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新疆西天山晚古生代花岗岩的岩石成因及构造意义

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摘要: 西天山造山带位于中亚造山带西南缘, 其岩浆记录成为探讨区域构造演化及成矿作用的重要窗口。针对西天山地区花岗岩岩石成因及构造环境的争议问题, 笔者以西天山伊犁地块北缘博罗科努和阿吾拉勒地区 4 处典型花岗岩体(果子沟、哈勒尕提、精河及那拉提岩体)为研究对象, 开展全岩地球化学、锆石 U-Pb 年代学及 Sr-Nd-Hf 同位素分析。这些岩体的主要岩石类型为二长花岗岩和钾长花岗岩, 锆石 U-Pb 定年结果揭示, 它们形成于 (368.1 ± 1.5) Ma(晚泥盆世)至 (301.9 ± 2.8) Ma(晚石炭世)之间。结合区域岩浆岩年代学数据, 将西天山北部岩浆作用分为两期, 即晚泥盆世—早石炭世和晚石炭世。本研究中花岗岩体均显示高硅(66.62%~76.08%)、富碱(6.72%~8.85%)、轻稀土富集、重稀土亏损且负 Eu 异常显著($\delta\text{Eu}=0.30\sim 0.97$)等特征。微量元素总体显示富集大离子亲石元素(Rb、Th 等)而亏损高场强元素(Nb、Ta、Ti 等)的特征, 与大陆岛弧环境下形成的花岗岩类似。晚泥盆世—早石炭世岩体的 $\varepsilon_{\text{Nd}}(t)$ 值为 $-1.3\sim -3.8$ 、 $\varepsilon_{\text{Hf}}(t)$ 值为 $+0.3\sim +5.0$, 暗示其源区以古老地壳熔融为主且存在地幔物质参与, 而晚石炭世岩体的 $\varepsilon_{\text{Nd}}(t)$ 值为 $+0.8\sim +5.9$ 、 $\varepsilon_{\text{Hf}}(t)$ 值为 $+4.1\sim +15.1$, 表明其源区主要为新生下地壳。综合前人研究, 认为 368~307 Ma 北天山洋向伊犁地块俯冲形成了 I 型花岗岩, 而 ~305 Ma 后碰撞阶段岩石圈折沉形成 A2 型钾长花岗岩和 I 型二长花岗岩。此外, 西天山伊犁地块北缘博罗科努地区的晚泥盆世—晚石炭世花岗岩类具有 Cu-Mo 的成矿潜力。

关键词: 花岗岩; 地球化学; 岩石成因; 构造意义; 西天山

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Petrogenesis and Tectonic Significance of the Late Paleozoic Granites from the Western Tianshan, Xinjiang

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Abstract: The Western Tianshan Orogen is located in the southwestern Central Asian Orogenic Belt (CAOB). The widespread magmatic rocks provide a critical window for investigating regional tectonic-metallogenic dynamics. To address controversies regarding the petrogenesis, tectonic setting of granitoids, and the closure timing of the North Tianshan Ocean in the Western Tianshan region, this study focuses on the Late Paleozoic granitoids (Guozigou, Halegati, Jinghe, and Nalati plutons) located along the northern margin of the Yili Block, through integrating geochronological, whole-rock elemental, and Sr-Nd-Hf isotopic analyses. The studied plutons are predominantly composed of monzonitic granite and potash feldspar granite. Zircon LA-ICP-MS U-Pb dating reveals that these plutons were emplaced between (368.1±1.5) Ma (Late Devonian) and (301.9±2.8) Ma (Late Carboniferous). Combined with regional geochronological data, the magmatism in the northern Yili Block can be temporally subdivided into two stages, late Devonian to early Carboniferous and late Carboniferous. The studied granitoids exhibit high silica ($\text{SiO}_2 = 66.62\% - 76.08\%$) and total alkali ($\text{K}_2\text{O} + \text{Na}_2\text{O} = 6.72\% - 8.85\%$) contents. In terms of rare earth elements, the studied samples show LREE-rich patterns with variable negative Eu anomalies ($\delta\text{Eu} = 0.30 - 0.97$). The trace element patterns of the studied rocks are characterized by enrichment in Rb and Th and depletion in Nb, Ta, and Ti, comparable to those of continental arc granites. The late Devonian granitoid samples show slightly enriched radiogenic isotopic signatures, with negative $\varepsilon_{\text{Nd}}(t)$ from -3.79 to -1.3 and $\varepsilon_{\text{Hf}}(t)$ from $+0.3$ to $+5.0$, indicating magma sources dominated by ancient crustal materials with mantle-derived contributions. In contrast, the Late Carboniferous granitoids show more radiogenic $\varepsilon_{\text{Nd}}(t)$ ($+0.8$ to $+5.9$) and $\varepsilon_{\text{Hf}}(t)$ ($+4.1$ to $+15.1$) values, indicative of a juvenile lower crustal origin. Integrating previous studies, we propose that the 368–307 Ma granitoids are of I-type granite and were formed associated with the northward subduction of the Northern Tianshan Ocean beneath the Yili Block, whereas later A2-type potash feldspar granites and I-type monzonitic granites in the context of post-collisional lithospheric delamination initiated at ~ 305 Ma. Additionally, the Late Devonian-Early Carboniferous to Late Carboniferous granitoids in the Borohoro region exhibit significant potential for Cu-Mo mineralization.

Keywords: Granite; geochemistry; petrogenesis; tectonic significance; Western Tianshan

中亚造山带位于西伯利亚板块、塔里木板块、华北板块和东欧板块之间, 是全球规模最大、最典型的显生宙增生型造山带之一。它由多期岛弧、微陆块、增生杂岩、蛇绿混杂岩等构造块体拼贴而成, 记录了新元古代—中生代古亚洲洋的长期俯冲—增生演化过程(Yin et al., 2017; 杨高学等, 2021)。天山造山带位于中亚造山带的西南部, 是中亚造山带的重要组成部分, 以 88°E 为界可将其分为东天山造山带和西天山造山带(李锦轶等, 2006; 朱志新等, 2012)。西天山造山带由前寒武纪微陆块结晶基底、古生代洋壳残片与

陆缘弧相互拼贴增生而成, 具有独特的构造特征和复杂的成矿规律, 备受地质学界关注(李锦轶等, 2006; Xiao et al., 2010; 朱志新等, 2013; 王宗秀等, 2017)。

西天山造山带内发育多期多类型的岩浆岩, 其中尤以晚古生代花岗岩规模最大、分布最广, 且与成矿关系最密切(顾雪祥等, 2014)。岩浆岩主要由早石炭世(~ 344 Ma)I型花岗岩和晚石炭世—早二叠世($311 \sim 294$ Ma)A型花岗岩组成(Han et al., 2010; Tao et al., 2022), 是西天山古生代洋—陆转化及洋盆闭合后裂谷拉伸的重要地质记录(夏林圻等, 2002; 张连昌等,

2022)。已有研究表明,西天山北部晚古生代的岩浆活动大致可分为中晚泥盆世—早石炭世、晚石炭世和早中二叠世3期,对应于北天山洋的俯冲消减、洋盆闭合和陆内伸展过程(安芳等,2008; Gao et al., 2009; Tang et al., 2010; 顾雪祥等, 2013, 2014; 薛春纪等, 2014; Huang et al., 2020; Chen et al., 2021)。北天山洋在晚奥陶世前开始向伊犁—中天山板块俯冲消减(胡霄琴等, 2008; Xiao et al., 2008; 王勇, 2019),大规模洋陆俯冲作用集中发生于泥盆纪—早石炭世,一系列中酸性岩体侵入以及火山喷发形成了博罗科努晚古生代岛弧带(Wang et al., 2007; Zhu et al., 2009; 张力强, 2014; 顾雪祥等, 2016; Xie et al., 2022)。北天山巴音沟蛇绿岩中辉长岩(344 Ma)和斜长花岗岩(325 Ma)的年龄表明早石炭世仍发育洋盆(徐学义等, 2006a, 2006b)。北天山洋最终闭合时限仍存在争议,前人提出了早石炭世(李永军等, 2010; Xia et al., 2012)、晚石炭世(Windley et al., 1990; Wang et al., 2006)或早二叠世(王新利等, 2013; Xiao et al., 2013, 2014; Li et al., 2015)闭合的不同观点。相应地,关于西天山北部石炭纪的构造环境也存在岛弧(Han et al., 2011; 李永军等, 2012)、后碰撞(韩宝福等, 2004; 王京彬等, 2006; Gao et al., 2011)、裂谷(Xia et al., 2008)或者与地幔柱有关(Zhu et al., 2009; Xia et al., 2012)的不同认识。关于西天山石炭纪—二叠纪花岗岩类的成因,主要有壳幔混合形成(肖文交等, 2008; Long et al., 2011)和洋壳沉积物交代地幔楔参与部分熔融形成(Zhang et al., 2010)两种观点。

针对上述争议问题,笔者选择博罗科努晚古生代岛弧带和阿吾拉勒晚石炭世—二叠世裂谷带晚古生代花岗岩类(果子沟岩体、精河岩体、哈勒尕提岩体、那拉提岩体)作为研究对象,在岩相学观察的基础上,对各地区花岗岩开展锆石 U-Pb 年代学、全岩地球化学和 Sr-Nd-Hf 同位素等分析,查明这些花岗岩的成岩时代、地球化学特征及差异,以探讨它们的岩石成因、源区特征、构造意义,并为区域矿产资源评价及找矿勘查提供参考。

1 地质背景

西天山位于中亚造山带的西南缘(图 1a),夹于准噶尔地块和塔里木板块之间,被北天山断裂带、那拉提北缘断裂带和中天山南缘断裂带3条深断裂带分为4个构造单元,由北向南依次为北天山增生杂岩带、

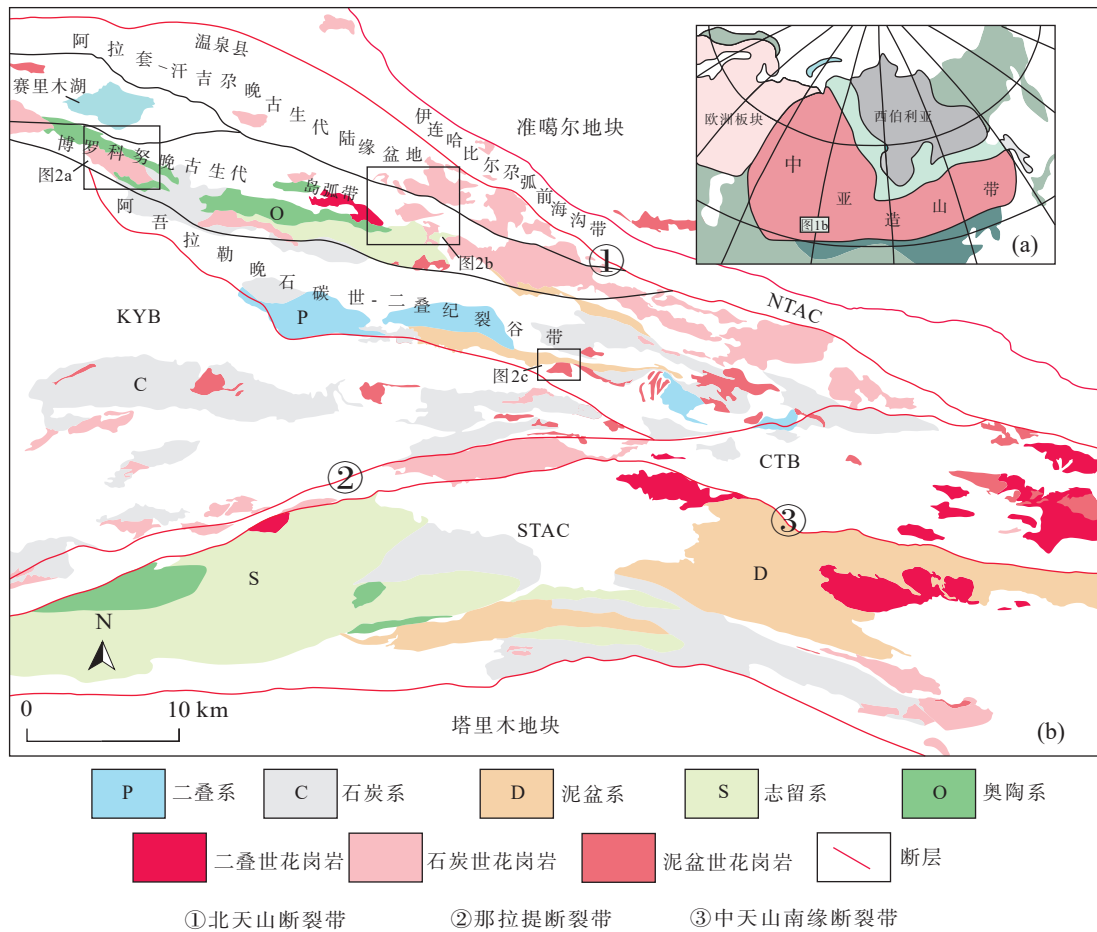
哈萨克—伊犁地块、中天山弧地体和南天山增生杂岩带(图 1b; 左国朝等, 2008; Long et al., 2011; Gao et al., 2015; 章永梅等, 2016; 张京渤等, 2019; Huang et al., 2020; 李丽娟等, 2024)。区内地层从志留系至二叠系均有发育,其中志留系、泥盆系和石炭系的地层出露最为广泛。

