代集中于 450 ~ 430 Ma,其

成因主要与北祁连洋闭合后的同碰撞或碰撞后伸展背景有关(Tseng *et al.*, 2009; 秦海鹏等, 2014; Yu *et al.*, 2015; Chen *et al.*, 2016, 2018; Fu *et al.*, 2018),缺少北祁连洋俯冲作用的相关记录。此外,屈吴山以东的南华山、卫宁北山地区也发育一定规模的花岗岩类和铜-金矿床(海连富等, 2023),而对这些花岗岩类的研究鲜有报道,已有成果也缺乏系统的岩石地球化学等证据制约。

具有高 Sr 及低 Y、Yb 元素含量的埃达克岩或埃达克质岩石不仅蕴含着丰富的大陆动力学信息,其本身也与 Cu、Au 等矿床的形成密切相关,在国际地质学界一直是讨论的焦点之一。与传统的 I 型、S 型和 A 型花岗岩相比,埃达克质岩石通常具有 $\text{SiO}_2 \geq 56\%$, $\text{Al}_2\text{O}_3 \geq 15\%$, 富 Na、贫 K, 高 Sr ($> 400 \times 10^{-6}$)、LREE 含量和 Sr/Y (> 20)、 $(\text{La}/\text{Yb})_N$ (> 10) 值, Y ($\leq 18 \times 10^{-6}$) 和 HREE 含量相对低,无 Eu 异常或轻微的负异常等一系列地球化学特征(Defant and Drummond, 1990; Martin *et al.*, 2005)。多数学者认为这些特征暗示该类岩石不仅与洋壳俯冲作用有关,还可能形成于加厚下地壳的直接熔融(Atherton and Petford, 1993; Chung *et al.*, 2003)、拆沉下地壳部分熔融(Gao *et al.*, 2004; Wang *et al.*, 2006)、幔

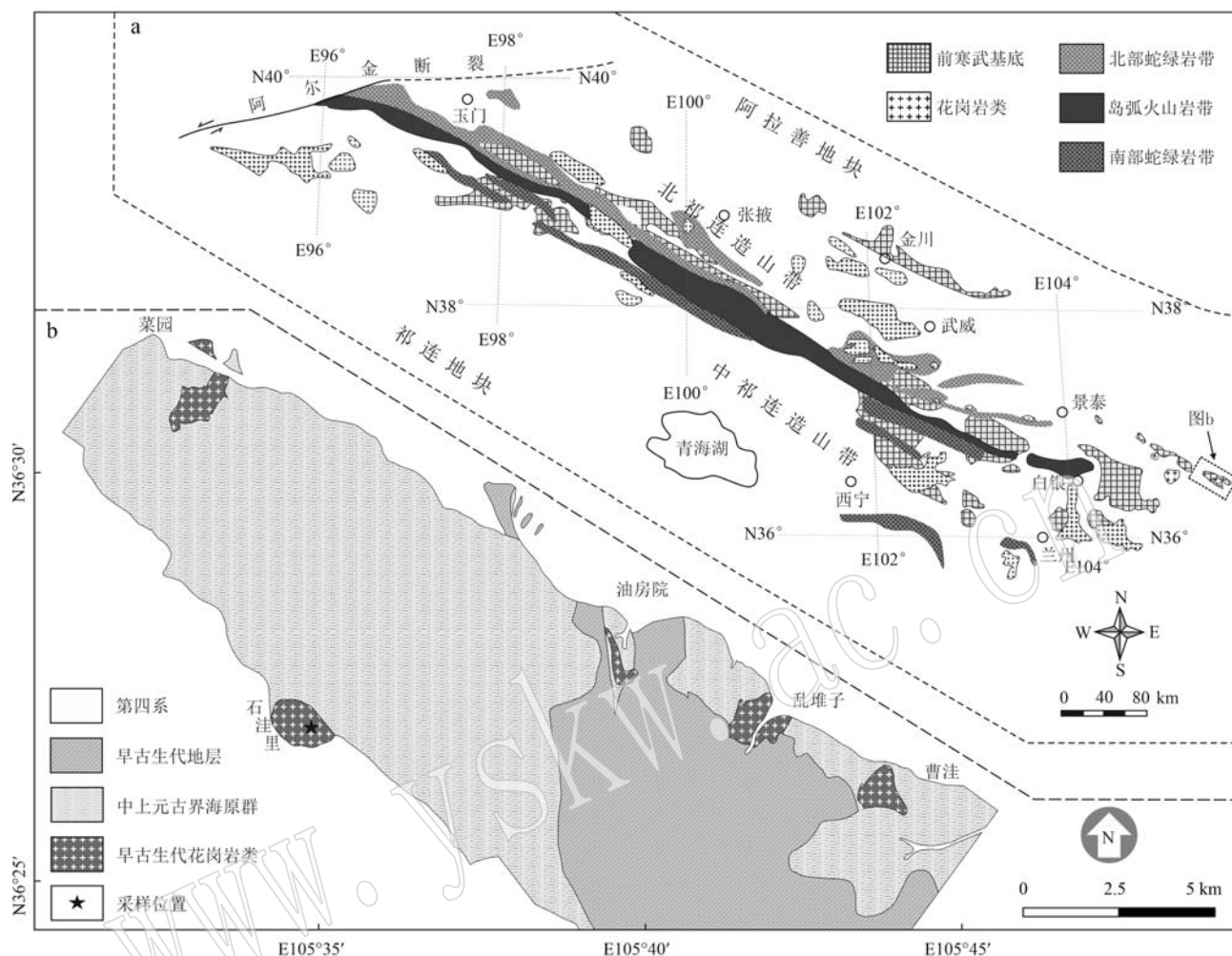


图1 北祁连造山带地质简图(a, 据 Chen *et al.*, 2018 修改)和南华山地区地质简图(b)

Fig. 1 Simplified geological map of the North Qilian orogenic belt showing distributions of the main tectonic units (a, modified after Chen *et al.*, 2018) and regional geological map of the Nanhushan area (b)

源玄武质岩浆的同化混染-分离结晶作用等 (Castillo *et al.*, 1999; Macpherson *et al.*, 2006)。埃达克质岩石可能记录了洋壳俯冲、大陆碰撞或伸展作用的关键证据, 研究其成因对探讨俯冲背景下的壳幔相互作用机制和大陆地壳增长具有重要意义。

鉴于此, 本文选择北祁连造山带东段宁夏南华山地区具有埃达克质岩石特征的石洼里花岗岩, 开展了锆石 LA-ICP-MS U-Pb 年代学分析, 并进行了系统的主、微量元素和锆石原位 Hf 同位素地球化学研究, 以探讨岩体侵位时代、成因及其形成的地球动力学背景, 欲为原特提斯洋在北祁连造山带东段的俯冲特征和演化过程提供新依据。

1 地质背景及岩石学特征

祁连造山带位于青藏高原北部, 夹持于塔里木板块、阿拉善地块和柴达木地块之间, 是一呈北西-南东向展布的大型早古生代复合造山带, 由南向北依次划分为南祁连褶皱带、中祁连变质基底和北祁连增生造山带 (冯益民等, 1996; 张建新等, 2015; 宋述光等, 2019; Yu *et al.*, 2021)。北祁连造山带北以阿拉善地块毗邻, 南接祁连地块 (图 1a), 被认为是在新元古代岩石圈裂陷作用基础上, 受早古生代大洋岩石圈俯冲影响而发育有完整沟-弧-盆构造体