研究区位于西天山造山带北部,处于伊犁地块北缘与北天山断裂带之间(图 1b)。伊犁地块北缘由南向北依次划分为阿吾拉勒晚石炭世—二叠世裂谷带、博罗科努晚古生代岛弧带、阿拉套汗吉尕晚古生代陆缘盆地、依连哈比尔尕晚古生代弧前海沟带等构造单元(顾雪祥等, 2013, 2014; 章永梅等, 2016)。笔者研究对象果子沟岩体、哈勒尕提岩体、精河岩体位于伊犁地块北缘博罗科努晚古生代岛弧带内,而那拉提岩体则位于阿吾拉勒晚石炭世—二叠世裂谷带内(图 1b)。区内发育大量火山岩和侵入岩,形成时代主要为加里东期和华力西期(李伍平等, 1995; Wang et al., 2007; 龙灵利等, 2008)。加里东期侵入岩主要分布于温泉县城南部,岩性为花岗闪长岩和二长花岗岩,主要侵入志留纪、奥陶纪和石炭纪地层。华力西期主要分3期,早期侵入岩分布在伊连哈比尔尕弧前海沟带和博罗科努晚古生代岛弧带(冷成彪等, 2006),岩性主要为花岗斑岩、花岗闪长斑岩和闪长玢岩等,主要侵入到石炭系、志留系中。华力西中期花岗岩主要分布于阿拉套汗吉尕晚古生代陆盆地和博罗科努晚古生代岛弧带,岩性为二长花岗岩、花岗岩、花岗闪长岩、花岗斑岩和流纹斑岩等,主要侵入泥盆纪—石炭纪地层。华力西晚期花岗岩主要分布于伊犁地块北缘及阿吾拉勒晚石炭世—二叠世裂谷带,岩性为闪长玢岩、二长花岗岩、黑云母花岗岩、花岗斑岩和流纹斑岩等(张东阳, 2011; 韩继全等, 2016; 张伟等, 2017; 郝增元等, 2018; 黄河等, 2024),主要侵入石炭纪—二叠纪地层(张连昌等, 2022)。

2 岩石学特征

2.1 果子沟岩体

果子沟岩体位于赛里木湖南部(图 2a),呈 NW 向展布,岩体主要侵入上奥陶统呼独克达坂组(O_3h)、下志留统尼勒克河组(S_1n)之中。果子沟岩体主要为钾长花岗岩和花岗岩。钾长花岗岩的主要矿物有石英(40%~50%)、钾长石(30%~40%)、斜长石(5%~10%),



a. 研究区构造位置图(据 Huang et al., 2020 修改); b. 西天山地质简图(据顾雪祥等, 2014; 章永梅等, 2016; Huang et al., 2020; 朱生强等, 2024 修改)

图1 西天山及邻区区域地质简图

Fig. 1 The simplified regional geological map of the Western Tianshan and adjacent areas

钾长石呈板状,发生泥化(图 3a),斜长石绢云母化(图 3a、图 3b),含少量黑云母,呈片状,多色性明显,轻微绿泥石化(图 3a、图 3b)。花岗岩主要矿物为石英(45%~50%)、钾长石(20%~30%)、斜长石(10%~20%),次要矿物为黑云母(3%~6%),钾长石呈板状轻微泥化,斜长石局部被绢云母化,黑云母呈片状,多色性明显,轻微绿泥石化(图 3c)。

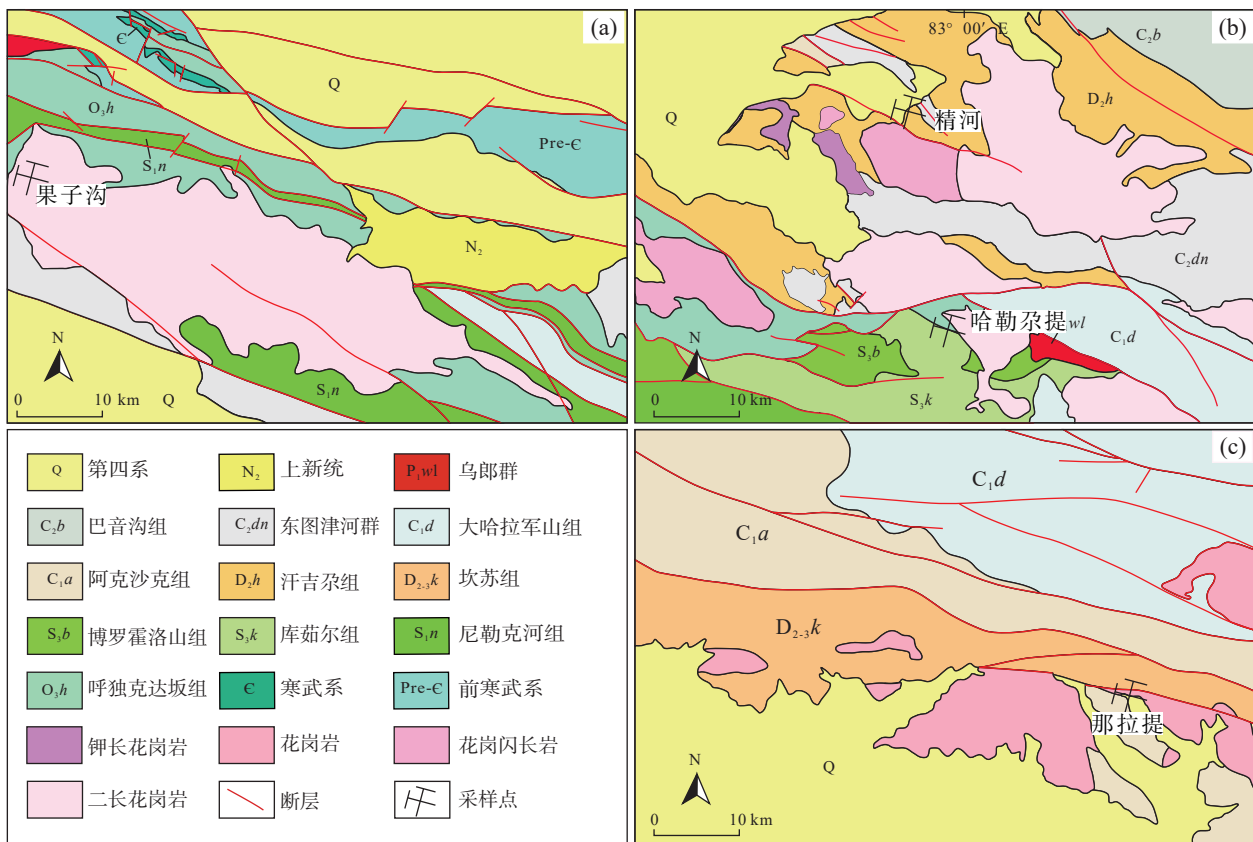
2.2 哈勒尕提岩体

哈勒尕提岩体位于博罗科努晚古生代岛弧带(图 2b),整体呈 NW 向展布。岩体主要侵入上志留统库茹尔组(S_3k)和博罗霍洛山组(S_3b)以及石炭系的东图津河群(C_2dn)和大哈拉军山组(C_1d)中。哈勒尕提岩体主要由花岗岩和二长花岗岩构成。花岗岩的主要矿物包括石英(30%~40%)、钾长石(20%~30%)、斜长石(15%~20%),其中钾长石呈板柱状,泥化(图 3d),斜长石绢云母化(图 3e),次要矿物为黑云母(2%~

5%),呈片状,一组极完全解理(图 3e)。二长花岗岩主要由石英(40%~50%)、钾长石(15%~20%)和斜长石(25%~35%)组成,其中石英表面较干净,钾长石无明显蚀变,斜长石可见绢云母化(图 3f);次要矿物为黑云母(1%~2%),片状,具一组极完全解理,偏光镜下观察到强多色性(图 3f)。花岗岩与二长花岗岩相比,钾长石含量增多,黑云母含量相对增多但自形程度低。二长花岗岩呈细脉状穿插在岩体内部,与花岗岩呈侵入接触关系(姜寒冰等, 2014)。

2.3 精河岩体

精河岩体位于精河县附近,构造位置处于博罗科努晚古生代岛弧带内(图 2b)。岩体主要侵入石炭系东图津河群(C_2dn)、阿克沙克组(C_1a)以及泥盆系汗吉尕组(D_2h)。精河岩体岩性主要为二长花岗岩和花岗岩。二长花岗岩的主要造岩矿物为石英(35%~40%)、钾长石(30%~35%)、斜长石(25%~30%);次



a. 果子沟岩体(据赛里木湖幅 L-44-XXXIV 修改); b. 哈勒尕提和精河岩体(据阿拉尔幅 L-44-XXXVI 与精河幅 L-44-XXXV 修改); c. 那拉提岩体(据新源幅 K-44-VI 修改)

图2 研究区地质简图

Fig. 2 Geological maps of the study areas

要矿物为黑云母(2%~3%)、角闪石(1%~2%), 钾长石发生泥化(图 3g), 斜长石发育卡纳复合双晶且绢云母化(图 3h), 黑云母局部绿泥石化(图 3h), 角闪石发育菱形解理(图 3h)。花岗岩主要造岩矿物为石英(40%~60%)、钾长石(15%~20%)、斜长石(25%~30%), 其中钾长石与斜长石均呈板柱状(图 3i); 次要矿物为黑云母(5%~8%)和角闪石(3%~5%), 其中黑云母呈片状, 绿泥石化, 一组极完全解理, 角闪石自形程度较好, 呈现两组解理(图 3i)。

2.4 那拉提岩体

那拉提岩体分布于阿吾拉勒晚石炭世—二叠世裂谷带南坡(左国朝等, 2008; 朱志新等, 2013), 主要侵入泥盆系坎苏组(D₂₋₃k)和石炭系大哈拉军山组(C₁d)地层。岩体与围岩之间呈不规则侵入接触, 岩体长轴与构造线走向大体一致(图 2c)。岩性为钾长花岗岩, 主要矿物为石英(40%~45%)、钾长石(30%~40%)、斜长石(20%~25%), 其中钾长石呈板状, 斜长石发育聚片双晶(图 3j、图 3k); 次要矿物为黑云母(2%~