系的增生型造山带。北祁连造山带由南部的早古生代洋中脊蛇绿岩带、中部的岛弧火山岩带和北部的弧后 SSZ 型蛇绿岩带组成(图 1a, 张招崇等, 1997; Song *et al.*, 2013; 夏林圻等, 2016; 宋述光等, 2019)。此外, 该造山带分布有大量的早古生代花岗岩类, 从西段的昌马-大岔大坂-走廊南山, 到东段雷公山-老虎山-屈吴山-南华山一带均有分布。前人对区域内花岗岩类进行了较为详细的年代学和岩石成因研究, 普遍认识到造山带西段花岗岩类侵位较早(520~463 Ma), 以 S 型花岗岩和具高 Sr/Y 值的花岗岩为主, 岩石的产出主要受北祁连洋俯冲及其诱发的弧后伸展控制(吴才来等, 2004, 2010; Wu *et al.*, 2011; 熊子良等, 2012; Chen *et al.*, 2014; 卜涛等, 2019; Li *et al.*, 2020), 而东段花岗岩类则侵位相对较晚(466~402 Ma), 主要为具高 Sr/Y 值

的石英闪长岩、花岗闪长岩和花岗岩(王金荣等, 2006; Tseng *et al.*, 2009; 秦海鹏等, 2014; Yu *et al.*, 2015; Chen *et al.*, 2016; Yang *et al.*, 2019)。

本文报道的石洼里岩体位于北祁连造山带东段的宁夏南华山地区, 主要侵入到中元古代海源群变质岩系中, 出露面积约 5 km²(图 1b)。岩性以花岗岩为主, 受后期构造活动的影响, 岩石发生弱变形(图 2a)。花岗岩为中粗粒结构、块状构造, 主要由石英(约 35%)、钾长石(10%~15%)、斜长石(45%~50%)及少量黑云母构成。斜长石为自形-半自形板状, 表面多发生绢云母化蚀变, 粒径 0.5~2 mm 不等, 常见聚片双晶结构(图 2b); 钾长石呈半自形粒状, 粒径 0.5~2 mm, 发育格子双晶(图 2b); 石英自形程度较差, 粒径 0.1~2 mm 不等; 另有少量锆石、磁铁矿等副矿物。

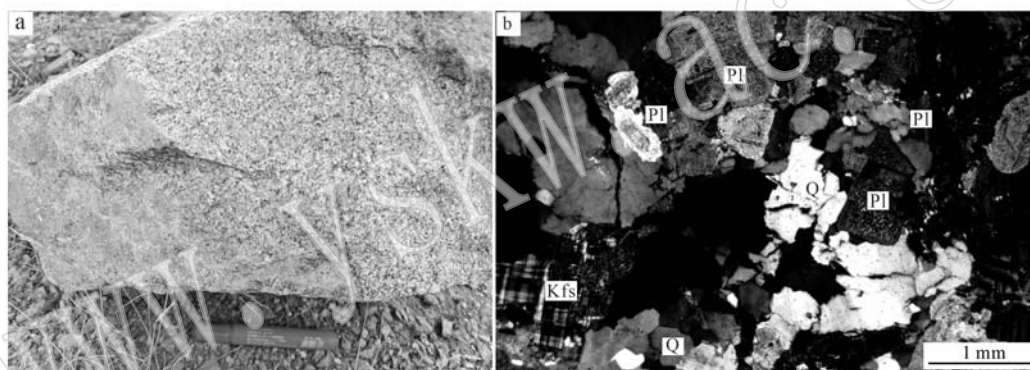


图 2 石洼里花岗岩的野外及镜下显微照片

Fig. 2 Field photograph and microphotograph of the Shiwali granites

a—中粗粒花岗岩野外照片; b—中粗粒花岗岩主要由石英、斜长石、钾长石及少量黑云母构成, 部分斜长石绢云母化(正交偏光); Pl—斜长石; Kfs—钾长石; Q—石英

a—field photograph of Shiwali granite showing medium-coarse grained texture; b—Shiwali granite is mainly composed of quartz, plagioclase, K-feldspar and biotite, with sericitization of plagioclase (crossed polarizer); Pl—plagioclase; Kfs—K-feldspar; Q—quartz

2 测试方法

本文对出露于北祁连造山带东段宁夏南华山地区的石洼里花岗岩开展了全岩主量-微量元素分析、锆石 U-Pb 定年和原位 Hf 同位素测试, 采样地理坐标 36°28′22″N, 105°35′15″E(图 1b)。

2.1 锆石 U-Pb 定年和原位 Hf 同位素测试

样品的破碎和挑选由武汉上谱分析科技有限公司完成, 利用重磁技术对锆石进行分选。锆石制靶后, 磨蚀至锆石核部出露, 进行阴极发光(CL)显微照相, 结合反射光和透射光, 观察锆石的内部结构,

随后利用 LA-(MC)-ICP-MS 进行锆石 U-Pb 定年和 Hf 同位素分析。锆石 U-Pb 定年 GeolasPro 激光剥蚀系统由 COMPEXPro 102 ArF 193 nm 准分子激光器和 MicroLas 光学系统组成, ICP-MS 型号为 Agilent 7900, 激光束斑直径 32 μm, 采用 He 作为剥蚀物质的载气, 氩气为补偿气以调节灵敏度(Hu *et al.*, 2015)。U-Pb 同位素定年和微量元素含量处理中采用锆石标准 91500 和玻璃标准物质 NIST610 作外标分别进行同位素和微量元素分馏校正。每个时间分辨分析数据包括大约 20~30 s 的空白信号和 50 s 的样品信号, 详细的仪器参数和分析流程见 Zong 等(2017)。离线数据处理采用 ICPMSDataCal 程序

(Liu *et al.*, 2010)完成,U-Pb 年龄谐和图绘制和年龄权重平均值计算均采用 Isoplot/Ex_ver3 (Ludwig, 2003)完成。微区原位锆石 Hf 同位素测试利用激光剥蚀多接收杯等离子体质谱(LA-MC-ICP-MS)完成,激光剥蚀系统为 Geolas HD, MC-ICP-MS 为 Neptune Plus,激光斑束为 32 μm ,实际输出能量密度约为 7.0 J/cm²。载气使用氦气,并在剥蚀池之后引入少量氮气以提高 Hf 元素灵敏(Hu *et al.*, 2012)。为确保分析数据的可靠性,Plešovice、91500 和 GJ-1 三个国际锆石标准与实际样品同时分析,Plešovice 用于进行外标校正以进一步优化分析测试结果,91500 和 GJ-1 作为第二标样监控数据校正质量,分析精度优于 0.000 02,测试值与推荐值确保在误差范围内一致。标样推荐值请参考 Zhang 等(2020),离线数据处理采用 ICPMSDataCal 程序(Liu *et al.*, 2010)完成。

2.2 全岩地球化学分析

全岩主量和微量元素分析在武汉上谱分析科技有限公司完成。首先在室内对岩石样品进行详细的岩相学鉴定,挑选出新鲜无蚀变的样品,清除其表面的粉尘,粉碎至 200 目以下,然后进行主、微量元素测试。

主量元素分析仪器使用日本理学(Rigaku)生产的 ZSX Primus II 型波长色散 X 射线荧光光谱仪(XRF),测试电压 50 kV,电流 60 mA,主量各元素分析谱线均为 K α ,标准曲线使用国家标准物质岩石系列 GBW07101-14 建立。数据校正采用理论 α 系数法,测试相对标准偏差(RSD)<2%。

微量和稀土元素利用 Agilent 7700e 等离子体质谱仪(ICP-MS)分析完成,分析流程为:准确称取粉末样品 50 mg 置于 Teflon 坩埚中,用 1 mL 高纯 HNO₃ 和 1 mL 高纯 HF 在 190℃ 条件下加热 24 h 以上,将其蒸干后,加入 1 mL 高纯 HNO₃、1 mL MQ 水和 1 mL 内标 In(浓度为 1 $\times 10^{-6}$)再次加热 12 h 以上,后将溶液转入聚乙烯料瓶中,并用 2% HNO₃ 稀释至约 100 g 后,密闭保存以备 ICP-MS 测试。