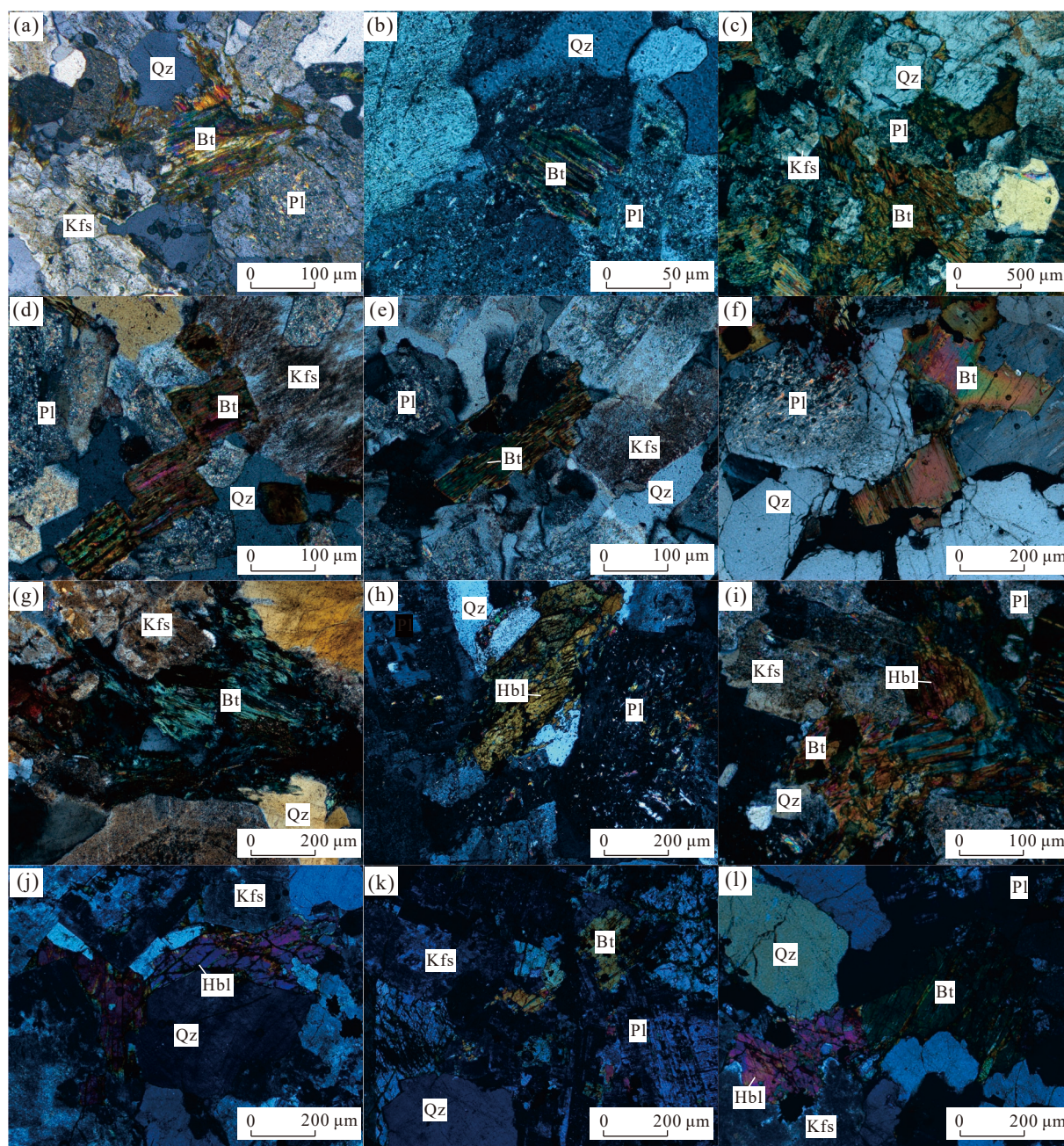
3%), 角闪石(1%~2%), 其中黑云母呈片状, 一组极完全解理(图 3k、图 3l), 角闪石发育菱形解理(图 3j), 充填于钾长石晶隙之间(图 3k)。

3 样品采集与分析方法

本研究共采集了果子沟花岗岩 4 件、钾长花岗岩 2 件, 哈勒尕提花岗岩 5 件、二长花岗岩样品 8 件, 精河岩体花岗岩 4 件、二长花岗岩 3 件, 那拉提钾长花岗岩 5 件(图 2)。其中, 对果子沟花岗岩(GZG-04)、精河花岗岩(JH-04)、二长花岗岩(JH-09)、哈勒尕提花岗岩(HL-02)、二长花岗岩(HL-09)、那拉提钾长花岗岩(NLT-08)共 6 件样品开展了锆石 U-Pb 年代学研究; 除 JH-04 之外的其余 5 件样品同时开展了锆石 Hf 同位素分析。此外, 还对部分样品开展了全岩主微量元素与 Sr-Nd 同位素分析。

3.1 锆石 U-Pb 年代学分析

样品前处理、制靶、阴极发光(CL)图像采集均在



a、b.果子沟钾长花岗岩；c.果子沟花岗岩；d、e.哈勒尕提花岗岩；f.哈勒尕提二长花岗岩；g、h.精河二长花岗岩；i.精河花岗岩；j、k、l.那拉提钾长花岗岩；Qz. 石英；Kfs. 钾长石；Pl. 斜长石；Bt. 黑云母；Hbl. 角闪石

图3 西天山晚古生代典型花岗岩类显微镜正交偏光下照片

Fig. 3 The microscopic photographs of typical Late Paleozoic granitoids in the Western Tianshan

河北省廊坊区域地质矿产调查研究所完成。样品经严格破碎、重液分离和磁选后,在双目镜下挑选出晶型完好、无裂隙且干净透明的锆石晶体,将其粘贴制成环氧树脂样品靶并抛光打磨使锆石露出中心后,结合透射光、反射光完成锆石阴极发光(CL)图像的采集。锆石 U-Pb 同位素定年在中国地质大学(武汉)地质过程与矿产资源国家重点实验室利用 LA-ICP-MS

分析完成,分析用激光剥蚀系统为 GeoLas2005,等离子体质谱仪为 Agilent7500a,激光能量为 70 mJ,频率 8 Hz,实验分析所采用激光束斑直径 32 μm ,激光剥蚀过程中采用氦气作载体,氩气为补偿气以调节灵敏度,每个分析数据包括大约 20~30 s 的空白信号和 50 的样品信号。采用国际标准锆石 91 500 做外标进行同位素质量分馏校正,每隔 6 个数据点测试两个 91 500

标样;具体分析条件及流程详见文献(Liu et al., 2010)。锆石 U-Pb 年龄谐和图的绘制和加权平均年龄的计算则采用 Isoplot 软件完成。

3.2 主微量元素分析

全岩主微量元素分析在澳实分析检测(广州)有限公司完成。将样品严格破碎后缩分出 300 g, 再研磨至 75 μm (200 目)以下的粉末样。将烘干(105 $^{\circ}\text{C}$)后的试样精确称量, 置入铂金坩锅, 加入四硼酸锂-偏硼酸锂-硝酸锂混合熔剂充分混匀, 于高精密熔样机 1 050 $^{\circ}\text{C}$ 熔融, 熔浆倒入铂金模, 冷却形成熔片, 经质量检验合格后, 再用 ME-XRF26X 荧光光谱仪测定主量元素组成。同时精确称取另一份干燥后的试样, 马弗炉 1 000 $^{\circ}\text{C}$ 有氧灼烧, 冷却后再精确称重, 试样灼烧前、灼烧后的重量差即是烧失量(LOI)。全岩微量元素利用 Agilent7700e ICP-MS 分析完成。将 200 目样品置于 105 $^{\circ}\text{C}$ 烘箱中烘干 12 h, 精确称取粉末样品 50 mg 置于 Teflon 溶样弹中, 先后依次缓慢加入 1 ml 高纯 HNO_3 和 1 ml 高纯 HF, 将 Teflon 溶样弹放入钢套, 拧紧后置于 190 $^{\circ}\text{C}$ 烘箱中加热 24 h 以上, 待溶样弹冷却, 开盖后置于 140 $^{\circ}\text{C}$ 电热板上蒸干, 然后加入 1 ml HNO_3 并再次蒸干, 加入 1 ml 高纯 HNO_3 、1 ml MQ 水和 1 ml 内标 In(浓度为 1×10^{-6}), 再次将 Teflon 溶样弹放入钢套, 拧紧后置于 190 $^{\circ}\text{C}$ 烘箱中加热 12 h 以上, 将溶液转入聚乙烯料瓶中, 并用 2% HNO_3 稀释至 100 g 以备 ICP-MS 测试。

3.3 全岩 Sr-Nd 和锆石 Hf 同位素分析

全岩 Sr-Nd 同位素测试前处理及分析在武汉上谱分析科技有限责任公司完成, 采用的仪器为美国 Thermo Fisher Scientific 公司的 MC-ICP-MS(Neptune Plus)。分析过程中, 采用 $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ 和 $^{156}\text{Nd}/^{144}\text{Nd}=0.7219$ 对 Sr 和 Nd 同位素比值进行质量分馏校正, 并使用 NBS987 和 JNdi 作为标样, 标样测定的结果分别为 $^{87}\text{Sr}/^{86}\text{Sr}=0.710248\pm 0.000011(2\text{SD})$ 和 $^{143}\text{Nd}/^{144}\text{Nd}=0.512113\pm 0.000009(2\text{SD})$ 。

锆石微区原位 Hf 同位素分析在武汉上谱分析科技有限责任公司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 Geo-LasPro HD, MC-ICP-MS 为 Neptune Plus, 分析过程同时配备了信号平滑装置以提高信号稳定性和同位素比值测试精密度(Hu et al., 2015)。载气使用氦气, 并在剥蚀池之后引入少量氮气以提高 Hf 元素灵敏度(Hu et al., 2012)。分析采用 Neptune Plus 新设计高性能锥组

合。91 500、GJ-1、TEM3 个国际锆石标准与实际样品同时分析, 91 500 的标准推荐值 0.282 308, GJ-1 的标准推荐值 0.282 013, TEM 的标准推荐值 0.282 677。

4 分析结果

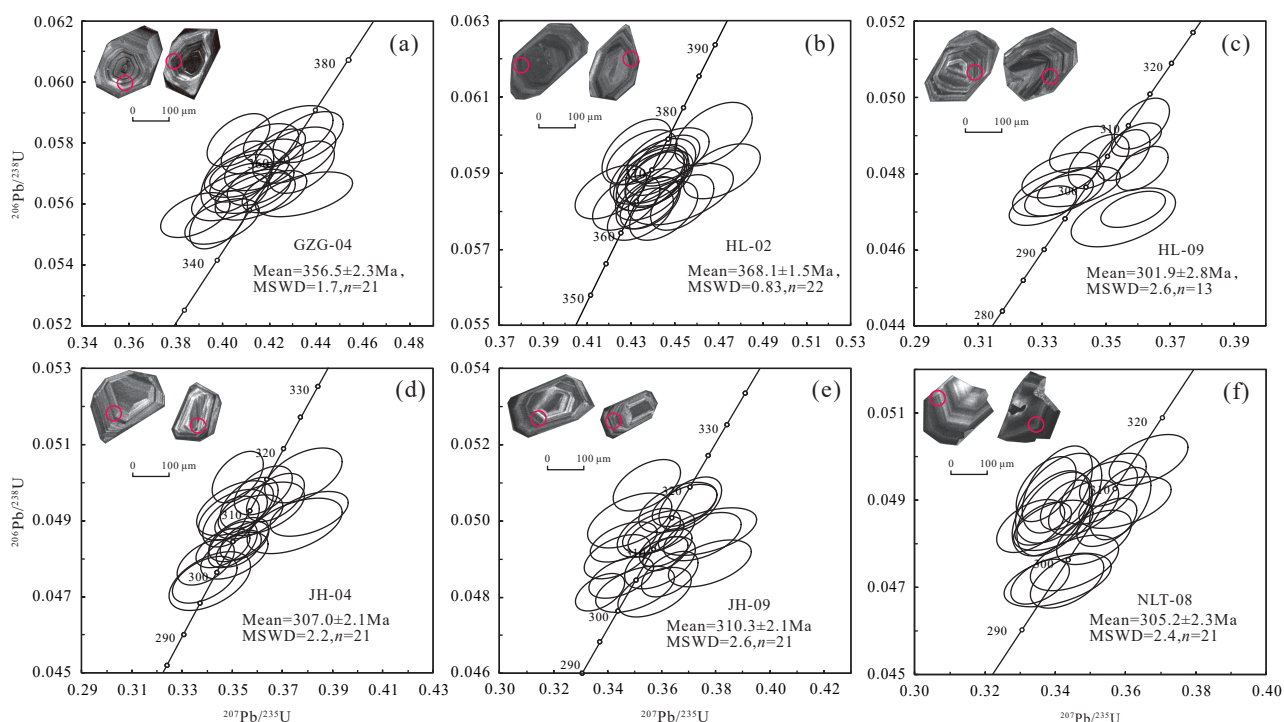
4.1 锆石 U-Pb 年龄

果子沟花岗岩(GZG-04)锆石以短柱状为主, 长为 150~220 μm , 长宽比为 3: 2~5: 2, Th、U 含量分别为 167×10^{-6} ~ 730×10^{-6} 和 189×10^{-6} ~ 527×10^{-6} , Th/U 值为 0.83~1.46(表 1)。所有锆石均发育震荡环带, 显示岩浆锆石的特征。在 U-Pb 谐和图解上, 21 个测点的年龄数据分布在谐和线附近(图 4a), $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(356.5\pm 2.3)\text{Ma}(n=21, \text{MSWD}=1.7)$ (图 4a)。哈拉尕提岩体锆石大多为长柱状, 其中 HL-02 锆石长 150~300 μm , 长宽比为 3: 1~3: 2, Th、U 含量分别为 37×10^{-6} ~ 527×10^{-6} 和 83×10^{-6} ~ 320×10^{-6} , Th/U 值为 0.44~1.69, 在锆石的 U-Pb 谐和图解上, 22 个测点均分布在谐和线附近(图 4b), $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $368.1\pm 1.5\text{Ma}(\text{MSWD}=0.83, n=22)$ (图 4b)。HL-09 锆石长为 100~300 μm , 长宽比为 3: 1~3: 2。Th、U 含量分别为 69×10^{-6} ~ 520×10^{-6} 和 143×10^{-6} ~ 755×10^{-6} , Th/U 值为 0.38~0.77, 在锆石的 U-Pb 谐和图解上, 13 个测点均分布在谐和线附近(图 4c), $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(301.9\pm 2.8)\text{Ma}(\text{MSWD}=2.6, n=13)$ (图 4c)。精河岩体中的锆石多为长柱状, 自形程度较好, 花岗岩(JH-04)锆石长为 100~200 μm , 长宽比为 2: 1~3: 2, Th、U 含量分别为 45×10^{-6} ~ 397×10^{-6} 和 89×10^{-6} ~ 454×10^{-6} , Th/U 为 0.48~0.87。21 个测点落在谐和曲线附近, $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(307.0\pm 2.1)\text{Ma}(\text{MSWD}=2.2, n=21)$ (图 4d); JH-09 锆石长为 150~240 μm , 长宽比为 3: 2~5: 2, Th 含量为 70×10^{-6} ~ 256×10^{-6} , U 含量为 119×10^{-6} ~ 404×10^{-6} , Th/U 值为 0.47~0.87, 显示岩浆锆石特征, 21 个测点落在了谐和曲线附近(图 4e), $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(310.3\pm 2.1)\text{Ma}(\text{MSWD}=2.6, n=21)$ (图 4e)。那拉提钾长花岗岩(NLT)的锆石多呈不规则状, 少量发育震荡环带(图 4f), 长为 150~200 μm , 长宽比为 3: 2, Th、U 含量分别为 144×10^{-6} ~ 1375×10^{-6} 和 217×10^{-6} ~ 1372×10^{-6} , Th/U 值为 0.65~1.58, 21 个测点落在谐和曲线附近, $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为 $(305.2\pm 2.3)\text{Ma}(\text{MSWD}=2.4, n=21)$ (图 4f)。上述 4 个岩体可分为晚泥盆世—早石炭世

表1 西天山晚古生代花岗岩体的锆石 U-Pb 测年结果汇总表

Tab. 1 Summary of MC-ICP-MS U-Pb date of zircon from the Late Paleozoic granites in the Western Tianshan

样品号	Th	U	Th/U	加权平均年龄 (Ma, 1σ)
GZG04	167~730	189~527	0.83~1.45	356.5±2.3
HL~02	37~527	83~320	0.45~1.69	368.1±1.5
HL09	69~520	143~755	0.38~0.77	301.9±2.8
JH~04	45.4~396.6	89~454	0.48~0.87	307.0±2.1
JH~09	70~256	119~404	0.47~0.87	310.3±2.1
NLT~08	144~1375	217~1372	0.65~1.58	305.2±2.3



a. 果子沟花岗岩 (GZG-04); b. 哈勒尕提花岗岩 (HL-02); c. 哈勒尕提二长花岗岩 (HL-09); d. 精河花岗岩 (JH-04); e. 精河二长花岗岩 (JH-09); f. 那拉提钾长花岗岩 (NLT-08)

图4 西天山晚古生代花岗岩的锆石 U-Pb 年龄谱和图

Fig. 4 The zircon U-Pb concordia diagram of Late Paleozoic granites in the Western Tianshan

(果子沟花岗岩、果子沟钾长花岗岩、哈勒尕提花岗岩)和晚石炭世(精河花岗岩、精河二长花岗岩、哈勒尕提二长花岗岩、那拉提钾长花岗岩)两组。

4.2 主量元素

4个岩体的主量元素和微量元素分析数据见表2。在 TAS 图解中,它们主要落入花岗岩与石英二长岩范围(图 5a),在 K_2O-SiO_2 图解中落入高钾钙碱性系列范围(图 5b),且属于钾质花岗岩范畴(图 5c)。晚泥盆世—早石炭世岩体 SiO_2 含量为 66.76%~77.19%,全碱(K_2O+Na_2O)含量为 7.49%~8.06%, Na_2O/K_2O 值为 0.60~0.96; 铝饱和指数 A/NKC 值为 1.02~1.19,属于弱过铝质花岗岩(图 5d)。晚石炭世岩体 SiO_2 含量为 66.62%~

76.08%,全碱含量为 6.71%~8.85%, Na_2O/K_2O 值为 0.74~1.28; A/NKC 值为 0.91~1.11,属于准铝质—弱过铝质花岗岩(图 5d)。

4.3 微量元素

晚泥盆世—早石炭世岩体稀土总含量(ΣREE)为 $103.92 \times 10^{-6} \sim 195.59 \times 10^{-6}$; $(La/Yb)_N$ 为 5.05~14.32, δEu 为 0.19~0.68。晚石炭世岩体 ΣREE 为 $60.34 \times 10^{-6} \sim 265.50 \times 10^{-6}$, $(La/Yb)_N$ 值 1.98~6.49, δEu 值为 0.30~0.97。在稀土元素球粒陨石标准化配分模式图(图 6)和微量元素原始地幔标准化模式图(图 7)中,两组岩体均表现出相似的配分曲线。稀土元素配分模式均呈 LREE 富集、HREE 相对平坦的右倾型,存在不同程

表 2 西天山晚古生代花岗岩体的主量元素 (%) 和微量元素 (10^{-6}) 分析结果汇总表Tab. 2 Summary of Major (%) and trace element (10^{-6}) data for the Late Paleozoic granites in the Western Tianshan

岩性	果子沟岩体			哈勒杂提岩体			精河岩体		
	钾长花岗岩	花岗岩	花岗岩	花岗岩	二长花岗岩	二长花岗岩	花岗岩	二长花岗岩	钾长花岗岩
SiO ₂	76.68~77.19 (76.94)	66.76~67.59 (67.20)	72.08~73.08 (72.58)	74.48~76.08 (75.41)	71.83~72.09 (71.98)	72.04~73.29 (72.67)	66.62~67.60 (67.17)		
Al ₂ O ₃	12.54~12.55 (12.55)	15.32~15.71 (15.57)	13.72~14.29 (14.01)	12.28~13.17 (12.77)	13.31~13.57 (13.42)	12.75~13.49 (13.12)	13.70~14.06 (13.94)		
CaO	0.35~0.63 (0.49)	1.90~2.23 (2.05)	1.04~1.68 (1.36)	0.81~1.18 (0.94)	1.98~2.41 (2.19)	1.06~2.29 (1.68)	0.95~1.90 (1.50)		
TF ₂ O ₃	1.09~1.24 (1.17)	3.59~3.79 (3.67)	2.26~2.72 (2.49)	1.57~1.86 (1.70)	3.09~3.36 (3.23)	3.12~3.22 (3.17)	5.11~6.24 (5.54)		
K ₂ O	4.69~4.75 (4.72)	4.11~4.17 (4.15)	3.91~4.75 (4.33)	4.50~4.67 (4.57)	3.36~3.67 (3.51)	3.49~3.52 (3.51)	3.71~4.46 (4.05)		
MgO	0.12~0.15 (0.14)	1.01~1.15 (1.08)	0.60~0.63 (0.62)	0.20~0.26 (0.22)	0.77~0.84 (0.81)	0.75~0.83 (0.79)	0.90~1.08 (0.99)		
Na ₂ O	3.21~3.26 (3.24)	3.47~3.95 (3.64)	2.86~3.58 (3.22)	3.36~3.55 (3.49)	3.22~3.39 (3.32)	3.35~3.51 (3.43)	4.39~4.75 (4.53)		
P ₂ O ₅	0.01~0.01 (0.01)	0.13~0.15 (0.14)	0.06~0.09 (0.08)	0.02~0.04 (0.03)	0.08~0.10 (0.09)	0.08~0.09 (0.09)	0.23~0.26 (0.25)		
LOI	0.62~0.83 (0.73)	1.15~2.47 (2.02)	1.28~1.51 (1.40)	0.35~0.40 (0.38)	0.71~0.84 (0.76)	0.56~1.07 (0.82)	0.47~0.98 (0.66)		
Total	99.98~100.12 (100.05)	99.84~100.28 (100.02)	99.78~100.92 (100.35)	99.47~99.87 (99.67)	99.54~99.90 (99.76)	99.59~99.79 (99.69)	99.28~99.78 (99.57)		
A/NKC	1.08~1.13 (1.11)	1.02~1.15 (1.10)	1.06~1.19 (1.13)	1.02~1.03 (1.03)	0.98~1.04 (1.01)	1.00~1.11 (1.06)	0.91~1.04 (0.96)		
A/NK	1.20~1.20 (1.20)	1.40~1.54 (1.49)	1.39~1.41 (1.40)	1.18~1.22 (1.19)	1.44~1.45 (1.45)	1.33~1.45 (1.39)	1.16~1.20 (1.18)		
Na ₂ O+K ₂ O	7.95~7.96 (7.96)	7.63~8.06 (7.78)	7.49~7.61 (7.55)	7.86~8.22 (8.05)	6.71~6.89 (6.83)	6.84~7.03 (6.94)	8.45~8.85 (8.58)		
Fe ₂ O ₃	0.59~0.67 (0.63)	1.77~1.91 (1.82)	1.16~1.40 (1.28)	0.85~0.99 (0.91)	1.53~1.67 (1.60)	1.55~1.63 (1.59)	2.65~3.18 (2.85)		
FeO	0.45~0.51 (0.48)	1.63~1.69 (1.66)	0.99~1.19 (1.09)	0.65~0.78 (0.71)	1.40~1.52 (1.47)	1.41~1.43 (1.42)	2.21~2.75 (2.42)		
Mg [#]	16.15~21.56 (18.86)	36.27~37.81 (37.28)	31.79~34.85 (33.32)	20.18~21.80 (20.73)	32.78~34.12 (33.40)	32.46~34.08 (33.27)	24.52~27.75 (26.42)		
Rb	221~229 (225)	149~173 (158.83)	179.50~232 (205.75)	188.50~237 (215.17)	127~145.50 (137.17)	114~141 (127.50)	94~124.50 (112.42)		
Ba	93.60~146 (119.80)	610~696 (640.67)	447~548 (497.50)	175.50~412 (257.67)	463~499 (482.67)	482~511 (496.50)	463~663 (587.20)		
Cs	6.85~7.50 (7.18)	4.70~9.93 (8.03)	7.46~12.60 (10.03)	17.30~18.65 (18.08)	8.96~9.66 (9.31)	3.72~12.30 (8.01)	0.72~1.33 (0.96)		
Nb	18.40~22.60 (20.50)	21.80~23.70 (22.97)	15.50~16.30 (15.90)	8.70~9.40 (9.13)	9.30~10.20 (9.73)	8.90~9.70 (9.30)	12.60~14.60 (13.64)		
Ta	2.80~2.90 (2.85)	1.60~1.70 (1.63)	1.30~1.60 (1.45)	1.10~1.80 (1.40)	0.70~0.90 (0.80)	0.70~1.10 (0.90)	0.80~0.90 (0.88)		
Zr	94~96 (95.00)	260~326 (289.00)	194~209 (201.50)	133~163.00 (152)	230~263.00 (241)	220~224.00 (222)	437~517 (478)		
Hf	3.60~3.80 (3.70)	6.60~8.10 (7.20)	5.50~5.90 (5.70)	4.50~5.40 (4.83)	5.90~6.90 (6.30)	5.90~6.00 (5.95)	10.40~11.80 (11.06)		
Sr	29.10~45.80 (37.45)	178~292 (216.17)	112.50~177.50 (145)	40.90~85.70 (56.70)	148~159.50 (153.67)	102.50~153 (127.75)	134~197.50 (167.20)		