3 分析结果

3.1 锆石 U-Pb 年龄

石洼里花岗岩的锆石 CL-U-Pb 同位素年龄测试结果列于表 1 和图 3。锆石为无色-淡黄色透明状,呈自形-半自形长柱状,长度 50~150 μm ,长宽比多

介于 2:1~3:1 之间,发育明显的振荡环带(图 3a)。对该样品中 15 颗锆石的 15 个点进行了测定,所测锆石 U 和 Th 含量分别为 1 421 $\times 10^{-6}$ ~4 601 $\times 10^{-6}$ 和 218 $\times 10^{-6}$ ~2 457 $\times 10^{-6}$,Th/U 值为 0.12~1.00,与岩浆成因锆石的 Th/U 值(>0.1,Griffin *et al.*, 2004)一致,表明所分析的锆石为典型的岩浆成因锆石(Hoskin and Schaltegger, 2003)。所有数据点都位于谐和线上或附近(图 3b),²⁰⁶Pb/²³⁸U 年龄变化范围较大,5 颗继承锆石核部的²⁰⁶Pb/²³⁸U 年龄变化于 1 098~564 Ma 之间;其余 10 个测点中,2 颗锆石具有相对较年轻的年龄 423 和 421 Ma,可能与后期热液蚀变作用有关;2 颗锆石具有相对较老的年龄 484 和 474 Ma,可能为捕获锆石;剩余 6 个点的²⁰⁶Pb/²³⁸U 年龄集中于 456~449 Ma 之间,加权平均年龄为 452 ± 4 Ma(图 3c),该年龄代表了石洼里岩体的侵位年龄,岩体为晚奥陶世岩浆活动的产物。

3.2 全岩主、微量元素

本文对石洼里岩体 7 件花岗岩样品进行了元素地球化学分析,全岩主量和微量元素测试结果及特征值列于表 2。样品具有较高的 SiO₂(68.60%~71.42%)、Al₂O₃(14.95%~15.75%)、Na₂O(5.06%~5.79%) 和 Na₂O+K₂O(7.55%~8.16%) 含量,中等的 K₂O(2.23%~3.10%)、MgO(0.91%~1.73%) 含量和较高的 Mg[#]值(55~59),较低的 Fe₂O₃^T(1.40%~2.46%) 和 CaO(0.98%~1.93%) 含量。在 TAS 岩石分类图解上样品点主要落入花岗闪长岩-花岗岩区域(图 4a),为亚碱性系列岩石。结合其较高的 Na₂O 含量和较低的 K₂O/Na₂O 值(0.39~0.61)特征,岩石为中钾钙碱性岩系和富钠质岩石(图 4b、4c)。样品铝饱和指数(A/CNK)为 1.05~1.12,显示弱过铝质 I 型花岗岩特征(图 4d)。

石洼里花岗岩稀土元素(REE)总量为 71.40 $\times 10^{-6}$ ~122.36 $\times 10^{-6}$,整体具 LREE 富集、HREE 亏损的特征,稀土元素球粒陨石标准化配分型式呈明显的右倾型(图 5a),(La/Yb)_N 变化范围较大(16.93~30.70),指示轻、重稀土元素分异明显。Eu/Eu* 介于 0.89~1.02 之间,无明显的 Eu 负异常。微量元素方面,岩石富集大离子亲石元素(LILE,如 Ba、Sr、K),亏损高场强元素(HFSE,如 Nb、Ta、P、Ti),在原始地幔标准化蛛网图上,具有明显的 Ba、Sr 和 K 正异常,Nb、Ta、P 和 Ti 负异常(图 5b)。

3.3 锆石原位 Hf 同位素

在锆石 U-Pb 年代学的基础上,对石洼里花岗岩

表 1 石洼里花岗岩锆石 LA-ICP-MS U-Pb 定年分析结果
Table 1 LA-ICP-MS zircon U-Pb dating results of the Shiwali granites

测试点号	$w_B/10^{-6}$				Th/U	同位素比值				年龄/Ma						
	Pb		Th			$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$				
SWL-6(Zr)-01	316	1 259	3 376	0.37	0.063 5	0.001 8	0.689 1	0.020 2	0.077 9	0.000 9	728	61	532	12	484	6
SWL-6(Zr)-02	246	359	3 117	0.12	0.062 3	0.001 7	0.629 4	0.021 5	0.072 3	0.001 3	687	57	496	13	450	8
SWL-6(Zr)-03	411	1 193	3 255	0.37	0.068 3	0.001 4	1.099 1	0.030 4	0.115 2	0.002 1	876	41	753	15	703	12
SWL-6(Zr)-04	318	853	1 421	0.60	0.074 2	0.001 6	1.918 1	0.047 7	0.185 5	0.002 5	1 056	44	1087	17	1 097	13
SWL-6(Zr)-05	237	1 883	1 892	1.00	0.061 1	0.001 6	0.776 6	0.020 9	0.091 4	0.001 1	643	56	584	12	564	6
SWL-6(Zr)-06	267	1 652	3 053	0.54	0.067 6	0.001 8	0.537 0	0.018 5	0.067 9	0.000 7	457	85	436	17	423	4
SWL-6(Zr)-07	198	1 284	2 403	0.53	0.057 9	0.002 5	0.539 6	0.020 5	0.067 5	0.001 0	528	96	438	14	421	6
SWL-6(Zr)-08	211	1 017	2 272	0.45	0.063 9	0.001 6	0.675 0	0.016 8	0.076 3	0.000 7	737	55	524	10	474	4
SWL-6(Zr)-09	392	1 695	4 601	0.37	0.057 7	0.001 4	0.581 4	0.014 6	0.072 6	0.000 7	520	54	465	9	452	4
SWL-6(Zr)-10	372	1 538	2 573	0.60	0.064 7	0.001 5	0.941 4	0.029 8	0.108 1	0.001 6	1 209	109	674	16	662	9
SWL-6(Zr)-11	206	1 270	2 438	0.52	0.056 2	0.001 5	0.567 6	0.016 6	0.073 0	0.001 0	461	27	456	11	454	6
SWL-6(Zr)-12	144	218	1 782	0.12	0.057 9	0.001 7	0.587 0	0.018 8	0.073 3	0.001 0	524	67	469	12	456	6
SWL-6(Zr)-13	358	1 422	3 143	0.45	0.080 8	0.006 1	2.023 3	0.050 0	0.185 6	0.003 0	1 217	153	1 123	69	1 098	14
SWL-6(Zr)-14	305	1 540	3 461	0.44	0.061 4	0.001 4	0.612 9	0.014 6	0.072 2	0.000 8	654	45	485	9	449	5
SWL-6(Zr)-15	297	2 457	3 164	0.78	0.055 8	0.001 3	0.562 2	0.013 9	0.072 9	0.000 9	456	50	453	9	454	5