续表 2

岩性	果子沟岩体			哈勒奈提岩体			精河岩体			那拉提岩体
	钾长花岗岩	花岗岩	花岗岩	花岗岩	二长花岗岩	花岗岩	二长花岗岩	花岗岩		
Ga	14.00~14.90 (14.45)	18.00~18.60 (18.30)	16.70~18.00 (17.35)	15.50~16.50 (16.03)	16.70~17.50 (17.10)	14.90~18.80 (16.85)	19.00~21.70 (20.28)			
Th	29.30~38.40 (33.85)	15.35~17.40 (16.60)	24.20~33.80 (29.00)	20.50~22.40 (21.63)	10.85~13.50 (12.60)	10.00~13.00 (11.50)	7.66~10.20 (8.89)			
U	5.03~6.04 (5.54)	3.24~3.52 (3.37)	3.88~5.83 (4.86)	2.28~3.48 (3.02)	1.41~2.46 (2.03)	2.27~2.29 (2.28)	0.95~2.38 (1.58)			
V	5.00~5.00 (5.00)	39.00~43.00 (41.33)	20.00~21.00 (20.50)	7.00~10.00 (8.00)	37.00~40.00 (38.67)	37.00~37.00 (37.00)	27.00~36.00 (32.00)			
Y	22.20~23.20 (22.70)	20.40~30.10 (24.33)	19.50~19.60 (19.55)	20.90~30.10 (25.53)	31.50~34.90 (32.93)	30.80~34.60 (32.70)	43.30~72.10 (63.64)			
Ti	480~600 (540)	3000~3120 (3060)	1560~1800 (1680)	900~1260 (1040)	2520~2760 (2660)	2520~2700 (2610)	5520~5940 (5664)			
La	20.60~23.50 (22.05)	32.10~41.80 (36.20)	38.90~41.10 (40.00)	7.70~22.40 (16.70)	28.30~29.10 (28.80)	30.00~31.10 (30.55)	21.00~47.60 (28.86)			
Ce	44.90~49.60 (47.25)	65.60~84.20 (73.30)	82.60~83.20 (82.90)	27.60~57.90 (45.17)	62.30~64.00 (63.37)	62.60~68.00 (65.30)	41.60~101 (67.38)			
Pr	4.81~5.42 (5.12)	7.40~9.22 (8.15)	8.71~9.03 (8.87)	2.02~5.54 (4.08)	7.23~7.37 (7.30)	6.74~7.16 (6.95)	4.92~11.40 (8.45)			
Nd	16.50~18.30 (17.40)	26.40~32.70 (29.17)	30.40~31.60 (31.00)	7.70~19.50 (14.57)	27.30~27.70 (27.57)	27.10~28.20 (27.65)	22.90~49.50 (38.98)			
Sm	3.30~3.69 (3.50)	5.12~6.25 (5.68)	5.18~5.71 (5.45)	2.19~4.33 (3.54)	5.84~6.22 (5.97)	5.97~6.22 (6.10)	6.04~11.00 (9.40)			
Eu	0.20~0.27 (0.24)	1.10~1.21 (1.14)	0.66~0.68 (0.67)	0.41~0.81 (0.55)	1.02~1.15 (1.08)	1.10~1.15 (1.13)	2.00~2.73 (2.40)			
Gd	2.97~3.52 (3.25)	4.47~5.68 (5.03)	4.34~4.64 (4.49)	2.50~4.31 (3.58)	5.79~6.09 (5.90)	5.23~5.54 (5.39)	6.42~11.85 (10.14)			
Tb	0.51~0.55 (0.53)	0.66~0.86 (0.75)	0.62~0.66 (0.64)	0.46~0.74 (0.62)	0.94~0.99 (0.96)	0.88~1.00 (0.94)	1.13~1.96 (1.71)			
Dy	3.46~3.51 (3.49)	3.75~5.33 (4.49)	3.48~3.68 (3.58)	3.24~4.89 (4.07)	5.65~6.16 (5.85)	5.23~5.74 (5.49)	6.49~11.70 (10.10)			
Ho	0.73~0.75 (0.74)	0.75~1.07 (0.88)	0.70~0.71 (0.71)	0.76~1.05 (0.90)	1.19~1.24 (1.21)	1.12~1.18 (1.15)	1.44~2.56 (2.24)			
Er	2.23~2.38 (2.31)	2.19~3.10 (2.59)	1.91~1.96 (1.94)	2.34~3.14 (2.74)	3.44~3.66 (3.53)	3.32~3.61 (3.47)	4.39~8.27 (7.01)			
Tm	0.36~0.37 (0.37)	0.32~0.46 (0.37)	0.28~0.29 (0.29)	0.38~0.46 (0.43)	0.48~0.54 (0.50)	0.48~0.55 (0.52)	0.71~1.25 (1.06)			
Yb	2.63~2.77 (2.70)	2.18~3.22 (2.55)	1.95~2.03 (1.99)	2.62~3.29 (2.98)	3.15~3.58 (3.39)	3.14~3.65 (3.40)	4.94~8.33 (7.05)			
Lu	0.43~0.44 (0.44)	0.33~0.49 (0.38)	0.28~0.29 (0.29)	0.42~0.48 (0.45)	0.46~0.53 (0.49)	0.50~0.52 (0.51)	0.73~1.21 (1.04)			
ΣREE	103.92~114.78 (109.35)	152.37~195.59 (170.69)	182.69~182.90 (182.80)	60.34~122.34 (100.37)	153.37~158.14 (155.92)	153.41~163.62 (158.52)	124.71~265.50 (195.82)			
(La/Yb) _N	5.05~6.07 (5.56)	8.82~10.48 (9.77)	13.02~14.32 (13.67)	2.00~5.01 (3.71)	5.50~6.10 (5.79)	5.79~6.49 (6.14)	1.98~4.64 (2.82)			
δEu	0.19~0.23 (0.21)	0.61~0.68 (0.64)	0.38~0.43 (0.41)	0.30~0.58 (0.47)	0.52~0.59 (0.55)	0.58~0.59 (0.59)	0.61~0.97 (0.77)			
T _z /°C	710~719 (715)	781~795 (787)	753~790 (772)	731~751 (740)	752~759 (755)	742~787 (765)	805~870 (830)			

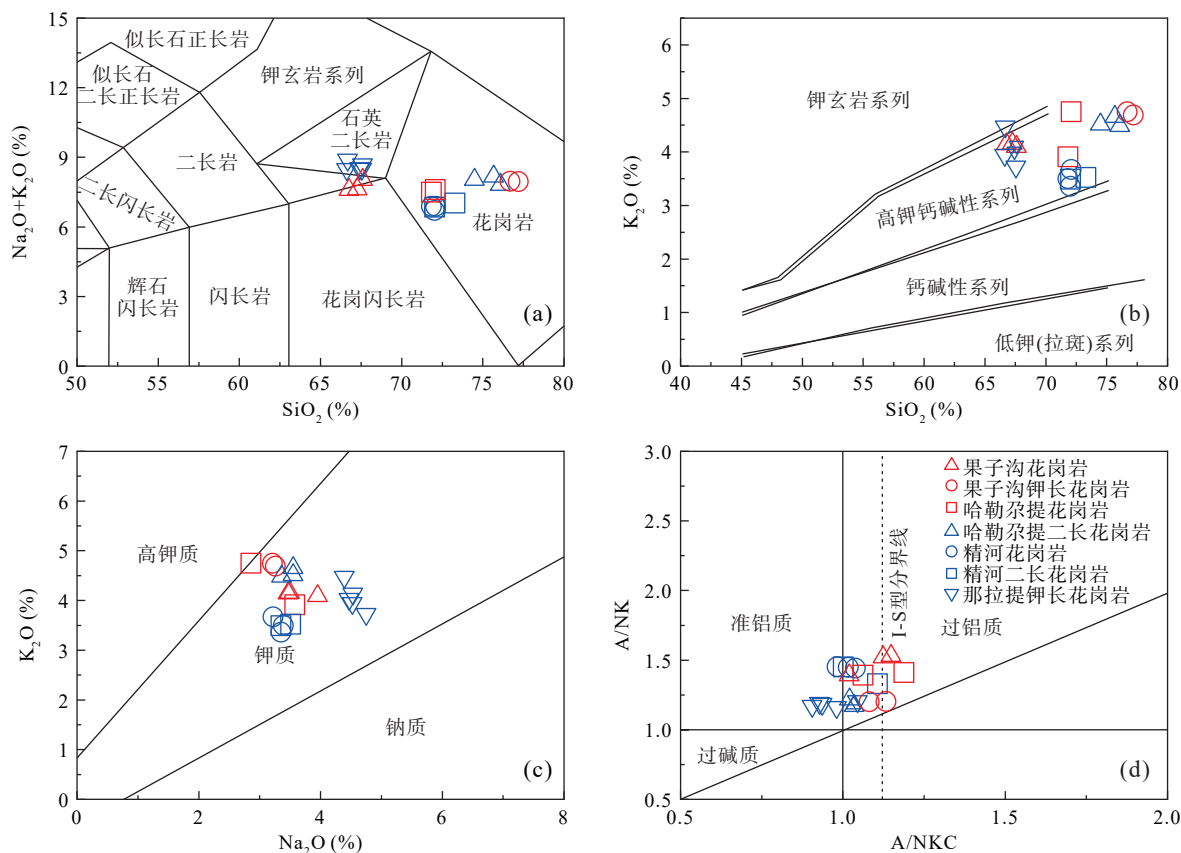


图5 西天山晚古生代花岗岩的全碱-二氧化硅(TAS)图(a, 据 Middlemost, 1994)、 K_2O-SiO_2 图(b, 据 Peccerillo et al., 1976)、 Na_2O-K_2O 图(c, 据 Middlemost, 1972)和 $A/NK-A/NK$ 图(d, 据 Maniar et al., 1989)

Fig. 5 (a) Geochemical classification diagrams of TAS, (b) K_2O vs. SiO_2 , (c) Na_2O vs. K_2O , (d) $A/NK-A/NK$ of late Paleozoic granites in the Western Tianshan

度的 Eu 负异常, 其中, 前者相较于后者 Eu 异常更明显; 微量元素蛛网图显示, 所有岩体均表现为富集 K、Rb、Th 等大离子亲石元素而亏损 Nb、Ta、Ti 等高场强元素, 前者具有明显的 Ba 亏损, 而后者 Nb、Ta 更亏损。

4.4 全岩 Sr-Nd 同位素

晚泥盆世—早石炭世岩体 $^{87}Sr/^{86}Sr$ 值为 0.7159~0.7772, $^{143}Nd/^{144}Nd$ 值为 0.512233~0.512395(表 3), 根据锆石 U-Pb 年龄计算获得 $(^{87}Sr/^{86}Sr)_i$ 值为 0.7065~0.7095, $\epsilon_{Nd}(t)$ 均为负值, 介于 -1.3~-3.8, 二阶段模式年龄 T_{DM2-Nd} 为 1219~1428 Ma。晚石炭世岩体的 $^{87}Sr/^{86}Sr$ 值为 0.7140~0.7718, $^{143}Nd/^{144}Nd$ 值为 0.512515~0.512859, 其 $(^{87}Sr/^{86}Sr)_i$ 值为 0.7050~0.7062, $\epsilon_{Nd}(t)$ 值介于 +0.8~+6, T_{DM2-Nd} 年龄为 581~1044 Ma。

4.5 锆石 Hf 同位素

晚泥盆世—早石炭世岩体的 $^{176}Hf/^{177}Hf$ 值为 0.282556~0.282702(表 4), 依据锆石 U-Pb 年龄计算 $\epsilon_{Hf}(t)$ 值为 +0.3~+5.0, 二阶段 Hf 模式年龄 T_{DM2-Hf}

值为 1039~1351 Ma。晚石炭世岩体的 $^{176}Hf/^{177}Hf$ 值为 0.282706~0.283027, $\epsilon_{Hf}(t)$ 值为 +4.1~+15.1, T_{DM2-Hf} 为 358~1060 Ma。

5 讨论

5.1 岩石成因

根据岩浆源区性质和形成机制差异, 花岗岩可分为 I 型、S 型、A 型和 M 型(Chappell, 1999)。果子沟岩体、哈勒尕提岩体暗色矿物以黑云母为主, 精河岩体和那拉提岩体以黑云母、角闪石为主, 均未发现原生过铝质矿物(白云母、瑾青石等), 因此它们不属于 S 型花岗岩。主量元素特征显示, 晚泥盆世—早石炭世果子沟钾长花岗岩、花岗岩、哈勒尕提花岗岩和晚石炭世哈勒尕提二长花岗岩、精河花岗岩和二长花岗岩高硅($SiO_2=66.76\%\sim77.19\%$)、富碱($K_2O+Na_2O=6.71\%\sim8.39\%$)、富钾($K_2O=3.09\%\sim4.75\%$)、贫

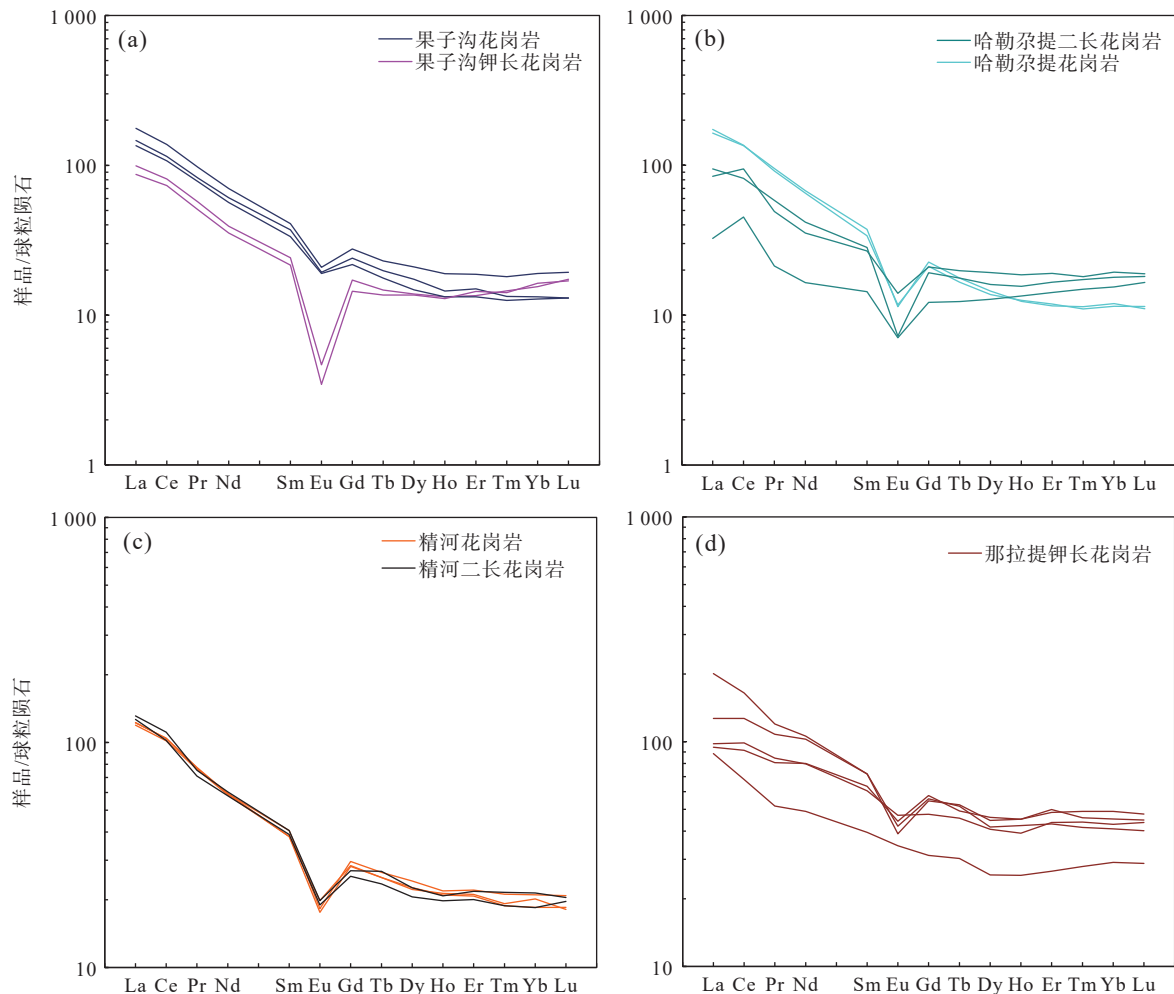


图6 西天山晚古生代花岗岩的稀土元素配分模式图(球粒陨石标准化数据来自 Sun et al., 1989)

Fig. 6 Chondrite-normalized REE patterns of late Paleozoic granites in the Western Tianshan

铝(图 8a、图 8b、图 8c), 属高钾钙碱性系列花岗岩; $10^4\text{Ga}/\text{Al}$ 值介于 2.1~2.63(均值为 2.32), SiO_2 与 P_2O_5 呈负相关关系(图 8d), 呈 I 型花岗岩的特征(杜开明, 2021), 而有别于 A 型花岗岩。那拉提钾长花岗岩的 SiO_2 含量稍低(66.62%~67.60%)、富碱, 属准铝质, 具高钾钙碱性—钾玄岩过渡系列花岗岩的特征; $10^4\text{Ga}/\text{Al}$ 的值介于 2.62~2.92, Zr 含量介于 $437\times 10^{-6}\sim 517\times 10^{-6}$, $\text{Zr}+\text{Y}+\text{Nb}+\text{Ce}$ 含量介于 $563.5\times 10^{-6}\sim 670\times 10^{-6}$, 显示出与 A 型花岗岩相似的地球化学特征(PérEz-SobA et al., 2010; Breiter et al., 2013; Wang et al., 2018; 卜涛等, 2022), 而非典型的高分异花岗岩, 理由如下: 那拉提钾长花岗岩 FeO^{T} 含量 4.6%~5.6%(>1%, 王强等, 2000), 据锆石饱和温度公式 $T_{\text{Zr}}(^{\circ}\text{C})=10\,108/(\text{LnDzr}(496\,000/\text{熔体})+1.16\text{M}+0.32)-273.15$ (Boehnke et al., 2013), 计算获得其锆石饱和温度为 805~870 $^{\circ}\text{C}$ (吴福元等, 2017); 其次, 那拉提钾长花岗岩 Rb 的含量

$94\times 10^{-6}\sim 124\times 10^{-6}$ ($<270\times 10^{-6}$; Pearce et al., 1984), Cs 含量 $0.72\times 10^{-6}\sim 1.33\times 10^{-6}$, 显示结晶分异过程中 Cs 含量未显著增大, 也不同于高分异花岗岩(吴福元等, 2017, 卜涛等, 2024), 最后, 那拉提钾长花岗岩的 Zr/Hf 值平均 39, 说明研究区岩体形成过程中经历了中等分异(Breiter et al., 2014; 朱生强等, 2024), 微量元素 Y/Nb、Ce/Nb 值分别为 3.44~5.19、3.30~7.06 进一步表明那拉提钾长花岗岩区别于高分异花岗岩与 A2 型花岗岩相类似(Eby, 1992; 郝增元等, 2018)。综上所述, 研究区果子沟岩体、哈勒尕提岩体、精河岩体为弱过铝质 I 型花岗岩, 那拉提岩体为准铝质 A2 型花岗岩。

在哈克图解上晚泥盆世—早石炭世果子沟花岗岩、哈勒尕提花岗岩和晚石炭世哈勒尕提二长花岗岩、精河花岗岩和二长花岗岩、那拉提钾长花岗岩随着 SiO_2 含量的增加, Al_2O_3 、 Na_2O 、 K_2O 无明显变化而 P_2O_5 、 MgO 、 $\text{Fe}_2\text{O}_3^{\text{T}}$ 、 TiO_2 与微量元素 Ba、Zr 逐渐降低,

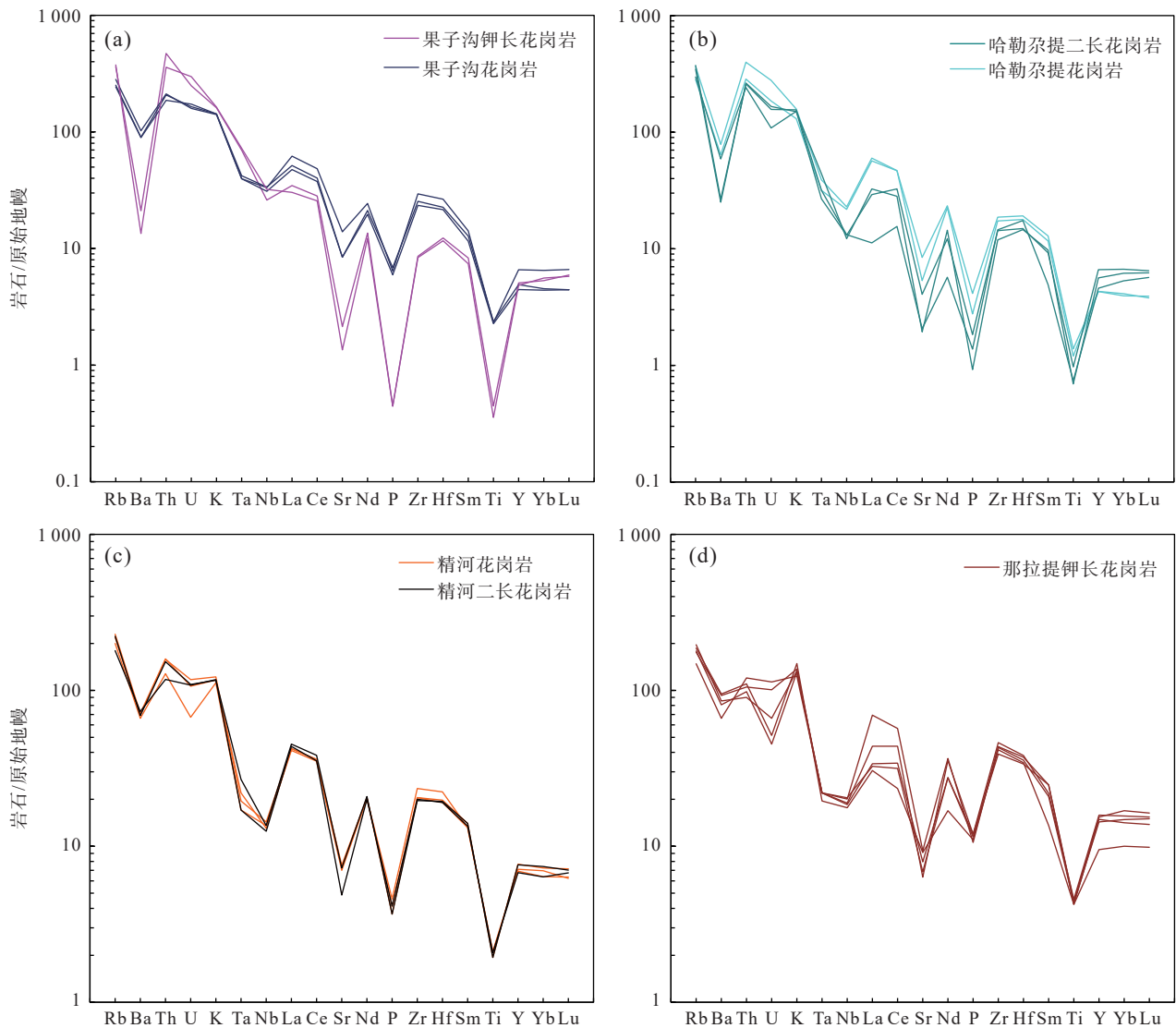


图7 西天山晚古生代花岗岩的微量元素蛛网图(原始地幔标准化数据来自 Sun et al., 1989)

Fig. 7 Primitive mantle-normalized trace elements spider diagrams of late Paleozoic granites in the Western Tianshan

呈负相关(图8),表明在岩浆演化中伴随着镁铁质基性矿物的分离结晶, SiO_2 与 P_2O_5 、 TiO_2 的负相关关系可能指示了磷灰石和含 Ti 矿物(如榍石、钛铁矿)的分离结晶或源区残留(图8d、图8g)。

5.2 源区特征

晚泥盆世—早石炭世岩体和晚石炭世岩体的 Nb/Ta 值分别为 6.6~14.62(均值 11.1)4.9~16.2(均值 11.9), 远小于幔源岩浆(~17.5)(Hofmann, 1988), 而接近于地壳物质(11~12), 暗示陆壳物质较程度卷入岩浆源区。同时, 它们的 Zr/Hf 值分别为 35.27~40.72(均值为 38.21)、36.6~43.9(均值为 40.54), 均显著高于壳源岩石(~33)(Taylor et al., 1995)而更接近幔源岩石(36)(Hofmann, 1988), 暗示源区存在地幔物

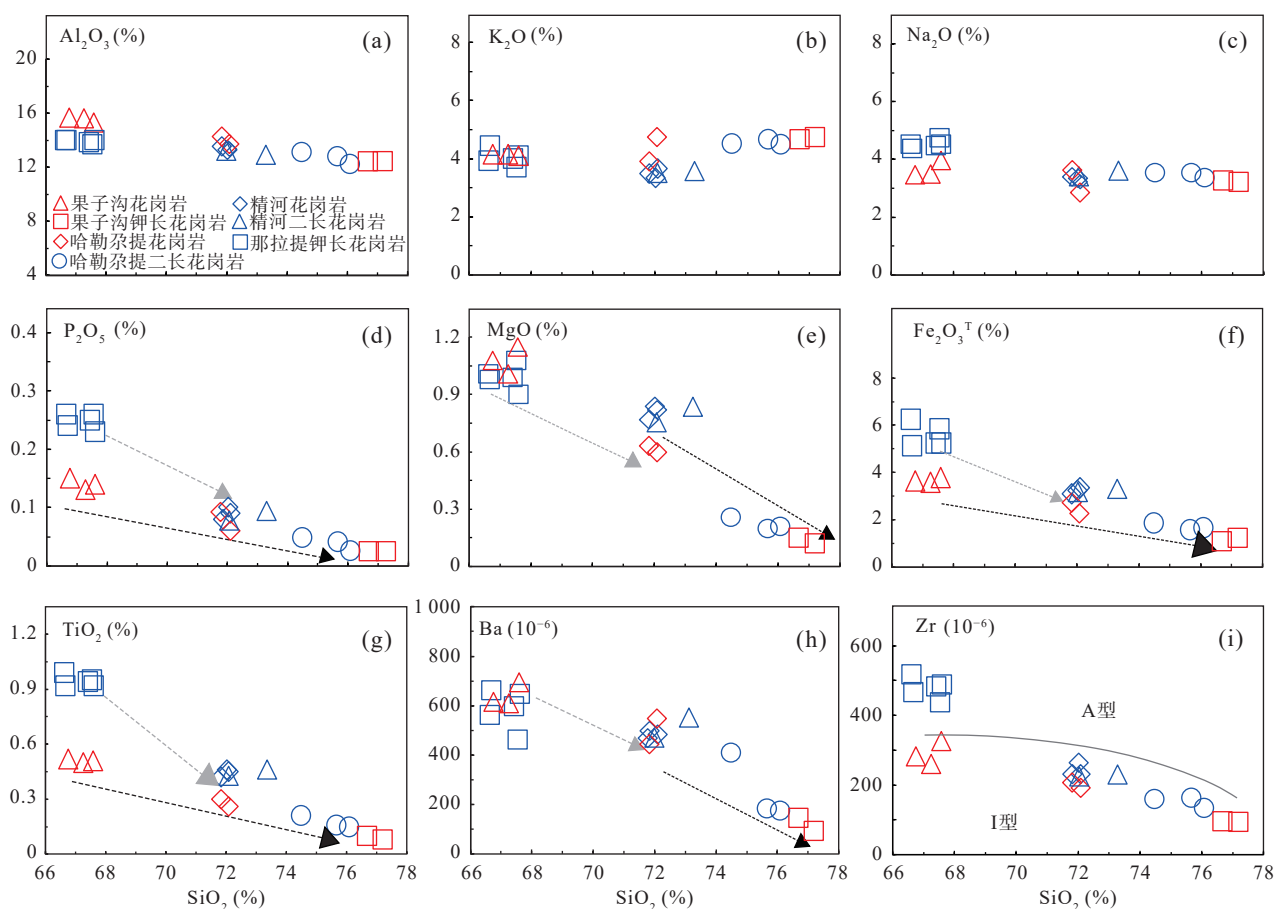
质的参与。两组花岗岩的 $\text{Mg}^\#$ 值分别为 22~38、20~34, 均小于 40(Rapp et al., 1995), 说明岩浆主要来源于下地壳的部分熔融。