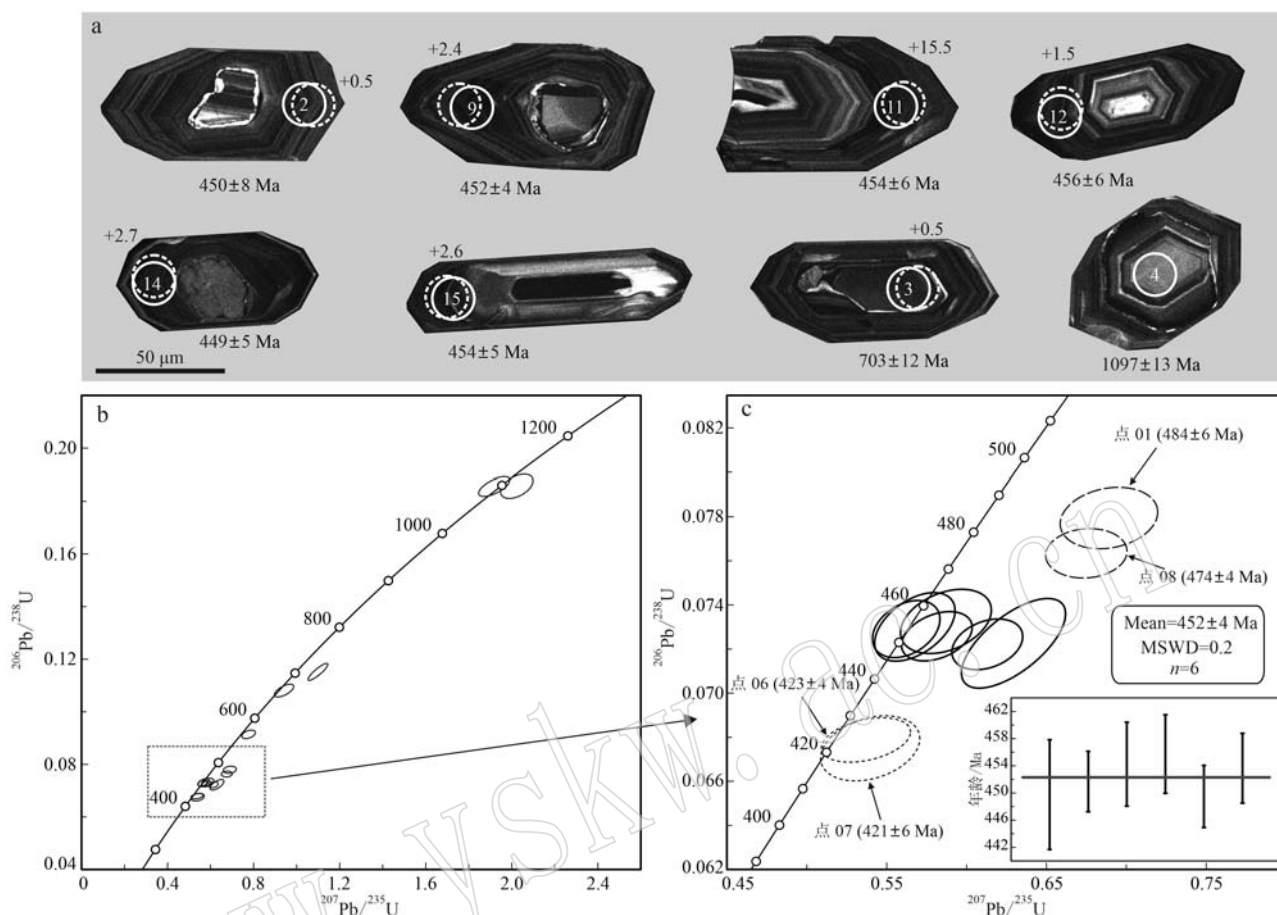


图3 石洼里花岗岩锆石阴极发光(CL)图像(a)、U-Pb年龄谐和图(b、c)

Fig. 3 Cathodoluminescence (CL) images (a) and U-Pb concordia diagrams (b, c) of zircons in Shiwalis granites

a 中实线圆圈和虚线圆圈分别代表 U-Pb 年龄和原位 Hf 同位素测试激光剥蚀点

The solid and dashed circles in a are the analyses spots of U-Pb dating and Hf isotope, respectively

进行了锆石原位 Hf 同位素分析,结果列于表 3 和图 6。花岗岩锆石 $^{176}\text{Lu}/^{177}\text{Hf}$ 值变化于 0.000 366 ~ 0.002 558 之间, $^{176}\text{Yb}/^{177}\text{Hf}$ 值介于 0.019 762 ~ 0.074 875 之间, $^{176}\text{Hf}/^{177}\text{Hf}$ 值为 0.282 360 ~ 0.282 935,其 $\varepsilon\text{Hf}(t)$ 值相对较高,变化范围为 +0.5 ~ +15.5 (图 6),对应的两阶段模式年龄为 1 477 ~ 446 Ma。

4 讨论

4.1 岩石成因

石洼里花岗岩主量元素显示其为中钾钙碱性弱过铝质岩石,与 I 型花岗岩特征相似 (Chappell and White, 1974),且岩石富集 Ba、Sr、K 等大离子亲石元素,亏损 Nb、Ta、P、Ti 等高场强元素,具有明显的 Nb-Ta 槽 (图 5b),显示出典型俯冲带弧岩浆岩的地

球化学特征 (Kelemen *et al.*, 2003)。另一方面,与传统 I 型花岗岩相比,石洼里花岗岩具有显著的高 Ba ($1.025 \times 10^{-6} \sim 1.250 \times 10^{-6}$)、Sr ($324 \times 10^{-6} \sim 577 \times 10^{-6}$) 和低 Y ($6.99 \times 10^{-6} \sim 7.69 \times 10^{-6}$)、Yb ($0.65 \times 10^{-6} \sim 0.71 \times 10^{-6}$) 含量,具有较高的 Sr/Y (45 ~ 79) 和 (La/Yb)_N (17 ~ 31) 值,且轻、重稀土元素分异明显,无明显 Eu 负异常,与典型俯冲带埃达克岩的地球化学特征 (Defant and Drummond, 1990) 一致,并且在埃达克岩判别图中,样品点全部落入埃达克岩区域内 (图 7a、7b)。关于埃达克岩的成因,前人提出如下几种模式: ① 俯冲洋壳部分熔融 (Defant and Drummond, 1990; Rapp *et al.*, 1999; Dokuz *et al.*, 2013); ② 加厚或拆沉下地壳部分熔融 (Atherton and Petford, 1993; Chung *et al.*, 2003; Gao *et al.*, 2004; Wang *et al.*, 2006); ③ 幔源玄武质岩浆的同化混染-分离结晶 (AFC) (Castillo *et al.*, 1999; Macpherson *et al.*,

表2 石洼里花岗岩主元素 ($w_B/\%$)、微量及稀土元素 ($w_B/10^{-6}$) 分析结果Table 2 Major ($w_B/\%$) and trace element ($w_B/10^{-6}$) compositions of the Shiwali granites

样号	SWL-1	SWL-2	SWL-3	SWL-4	SWL-5	SWL-6	SWL-7
SiO ₂	70.55	69.53	69.25	68.66	68.60	69.58	71.42
TiO ₂	0.26	0.26	0.31	0.29	0.30	0.26	0.18
Al ₂ O ₃	14.95	15.52	15.49	15.63	15.75	15.37	15.28
Fe ₂ O ₃ ^T	2.04	2.19	2.40	2.46	2.46	2.18	1.40
MnO	0.04	0.05	0.05	0.05	0.05	0.04	0.02
MgO	1.51	1.36	1.73	1.59	1.67	1.40	0.91
CaO	0.98	1.38	1.11	1.71	1.30	1.93	1.07
Na ₂ O	5.40	5.06	5.50	5.31	5.67	5.18	5.79
K ₂ O	2.63	3.10	2.56	2.61	2.40	2.38	2.23
P ₂ O ₅	0.12	0.12	0.14	0.14	0.14	0.12	0.07
LOI	1.34	1.13	1.47	1.429	1.51	1.22	0.94
Total	99.80	99.68	100.02	99.88	99.86	99.66	99.29
Mg [#]	59	55	59	56	57	56	56
A/CNK	1.11	1.09	1.12	1.07	1.10	1.05	1.10
Na ₂ O+K ₂ O	8.02	8.16	8.05	7.92	8.07	7.55	8.03
K ₂ O/Na ₂ O	0.49	0.61	0.46	0.49	0.42	0.46	0.39
Sc	3.95	4.51	4.58	4.68	4.93	4.29	2.95
V	32.8	37.2	40.4	43.4	39.5	35.6	22.1
Cr	22.31	20.65	26.90	27.05	30.48	23.39	20.13
Co	5.21	5.52	6.58	5.69	6.42	5.44	3.31
Ni	11.38	10.73	14.55	12.83	14.12	11.14	10.46
Cu	14.76	10.37	17.01	4.31	5.86	3.87	33.97
Zn	39.7	37.0	42.7	38.3	40.9	39.3	26.9
Rb	77.0	109.6	92.9	89.5	87.5	66.6	74.0
Sr	361	494	324	477	395	577	439
Y	7.69	6.99	7.12	7.21	7.61	7.33	7.33
Zr	115.5	104.3	123.3	124.0	127.1	115.6	118.3
Nb	9.03	8.70	8.46	8.04	8.37	9.46	8.68
Ba	1 068	1 109	1 220	1 250	1 159	1 070	1025
La	24.52	15.99	27.90	23.22	30.39	27.03	24.84
Ce	42.48	32.32	48.47	50.68	57.42	49.33	46.76
Pr	4.73	3.42	5.31	5.10	5.82	5.11	4.91
Nd	15.08	11.81	16.98	16.69	18.89	16.60	16.01
Sm	2.73	2.23	2.99	2.93	3.27	2.63	2.80
Eu	0.73	0.68	0.75	0.85	0.81	0.71	0.76
Gd	1.86	1.72	1.98	2.10	2.10	1.78	1.92
Tb	0.27	0.25	0.26	0.29	0.26	0.26	0.27
Dy	1.36	1.24	1.39	1.37	1.40	1.24	1.33
Ho	0.27	0.21	0.27	0.27	0.28	0.24	0.26
Er	0.78	0.64	0.75	0.73	0.80	0.75	0.74
Tm	0.11	0.10	0.10	0.09	0.10	0.10	0.10
Yb	0.69	0.68	0.65	0.65	0.71	0.70	0.68
Lu	0.11	0.11	0.10	0.11	0.11	0.11	0.10
Hf	2.90	2.93	3.01	3.01	3.14	3.14	2.18
Ta	0.64	0.65	0.56	0.55	0.55	0.76	0.62
Pb	19.37	16.97	11.68	12.16	11.33	21.12	15.44
Th	15.68	14.33	16.21	13.75	15.07	18.86	15.65
U	1.89	2.76	2.05	2.43	2.37	2.43	1.43
REE	95.71	71.40	107.92	105.10	122.36	106.60	101.48
Eu/Eu [*]	0.94	1.02	0.89	1.00	0.89	0.95	0.95
Sr/Y	46.98	70.71	45.48	66.13	51.91	78.68	59.86
(La/Yb) _N	25.45	16.93	30.70	25.69	30.68	27.84	26.20