晚泥盆世—早石炭世果子沟花岗岩、哈勒尕提花岗岩的 $(^{87}\text{Sr}/^{86}\text{Sr})_i$ 为 0.7063~0.7095, $\varepsilon_{\text{Nd}}(t)$ 值介于 -1.3~-3.79(图9a、图9b), 表明源区物质来自地壳或地壳物质发生过强烈混染。此外, Nd 同位素二阶段模式年龄 $T_{\text{DM}2-\text{Nd}}$ 介于 1219~1428 Ma, 表明其源区主要为较古老的地壳物质(朱生强等, 2024), 晚石炭世哈勒尕提二长花岗岩、精河花岗岩、那拉提钾长花岗岩相对于晚泥盆世—早石炭世具有较低的 $(^{87}\text{Sr}/^{86}\text{Sr})_i$, $\varepsilon_{\text{Nd}}(t)$ 值介于 +0.8~+5.9(图9a、图9b), $T_{\text{DM}2-\text{Nd}}$ 介于 581~1044 Ma, 可能与新生地壳部分熔融有关。这种

表3 西天山晚古生代花岗岩体的 Sr-Nd 同位素分析结果

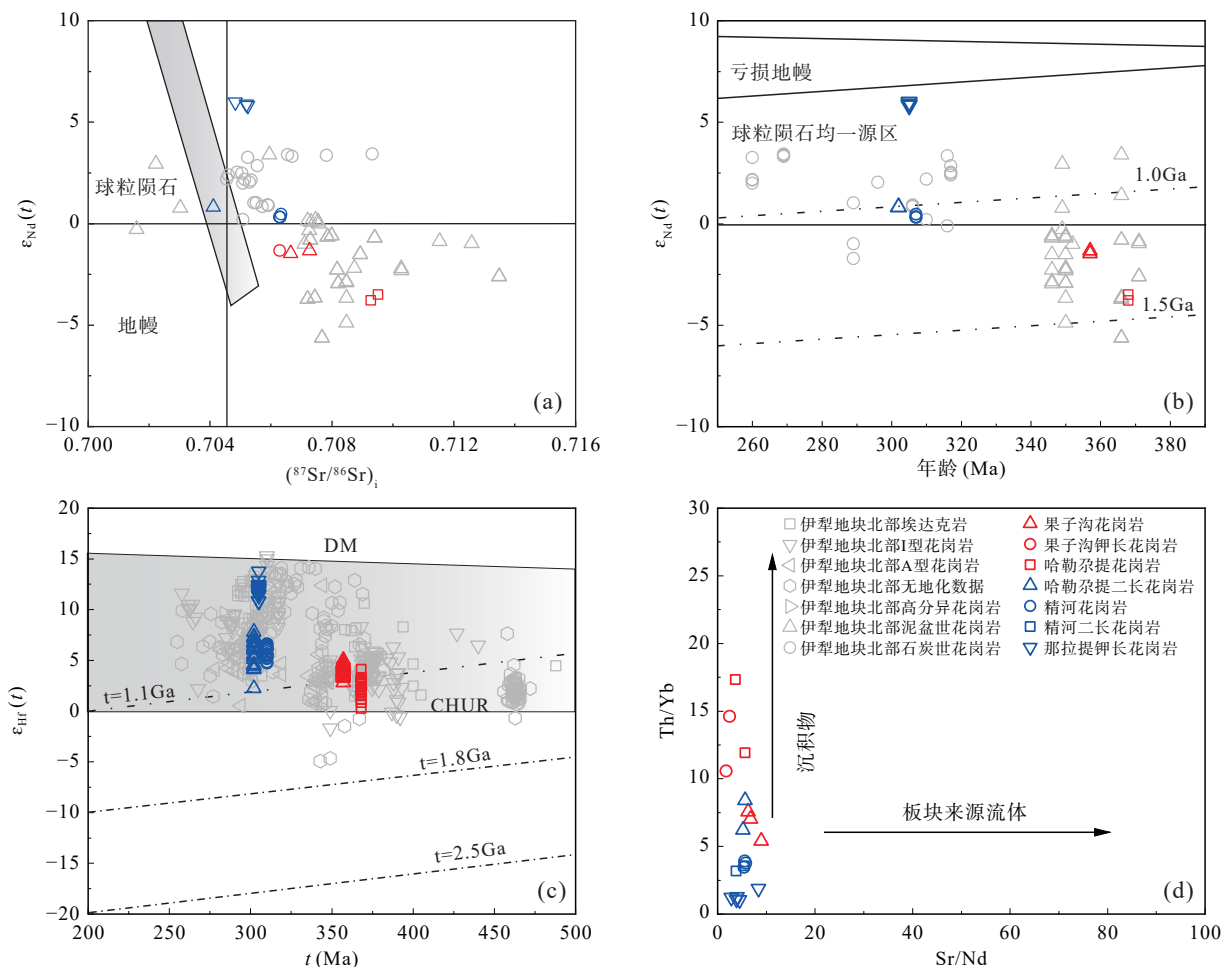
Tab. 3 Sr and Nd isotope compositions of the Late Paleozoic granites in the Western Tianshan

原始 样号	t(Ma)	Rb(10^{-6})	Sr(10^{-6})	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	Sm(10^{-6})	Nd(10^{-6})	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\varepsilon_{\text{Nd}}(0)$	$\varepsilon_{\text{Nd}}(t)$	T_{DM}	$T_{2\text{DM}}$
GZG-01	357	221	45.8	13.962 52	0.777 246	0.706 28	3.69	18.3	0.121 831	0.512 395	-4.74	-1.33	1 255	1 219
GZG-02	357	173.0	292	1.714 353	0.715 980	0.707 27	6.25	32.7	0.115 483	0.512 380	-5.03	-1.33	1 197	1 219
GZG-05	357	154.5	178.5	2.504 536	0.719 376	0.706 65	5.67	28.4	0.120 628	0.512 385	-4.94	-1.47	1 255	1 230
HL-01	368	179.5	177.5	2.926 194	0.724 614	0.709 28	5.71	31.6	0.109 177	0.512 233	-7.9	-3.79	1 338	1 428
HL-02	368	232	112.5	5.967 226	0.740 784	0.709 52	5.18	30.4	0.102 953	0.512 233	-7.9	-3.5	1 263	1 404
HL-10	302	220	40.9	15.564 54	0.771 886	0.705	4.33	19.5	0.134 164	0.512 555	-1.62	0.8	1 143	1 001
JH-05	307	139.0	153.5	2.620 254	0.717 723	0.706 28	5.84	27.7	0.127 385	0.512 515	-2.4	0.32	1 124	1 044
JH-06	307	127.0	148.0	2.483 013	0.717 094	0.706 25	5.84	27.3	0.129 251	0.512 520	-2.3	0.34	1 140	1 042
JH-07	307	145.5	159.5	2.639 607	0.717 825	0.706 18	6.22	27.7	0.135 673	0.512 540	-1.91	0.51	1 194	1 031
NLT-04	305	124.5	167.5	2.150 758	0.714 202	0.704 87	9.26	37.2	0.150 401	0.512 852	4.17	5.99	722	581
NLT-06	305	113.5	144.5	2.272 82	0.715 096	0.705 23	9.69	37.4	0.156 544	0.512 859	4.31	5.87	781	589
NLT-07	305	94.1	134.0	2.031 991	0.714 084	0.705 26	11.00	47.9	0.138 753	0.512 820	3.55	5.81	675	595

图8 西天山晚古生代花岗岩全岩 SiO_2 协变量图Fig. 8 The whole-rock SiO_2 covariation diagram of the late Paleozoic Granites in the Western Tianshan

相对亏损的放射性成因同位素特征在整个中亚造山带晚古生代—中生代普遍存在 (Han et al., 1997; Wu et al.,

2000; 王涛等, 2008; 冯光英等, 2016), 表明随着时间的推移, 有新的亏损地幔物质的加入。西天山地区晚石



a. $(^{87}Sr/^{86}Sr)_i - \epsilon_{Nd}(t)$ 图 (据 Han et al., 2011 修改); b. 年龄- $\epsilon_{Nd}(t)$ 图 (据 Huang et al., 2020 修改); c. 年龄- $\epsilon_{Hf}(t)$ 图 (据 Huang et al., 2020 修改); d. Sr/Nd-Th/Yb 图解 (据章永梅等, 2016 修改) 背景数据来自 (Long et al., 2011; Huang et al., 2020)

图9 西天山晚古生代花岗岩源区判别图

Fig. 9 Source discrimination plots for the late Paleozoic granites in Western Tianshan

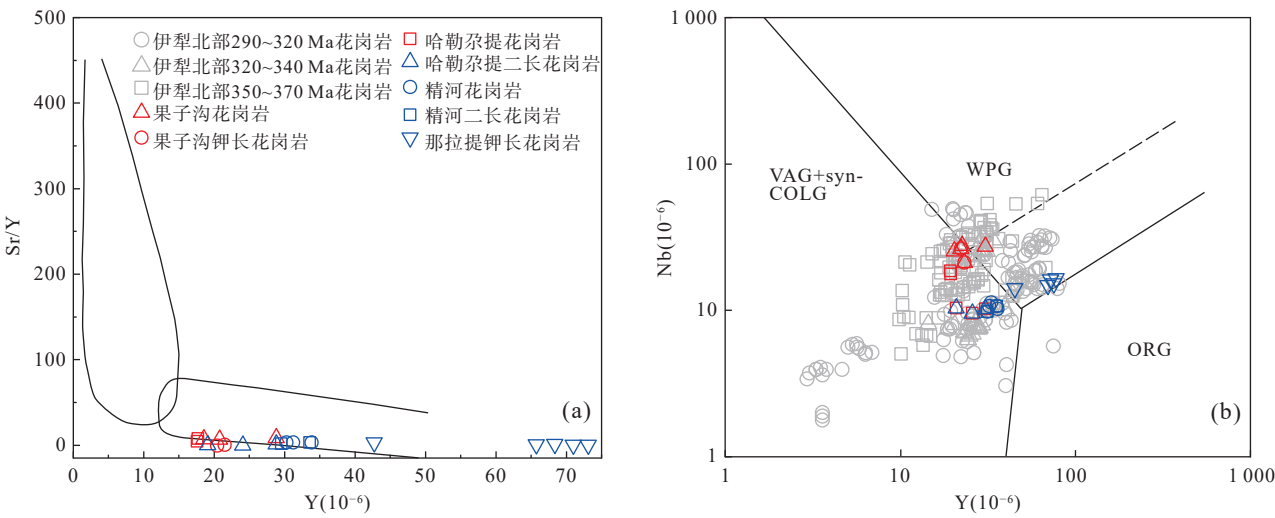
炭世同期的基性岩浆活动强烈 (Wang et al., 2006; Tang et al., 2013; 杨蓉等, 2017; 陈有忻等, 2023), 进一步表明该时期的花岗岩可能与幔源岩浆的底侵有关。