LOI—烧失量; $Mg^{\#} = 100 \times Mg^{2+} / (Mg^{2+} + 0.9 \times Fe_2O_3^T)$; $A/CNK = Al_2O_3 / (CaO + Na_2O + K_2O)$ (摩尔比)。

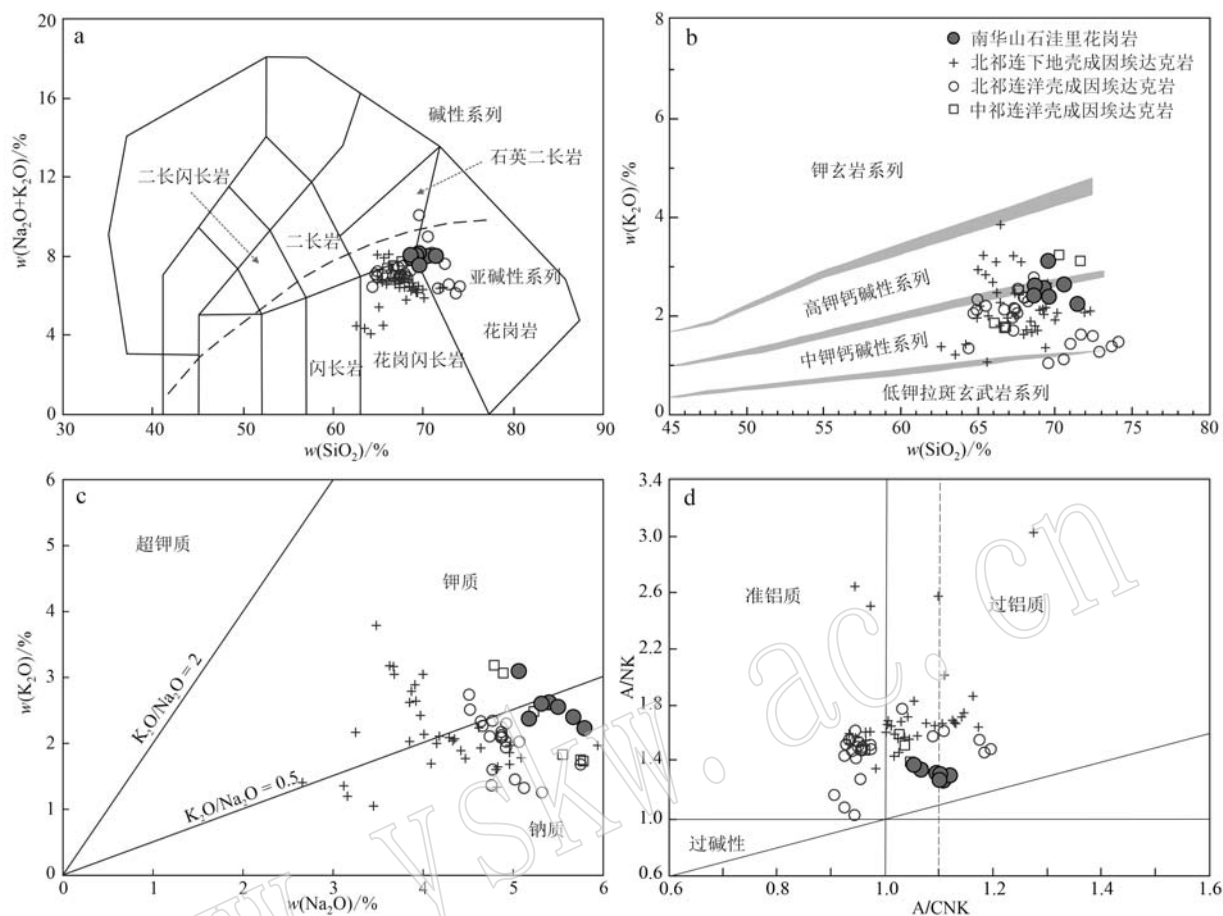


图4 石洼里花岗岩 TAS 分类图解(a, 据 Wilson, 1989), K_2O-SiO_2 关系图解(b, 据 Rollinson, 1993), K_2O-Na_2O 关系图解(c, 据 Foley *et al.*, 1987) 及 $A/NK-A/CNK$ 关系图解(d, 据 Maniar and Piccoli, 1989)

Fig. 4 TAS diagram (a, from Wilson, 1989), K_2O-SiO_2 diagram (b, from Rollinson, 1993), K_2O-Na_2O diagram (c, from Foley *et al.*, 1987) and $A/NK-A/CNK$ diagram (d, from Maniar and Piccoli, 1989) of the Shiwali granites
数据来源：北祁连下地壳成因埃达克岩 (Tseng *et al.*, 2009; Yu *et al.*, 2015; Zhang *et al.*, 2017; Yang *et al.*, 2019; Li *et al.*, 2020); 北祁连洋壳成因埃达克岩 (王金荣等, 2006; 陈育晓等, 2012; Chen *et al.*, 2016); 中祁连洋壳成因埃达克岩 (Yang *et al.*, 2015)
Data source: lower crust-derived adakites of the North Qilian (Tseng *et al.*, 2009; Yu *et al.*, 2015; Zhang *et al.*, 2017; Yang *et al.*, 2019; Li *et al.*, 2020); slab-derived adakites of the North Qilian (Wang Jinrong *et al.*, 2006; Chen Yuxiao *et al.*, 2012; Chen *et al.*, 2016); slab-derived adakites of the Central Qilian (Yang *et al.*, 2015)

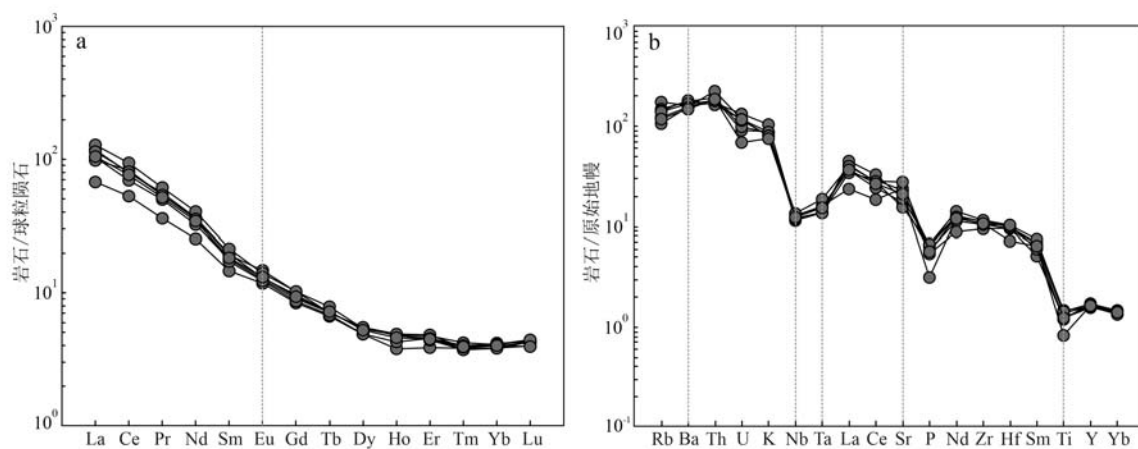


图5 石洼里花岗岩球粒陨石标准化稀土配分曲线(a)和原始地幔标准化微量元素蛛网图(b) (球粒陨石和原始地幔标准化数据引自 Sun and McDonough, 1989)

Fig. 5 Chondrite-normalized REE patterns (a) and primitive mantle-normalized trace element patterns (b) of the Shiwali granites (chondrite- and primitive mantle-normalized values are from Sun and McDonough, 1989)

表 3 石洼里花岗岩锆石 Hf 同位素分析结果
Table 3 Zircon Hf isotopic compositions of the Shiwali granites

测试点号	年龄/Ma	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	1σ	$\varepsilon\text{Hf}(0)$	$\varepsilon\text{Hf}(t)$	T_{DM}/Ma	$\text{TD}_{\text{Mc}}/\text{Ma}$	$f_{\text{Lu/Hf}}$
SWL-6(Zr)-01	484	0.038 982	0.000 868	0.282 514	0.000 034	-9.1	1.2	1 040	1 263	-0.97
SWL-6(Zr)-02	450	0.019 762	0.000 366	0.282 509	0.000 040	-9.3	0.5	1 034	1 278	-0.99
SWL-6(Zr)-03	703	0.027 733	0.000 914	0.282 360	0.000 018	-14.6	0.5	1 257	1 477	-0.97
SWL-6(Zr)-05	564	0.035 009	0.001 221	0.282 495	0.000 019	-9.8	2.2	1 077	1 275	-0.96
SWL-6(Zr)-06	423	0.074 875	0.002 558	0.282 553	0.000 051	-7.7	0.9	1 031	1 236	-0.92
SWL-6(Zr)-07	421	0.041 642	0.001 123	0.282 862	0.000 073	3.2	12.2	554	606	-0.97
SWL-6(Zr)-08	474	0.048 761	0.001 471	0.282 547	0.000 030	-8.0	2.0	1 011	1 213	-0.96
SWL-6(Zr)-09	452	0.033 222	0.001 174	0.282 568	0.000 024	-7.2	2.4	972	1 174	-0.96
SWL-6(Zr)-11	454	0.034 855	0.000 970	0.282 935	0.000 135	5.8	15.5	449	446	-0.97
SWL-6(Zr)-12	456	0.041 659	0.001 657	0.282 544	0.000 020	-8.1	1.5	1 019	1 228	-0.95
SWL-6(Zr)-14	449	0.044 865	0.001 621	0.282 582	0.000 015	-6.7	2.7	965	1 156	-0.95
SWL-6(Zr)-15	454	0.036 628	0.001 219	0.282 572	0.000 079	-7.1	2.6	968	1 167	-0.96

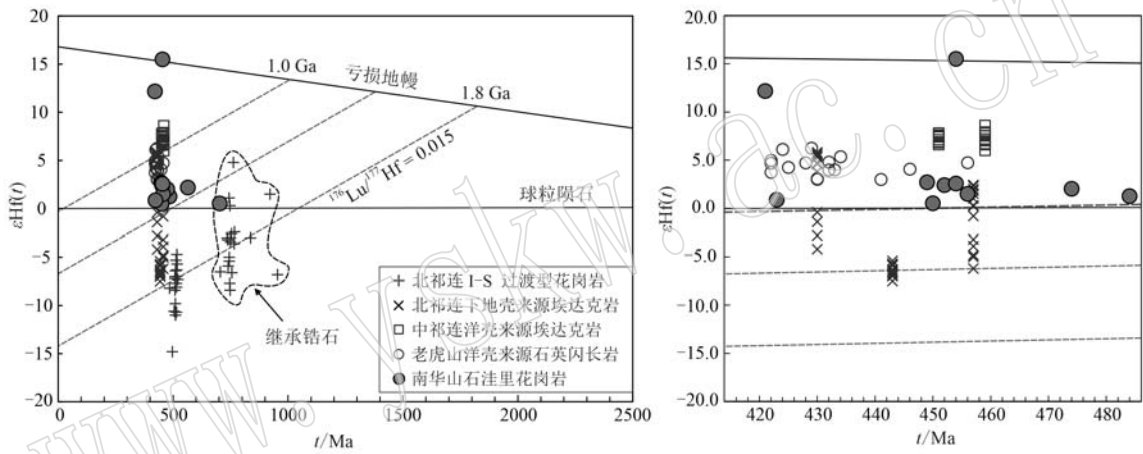


图 6 石洼里花岗岩锆石 Hf 同位素组成图

Fig. 6 Hf isotopic compositions of zircons from the Shiwali granites

数据来源: 北祁连 I-S 过渡型花岗岩据 Chen 等(2014); 老虎山洋壳来源石英闪长岩据 Fu 等(2018); 北祁连下地壳和中祁连洋壳埃达克岩数据来源同图 4

Date source: I-S transitional granites of North Qilian (Chen *et al.*, 2014); accreted oceanic crust-related quartz diorites of Laohushan (Fu *et al.*, 2018); see Fig. 4 for other data sources

2006); ④ 壳-幔岩浆混合作用(Streck *et al.*, 2007; 陈斌等, 2013)。

加厚下地壳部分熔融形成的埃达克质岩石通常具有高 SiO₂、低 MgO 含量和 Mg[#] 值(一般<40)、极低的 Cr 和 Ni 含量等特征,通常发育继承锆石或下地壳包体(Chung *et al.*, 2003)。石洼里埃达克岩虽然具有较高的 SiO₂ 含量,也发育有继承锆石(图 3),但野外观察并未发现岩体中含变质或变形特征的壳源包体。实验岩石学研究表明,加厚下地壳部分熔融形成高 Sr/Y 花岗岩类通常发生在较高的压力条件下(Rapp and Watson, 1995; Qian and Hermann, 2013),这暗示其源区残留相一般为榴辉岩(石榴子石和金红石,无斜长石)(张旗, 2015)。石洼里花岗

岩虽然轻重稀土元素强烈分异,但明显亏损中稀土元素,具有平坦的重稀土元素分布特征(图 5a),且不存在 Zr-Hf 负异常(图 5b),这暗示其源区缺乏金红石残留相矿物。此外,石洼里花岗岩 Nb/Ta 值与 SiO₂ 含量呈负相关关系(图 8c),且在 Nb/Ta-Zr/Sm 图解(图 8d)中,样品靠近角闪岩相熔融区域,而远离含金石榴辉岩熔体,表明石洼里花岗岩的源区以角闪石残留相矿物为主,这与埃达克质岩石判别图解显示的源区为含 10%石榴子石角闪岩相也是一致的(图 7),因此推测石洼里高 Sr/Y 花岗岩可能并非形成于高深(>40 km)环境的加厚下地壳熔融。拆沉下地壳熔融与加厚下地壳熔融类似,也需要一个较深和高压的熔融条件,且该过程熔体会与地幔