在年龄- $\epsilon_{Hf}(t)$ 图中, 晚泥盆世—早石炭世和晚石炭世岩体的 $\epsilon_{Hf}(t)$ 值均位于球粒陨石 CHUR 演化线与亏损地幔演化线之间 (图 9c)。结合前人研究, 幔源物质参与花岗岩成岩过程的方式可能有两种情形: 第一种为幔源岩浆与其诱发的地壳物质部分熔融形成的长英质岩浆在地壳深部混合形成壳幔混源岩浆 (邱检生等, 2008), 这种岩浆 $\epsilon_{Hf}(t)$ 变化于正值和负值之间; 第二种为幔源岩浆先底侵到地壳基底岩石中形成新生地壳, 然后在后期热事件的影响下, 由新生地壳和古老基底地壳构成的混合地壳原岩发生部分熔融而形成混合岩浆 (邱检生等, 2008), 这种岩浆的 $\epsilon_{Hf}(t)$ 均为正值 (Kemp et al., 2007; 王盼龙等, 2023)。笔者研究

的所有岩体锆石均为正的 $\epsilon_{Hf}(t)$ 值, 推测这些岩体的岩浆源区可能经历了后一种壳幔混合模式。晚石炭世哈勒尕提二长花岗岩、精河二长花岗岩、那拉提钾长花岗岩均比较接近亏损地幔演化线 (图 9c), 具有相对晚泥盆世—早石炭世岩体较高的 $\epsilon_{Hf}(t)$ 正值, 指示其源区是以新生下地壳部分熔融为主, 可能幔源物质比例增加 (张京渤等, 2019)。此外, 从 Sr/Nd-Th/Yb 图中可以看出果子沟岩体、哈勒尕提岩体洋壳沉积物参与较显著 (图 9d)。

5.3 构造背景

前人将西天山的岩浆活动划分为 3 期。其中, 中晚奥陶世 (约 460~395 Ma)、晚泥盆世—早石炭世 (约 375~310 Ma) 的岩浆活动与洋壳俯冲作用有关 (图 10), 而晚石炭世—二叠纪 (约 310~260 Ma) 的岩浆活动则与碰撞—后碰撞造山作用有关 (表 4; Gao et



a.Y-Sr/Y 图解(据章永梅等, 2016 修改); b.Y-Nb 构造判别图(据 Pearce et al., 1984 修改); 背景数据来源(章永梅等, 2016; 郝增元等, 2018; Huang et al., 2020; 杜开明, 2021); VAG.火山弧花岗岩; syn-COLG.同碰撞花岗岩; WPG.板内花岗岩; ORG.洋中脊花岗岩; Post-COLG.后碰撞花岗岩

图10 西天山晚古生代花岗岩构造环境判别图

Fig. 10 Tectonic discriminating diagrams for the late Paleozoic granites in Western Tianshan

表 4 西天山晚古生代花岗岩体的锆石 Lu-Hf 同位素分析结果

Tab. 4 Hf isotope data of zircon from the Late Paleozoic granites in the Western Tianshan

测点号	t(Ma)	¹⁷⁶ Hf/ ¹⁷⁷ Hf	2σ	ε _{Hf} (0)	ε _{Hf} (t)	t _{DM} (Ma)	t _{DM2} (Ma)	f _{LW} Hf
GZG-04	357	0.282 641-0.282 702	0.000 017-0.000 024	-2.50~-4.6	2.80~5.00	789~882	1 039~1 180	-0.93~-0.97
HL-02	368	0.282 556-0.282 664	0.000 016-0.000 029	-3.82~-7.64	0.30~4.10	826~980	1 106~1 351	-0.96~0.99
HL-09	302	0.282 706-0.282 811	0.000 019-0.000 039	-2.34~1.41	4.10~7.80	635~785	825~1 060	-0.89~-0.98
JH-09	310	0.282 723-0.282 777	0.000 016-0.000 036	-1.74~0.16	4.70~6.60	679~755	895~1 016	-0.93~0.97
NLT-08	305	0.282 828-0.283 027	0.000 015-0.000 03	1.99~9.01	8.20~15.10	341~623	358~795	-0.9~0.97

al., 2011; Xiao et al., 2013; Han et al., 2016; 俎波, 2016; 王冠南, 2018; 张连昌等, 2022; 黄河等, 2024; 孙吉明等, 2024)。

笔者研究的那拉提岩体具有 A2 型花岗岩的地球化学特征, 而晚古生代其他岩体均不同程度富集轻稀土、大离子亲石元素等, 而亏损重稀土、高场强元素等, 显示典型弧岩浆岩的地球化学特征(Gao et al., 2009; Long et al., 2011; Xiao et al., 2013)(图 6、图 7)。此外, 张力强等(2014)通过伊犁地块北缘奥陶系砂岩的地球化学研究, 提出其形成于活动大陆边缘环境(朱志新等, 2013); 章永梅等(2016)通过对伊犁地块北缘呼斯特杂岩体(380~365 Ma)研究, 认为其形成于北天山洋向伊犁地块俯冲的高峰期(Han et al., 2010; 顾雪祥等, 2014), 而早石炭世以后北天山洋进入收缩阶段(Wang et al., 2006; 王冠南, 2018)。综上所述, 笔者认为晚泥盆世—早石炭世果子沟花岗岩, 哈勒尕提花岗岩和晚石炭世精河花岗岩和二长花岗岩形成于

北天山洋向伊犁地块俯冲的构造环境, 而那拉提钾长花岗岩(305 Ma)和哈勒尕提二长花岗岩(301 Ma)可能形成于后碰撞的构造环境; 在这一俯冲-碰撞的构造转换, 暗示北天山洋的闭合时限可能早于晚石炭世。

5.4 成矿意义

西天山地区的矿床成因类型多样, 其中尤以中酸性侵入岩有关的斑岩-矽卡岩矿床最为发育(张连昌等, 2006; 朱永峰等, 2007; Yang et al., 2009; 毛景文等, 2014; Zhao et al., 2014; Gao et al., 2018; 李紫源等, 2021; Wang et al., 2024), 而博罗科努成矿带是西天山地区最重要的浅成低温热液型金矿床、斑岩型铜钼矿床、矽卡岩型铁铜钼铅锌矿床的产出地(王新利等, 2013, 2014, 2016; 顾雪祥等, 2014, 2016; 薛春纪等, 2014; Shen et al., 2017; Han et al., 2020; 张连昌等, 2022)。博罗科努成矿带与中酸性侵入岩有关的矽卡岩-斑岩-热液脉型

Fe、Cu、Mo、Pb、Zn 成矿系统,是在晚古生代北天山洋向伊犁地块之下俯冲的活动大陆边缘背景下形成的(顾雪祥等, 2014)。此外,前人提出后碰撞环境也是浅成低温热液型金矿形成的有利构造背景(张京渤等, 2019)。

前人研究表明,中亚成矿域斑岩 Cu-Mo 矿床主要出露在其西段,成矿岩石类型最常见二长花岗岩、花岗闪长岩、花岗岩、石英二长闪长岩、花岗闪长斑岩等,以钙碱性-高钾钙碱性为主,具高氧化性;成矿年代以古生代为特色,成矿构造背景多与俯冲岩浆弧有关,个别属后碰撞陆内造山背景(高俊等, 2019)。地处中亚造山带西段的西天山伊犁地块北缘以酸性侵入岩为主(黄杰等, 2018; 高俊等, 2019),并伴有铜多金属矿化作用,成岩成矿年代主要集中在泥盆世—早石炭世和晚石炭世—二叠世(王冠南, 2018)。文中研究对象位于伊犁地块北缘,也具有上述类似特征,

其主要岩性为二长花岗岩、花岗岩、钾长花岗岩,具高钾钙碱性特征, Sr/Y 值 1.59~9.7, 具有典型岛弧岩浆特征。

熔体的氧逸度($\text{Fe}_2\text{O}_3/\text{FeO}$, 值越大氧逸度越高)和结晶分异程度(Rb/Sr, 值越大分异程度越高)控制成矿专属性(冷成彪等, 2020)。Cu-Fe-Mo-Zn 主要与 $\text{Fe}_2\text{O}_3/\text{FeO}^T > 0.4$ 的氧化性岩浆有关,而 Au、Sn 与 $\text{Fe}_2\text{O}_3/\text{FeO}^T < 0.4$ 的还原性岩浆有关。晚泥盆世岩体和晚石炭世岩体的 $\text{Fe}_2\text{O}_3/\text{FeO}^T$ 值均为 0.55~0.60, $\text{Fe}_2\text{O}_3/\text{FeO}$ 值分别为 1.08~1.17、1.08~1.32, Rb/Sr 值分别为 0.6~2.1、0.6~5.4。在 SiO_2 - $\text{Fe}_2\text{O}_3/\text{FeO}^T$ 的图解中(图 11)所有样品均落入氧化性岩区域,在 Rb/Sr- $\text{Fe}_2\text{O}_3/\text{FeO}$ 的图解中,所有样品均在 Cu-Mo 成矿区域,说明该地区具有形成 Cu-Mo 矿床的潜力,值得进行更深层次的研究与勘探工作。

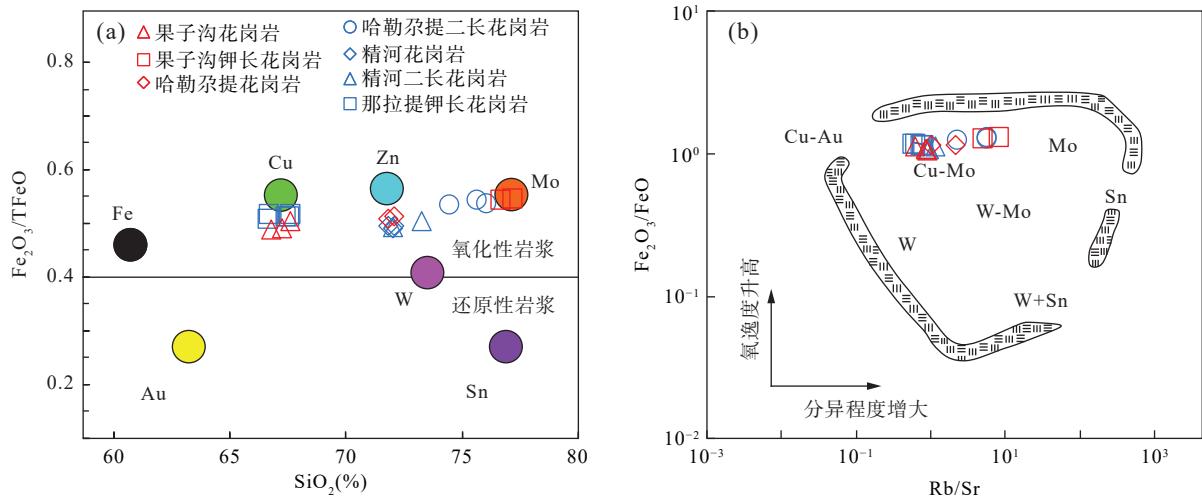


图 a 据 Meinert(1995)、冷成彪等(2020)修改, 图 b 据 Blevin 等(1996)、冷成彪等(2020)修改

图 11 岩石化学组成与金属成矿专属性判别图

Fig. 11 Discrimination diagrams showing the relationships between lithochemistry and mineralization of the granitoids

6 结论

(1)果子沟花岗岩,哈勒尕提花岗岩和二长花岗岩、精河花岗岩和二长花岗岩、那拉提钾长花岗岩的锆石 U-Pb 年龄分别为 (356.5 ± 2.3) Ma、 (368.1 ± 1.5) Ma 和 (301.9 ± 2.8) Ma, (307.0 ± 2.1) Ma 和 (310.3 ± 2.1) Ma、 (305.2 ± 2.3) Ma, 分为晚泥盆世—早石炭世和晚石炭世两期。

(2)果子沟花岗岩,哈勒尕提花岗岩和二长花岗岩、精河花岗岩和二长花岗岩高硅、富碱、贫铝,属弱

过铝质 I 型花岗岩;那拉提钾长花岗岩为准铝质 A2 型。4 个岩体总体上均为轻稀土富集的右倾型,轻稀土较重稀土分异明显,均不同程度富集大离子亲石元素 K、Rb、Th, 亏损 Nb、Ta、Ti、Sr、P 等高场强元素。

(3)晚泥盆世岩体形成于俯冲环境,岩浆来源于古老地壳部分熔融,而晚石炭世岩体主要形成于碰撞后环境,源于新生地壳部分熔融,两期均有幔源物质参与。

(4)博罗科努地区的晚泥盆世—晚石炭世花岗岩类具有 Cu-Mo 矿床的成矿潜力,值得进行更深层次的研究与勘探工作。

利益冲突声明 (Conflict of Interests):

所有作者声明不存在利益冲突。

All authors disclose no relevant conflict of interests.

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