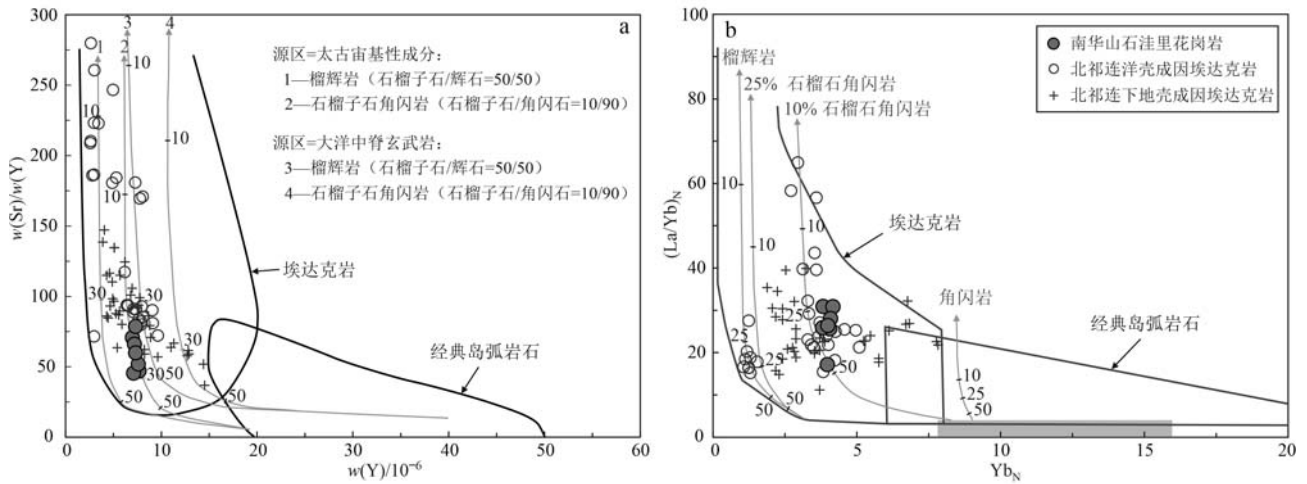


图7 石洼里花岗岩 $\text{Sr}/\text{Y}-\text{Y}$ (据 Defant and Drummond, 1990) 和 $(\text{La}/\text{Yb})_N-\text{Yb}_N$ 判别图解 (据 Martin *et al.*, 2005)

Fig. 7 Discrimination diagrams of $\text{Sr}/\text{Y}-\text{Y}$ (after Defant and Drummond, 1990) and $(\text{La}/\text{Yb})_N-\text{Yb}_N$ (after Martin *et al.*, 2005) for the Shiwali granites

图中带刻度的灰色曲线为部分熔融曲线; 北祁连洋壳和下地壳埃达克岩数据来源同图4

The grey curves with scale are partial melting curves, and see Fig. 4 for the data sources

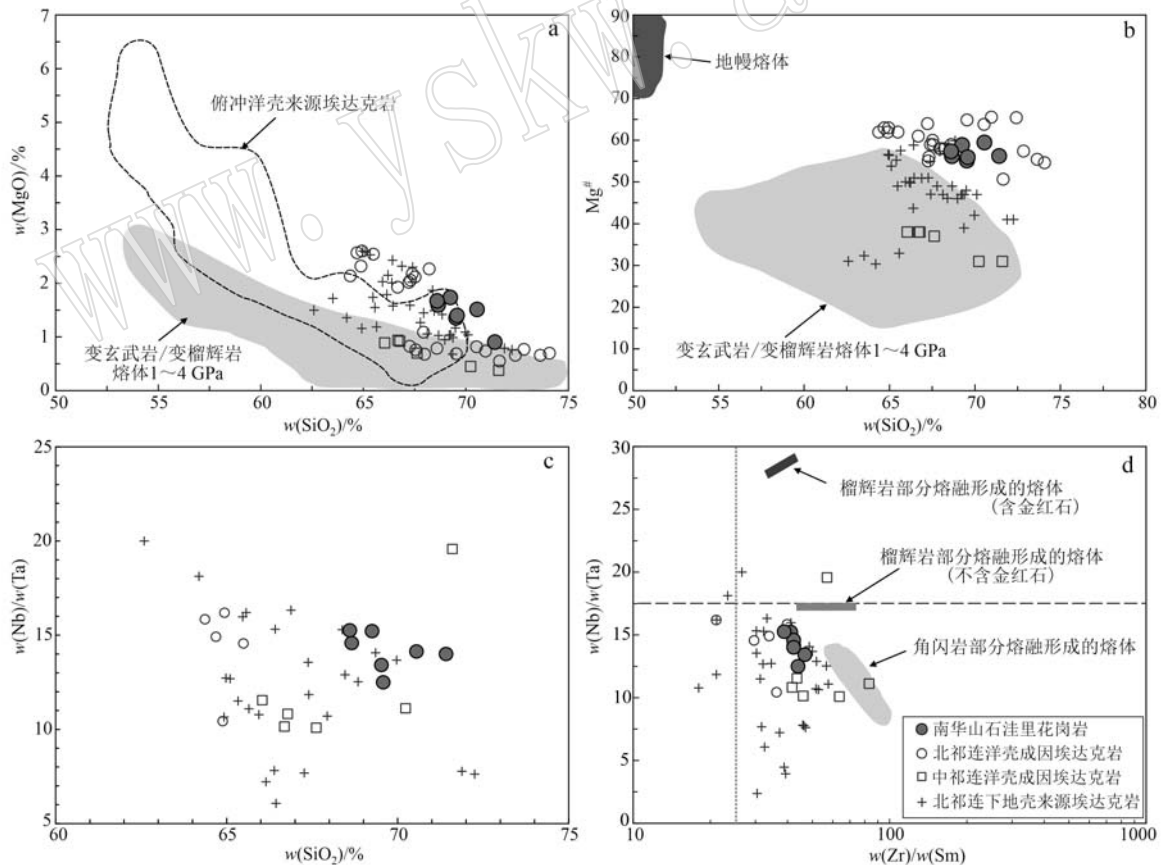


图8 石洼里花岗岩 $\text{MgO}-\text{SiO}_2$ (a)、 $\text{Mg}^\#-\text{SiO}_2$ (b) 和 $\text{Nb}/\text{Ta}-\text{SiO}_2$ (c)、 $\text{Nb}/\text{Ta}-\text{Zr}/\text{Sm}$ (d) 图解

Fig. 8 $\text{MgO}-\text{SiO}_2$ (a), $\text{Mg}^\#-\text{SiO}_2$ (b), $\text{Nb}/\text{Ta}-\text{SiO}_2$ (c) and $\text{Nb}/\text{Ta}-\text{Zr}/\text{Sm}$ (d) diagrams of the Shiwali granites

a 和 b 据 Rapp *et al.*, 1999; c 和 d 据 Foley *et al.*, 2002; 埃达克岩数据数据来源同图4

a and b after Rapp *et al.*, 1999; c and d after Foley *et al.*, 2002; see Fig. 4 for the data sources

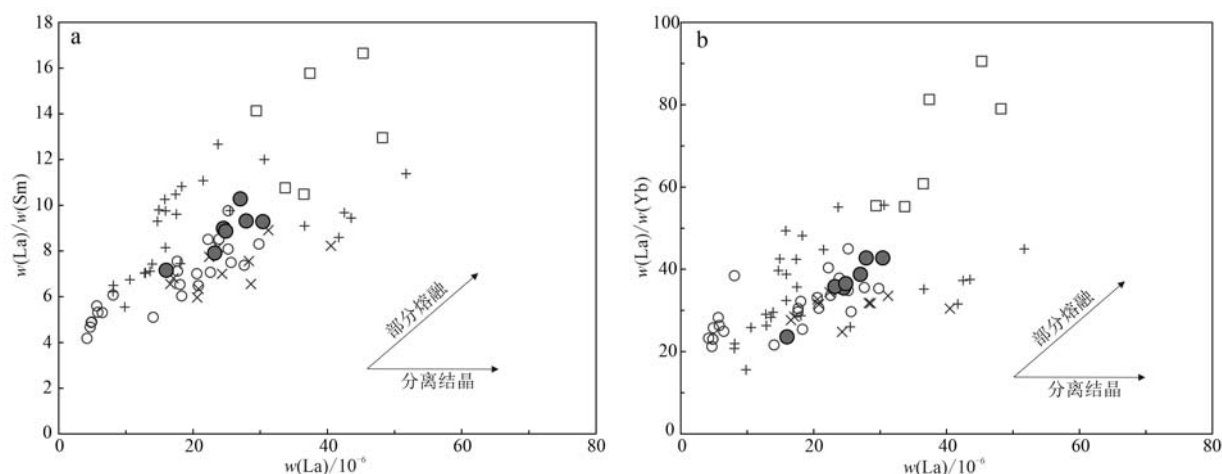


图 10 石洼里花岗岩的 La/Sm-La(a) 和 La/Yb-La(b) 关系图解

Fig. 10 La/Sm-La(a) and La/Yb-La(b) discrimination diagrams of the Shiwali granites

图例和数据来源同图 4

See Fig. 4 for the legends and data sources

然而值得注意的是, Rapp 等 (1999) 的实验结果表明, 在 1~4 GPa 条件下, 俯冲洋壳部分熔融产生的埃达克质熔体在上升过程中穿过地幔楔时会与地幔橄榄岩发生交代反应, 这将导致洋壳熔体中的 MgO、Cr、Ni 等含量升高, 而石洼里埃达克质花岗岩却具低 MgO (0.91%~1.73%)、Cr (20.13×10^{-6} ~ 30.48×10^{-6}) 和 Ni (10.46×10^{-6} ~ 14.55×10^{-6}) 含量, 与壳源熔体的含量一致 (Rapp and Watson, 1995; Springer and Seck, 1997; Qian and Hermann, 2013)。此外, 虽然石洼里埃达克岩具有较高的 $\varepsilon_{\text{Hf}}(t)$ 值 (+0.5~+15.5), 与北祁连造山带东段老虎山残余洋壳熔融石英闪长岩 (Fu *et al.*, 2018)、中祁连带巴米山 (Yang *et al.*, 2015) 洋壳成因埃达克岩大致相似 (图 6), 但其 $\varepsilon_{\text{Hf}}(t)$ 值主要集中在 +0.5~+2.7, 亏损地幔模式年龄 1477~446 Ma, 以中-新元古代为主, 暗示石洼里花岗岩可能来自陆缘岛弧下地壳的部分熔融, 其源区中可能存在早古生代的新生地壳。

上述讨论表明, 石洼里埃达克质花岗岩的岩浆源区更可能为岛弧基性下地壳并混入了以俯冲洋壳或沉积物为主的新生地壳成分。实验岩石学表明, 基性下地壳在 30~40 km 深度 (正常厚度地壳下部) 部分熔融即可形成埃达克质熔浆 (Qian and Hermann, 2013), 深度超过 40 km 则残留物中石榴子石含量较高 (>20%), 形成的熔体重稀土元素分馏过强 (如 Gd/Yb>8), 而石洼里花岗岩的 Gd/Yb 值介于 2.5~3.2, 与 30~40 km 深度下地壳熔体一致。因

此, 石洼里埃达克质花岗岩应该主要为岛弧基性下地壳部分熔融的产物。

4.2 地球动力学背景

北祁连造山带经历了早古生代洋壳俯冲及之后的陆-陆碰撞, 是一个典型的增生型造山带, 为原特提斯洋闭合的产物。区内出露的蛇绿岩、高压-超高压变质岩和岩浆岩的相关研究表明, 北祁连造山带具有典型增生造山带的“沟-弧-盆”体系 (张建新等, 2015; Xia *et al.*, 2016; 宋述光等, 2019; Yu *et al.*, 2021), 但北祁连原特提斯洋的俯冲极性和最终闭合过程则是长期争论的问题。前人研究表明, 北祁连洋的初始俯冲发生于约 520 Ma, 在 520~490 Ma 间发育一套完整的弧前蛇绿岩和岛弧岩浆岩 (Zhang *et al.*, 2007; Song *et al.*, 2013; Chen *et al.*, 2014), 具有向北俯冲极性。随着持续的北向俯冲, 在阿拉善地块南缘河西走廊沉降带形成弧后盆地, 发育 490~445 Ma 的九个泉-老虎山弧后蛇绿岩带 (钱青等, 2001; Song *et al.*, 2013; Fu *et al.*, 2022)。北祁连造山带发育大量的古生代花岗岩类, 形成时代介于 516~383 Ma 之间, 记录了北祁连原特提斯洋俯冲、弧-陆和陆-陆碰撞及碰撞后伸展的演化全过程, 虽然目前对于北祁连洋闭合时间存在不同认识 (西段和东段有差异), 但普遍认为至少在 440 Ma 已经闭合 (陈育晓等, 2012; 熊子良等, 2012; Song *et al.*, 2013; Chen *et al.*, 2015, 2016, 2018; Yu *et al.*, 2015; Yang *et al.*, 2019)。

本文研究的北祁连造山带东段宁夏南华山地区出露的石洼里高镁埃达克岩侵位于晚奥陶世(452 Ma),为俯冲洋壳部分熔融的产物,暗示北祁连原特提斯洋在南华山地区持续向北俯冲。然而从现今的构造格局来看,石洼里岩体位于北部蛇绿岩带(老虎山弧后盆地)以北(图1a),与南部北祁连大洋北向俯冲有关的白银岛弧带相距较远(Wang *et al.*, 2005),且北祁连洋的最晚俯冲记录是产于造山带西段的牛心山岩体,形成时代为477 Ma(吴才来等, 2010; Wu *et al.*, 2011),明显早于石洼里岩体(452 Ma),因此用北祁连洋壳的北向俯冲来解释石洼里花岗岩的形成不够合理。Fu等(2022)最新识别出北祁连造山带东段老虎山地区的玻安质蓝片岩和岛弧玄武岩(492~488 Ma)记录了洋内俯冲初始和岛弧弧前增生,是祁连洋向北的俯冲产物,且北祁连弧后盆地发育一条新的北倾俯冲带,形成了更年轻的SSZ型蛇绿岩(454~448 Ma)和岛弧岩浆岩(Fu *et al.*, 2018, 2020)。本文研究的石洼里高镁埃达克岩与老虎山SSZ型蛇绿岩的时代一致,可能同为老虎山弧后洋盆南向俯冲的产物。

综上所述,晚奥陶世时期,受北祁连原特提斯洋北向俯冲影响,石洼里埃达克质花岗岩形成于北祁连东段老虎山弧后洋壳的南向俯冲过程中。老虎山-宝积山-屈吴山一带的同碰撞埃达克岩(约440 Ma, Chen *et al.*, 2015, 2016, 2018; Fu *et al.*, 2018)和早志留世巨厚复理石建造的形成则标志着北祁连洋盆在奥陶纪末期闭合,进入志留纪碰撞造山阶段。

5 结论

(1) 北祁连造山带东段南华山地区石洼里花岗岩的锆石 LA-ICP-MS U-Pb 年龄为 452 ± 4 Ma, 岩体侵位于晚奥陶世。

(2) 岩石学和地球化学研究表明,石洼里花岗岩具有高 SiO_2 含量、 $\text{Mg}^\#$ 、 Sr/Y 和 La/Yb 值,地球化学特征与高镁埃达克岩相似,可能是在 30~40 km 深度的岛弧基性下地壳部分熔融的产物,其源区中可能存在早古生代的新生地壳。

(3) 石洼里高镁埃达克岩具弧岩浆岩地球化学特征,暗示受北祁连原特提斯洋北向俯冲影响,老虎山弧后洋壳在晚奥陶世时期向南发生俯冲消减作用。

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