

DOI: 10.19657/j.geoscience.1000-8527.202509010047

青藏高原东南缘后碰撞埃达克质岩石的地球化学特征及古高程指示

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摘要: 由于缺乏对青藏高原东南缘新生代以来隆升过程的详细刻画, 目前仍无法全面理解对青藏高原后碰撞以来隆升过程。青藏高原后碰撞背景下形成了一系列C型埃达克岩, 其独特的高 K_2O/Na_2O , 强烈的轻重稀土分异及低Yb特征被认为与地壳增厚相关, 因此记录了隆升过程的关键信息。本文对青藏高原东南缘滇西维西地区的埃达克质花岗岩和石英二长岩开展锆石U-Pb定年及Hf同位素以及全岩地球化学及Nd同位素研究, 以探究其成因及其与青藏高原东南缘地壳增厚和隆升过程的联系。结果显示维西花岗岩的结晶年龄为40 Ma, 石英二长岩结晶年龄为37~33 Ma, 表明这些岩石形成于中-晚始新世期间。维西地区的花岗岩和石英二长岩具有高 SiO_2 (67.2%~72.29%) 和 Al_2O_3 (15.13%~16.37%), 高 K_2O/Na_2O 比值(0.75~2.16), 高Sr(852×10^{-6} ~ 1725×10^{-6}), 贫Y(7.19×10^{-6} ~ 21.22×10^{-6})和Yb(0.53×10^{-6} ~ 1.81×10^{-6})的特征, Sr/Y比值介于42~143之间, 同时富集轻稀土元素, 亏损重稀土元素, 显示出明显的C型埃达克岩的特征。岩石成因分析表明维西花岗岩为增厚下地壳部分熔融的产物; 石英二长岩同样源自增厚下地壳部分熔融, 但下地壳熔体经受了与区域基性岩浆混合。岩浆岩(La/Yb)_N比值对青藏高原东南缘的地壳厚度和古高程进行恢复表明, 维西—剑川地区在中-晚始新世期间地壳厚度分别为(50±9) km和(53±17) km, 古高程分别为(2678±1480) m和(2947±641) m, 表明青藏高原东南缘的地壳厚度和古高程在渐新世之前就已经增厚和隆升至现今状态。该过程可能受后碰撞背景下区域岩石圈尺度块体挤出的控制。

关键词: 青藏高原东南缘; 滇西地区; 新生代; 埃达克岩; 高原隆升

中图分类号: P588.1

文献标志码: A

文章编号: 1000-8527(2026)04-0986-21

Geochemical Characteristics of Post-collisional Adakitic Rocks in the Southeastern Tibetan Plateau and Their Implications for Paleoelevation

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收稿日期: 2025-09-01; 修回日期: 2025-12-10; 编辑: 戚开静。

基金项目: 国家自然科学基金项目(42173047, 41502212, 42103025); 中央高校基本科研业务费(2652019056)。

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引用格式: 杨家瑞, 陈静, 李大鹏, 等. 青藏高原东南缘后碰撞埃达克质岩石的地球化学特征及古高程指示 [J]. 现代地质, 2026, 40 (4): 986-1006. DOI: 10.19657/j.geoscience.1000-8527.202509010047.

YANG Jiarui, CHEN Jing, LI Dapeng, et al. Geochemical Characteristics of Post-collisional Adakitic Rocks in the Southeastern Tibetan Plateau and Their Implications for Paleoelevation [J]. GEOSCIENCE, 2026, 40 (4): 986-1006. DOI: 10.19657/j.geoscience.1000-8527.202509010047.

Abstract: Due to the lack of detailed characterization of the Cenozoic uplift process along the southeastern Tibetan Plateau, the post-collision uplift history of the Tibetan Plateau remains poorly understood. A series of C-type Adakites have formed in the post-collisional setting of the Tibetan Plateau. Those rocks are characterized by high K_2O/Na_2O ratios, strong rare earth element (REE) fractionation, and low Yb contents, which are generally associated with crustal thickening and thus could provide key insights into the uplift history of the plateau. In this study, zircon U-Pb dating, zircon Hf isotopes, whole-rock geochemistry, and Nd isotopes are reported for the Adakitic granites and quartz monzodiorites from the Weixi area to explore their genesis and their relationship with crustal thickening and uplift in the southeastern Tibetan Plateau. The results show that the Weixi granites were crystallized at ~ 40 Ma, while the quartz monzodiorites were crystallized during 37–33 Ma, indicating their formation during the Middle to Late Eocene. These rocks exhibit high SiO_2 (67.2%–72.29%) and Al_2O_3 (15.13%–16.37%) contents. They are characterized by high K_2O/Na_2O ratios (0.75–2.16), elevated Sr concentrations (852×10^{-6} – 1725×10^{-6}), low Y (7.19×10^{-6} – 21.22×10^{-6}) and Yb (0.53×10^{-6} – 1.81×10^{-6}) contents, high Sr/Y ratios (42–143), and with strong rare earth element (REE) fractionation, which is consistent with C-type adakitic geochemical signatures. Petrogenetic analyses suggest that the Weixi granites was derived from partial melting of the thickened lower crust, while the quartz monzodiorites also originated from partial melting of the thickened lower crust but subsequently mixed with regional mafic magmas. The crustal thickness and paleo-elevation of the southeastern Tibetan Plateau were reconstructed using the $(La/Yb)_N$ ratios of these C-type dakite rocks from two sections in Weixi area. Results show that during the Middle to Late Eocene, the crustal thickness in the Weixi-Jianchuan area was (50 ± 9) km and (53 ± 17) km, respectively, with paleo-elevations of $(2,678 \pm 1480)$ m and $(2,947 \pm 641)$ m. These results suggest that crustal thickening and uplift of the southeastern Tibetan Plateau had already taken place before the Oligocene, reaching its current state. This process was possibly driven by regional lithospheric-scale extrusion during the post-collision tectonic setting.

Key words: Southeastern Tibetan Plateau; Western Yunnan; Cenozoic; adakitic rock; plateau uplift

0 引言

青藏高原在新生代以来的隆升历史一直是固体地球研究的热点问题。印度—欧亚大陆碰撞以来,在青藏高原和周缘地区发育并保存了大量后碰撞阶段的地质记录^[1–3]。大量基于稳定同位素和古生物学方法的研究表明,青藏高原大部分区域在始新世至中新世期间达到了现今的海拔高度^[4–11]。近年来,中酸性岩浆岩的全岩地球化学数据和同位素数据^[12–16]以及锆石等副矿物的成分^[17–18],被发现可以有效约束 Moho 面深度。基于碰撞造山带内岩浆岩 Sr/Y 和 $(La/Yb)_N$ 比值与地壳厚度及高程关系, Zhu 等^[19]和 Hu 等^[20]定量揭示了青藏高原内部喜马拉雅、拉萨、羌塘等不同块体白垩纪至新生代复杂的隆升历史。相比之下,青藏高原周缘地区尤其是青藏高原东南缘的隆升历史还需要更深入的研究。虽然青藏高原中部和东南缘的一系列构造^[21]、岩浆^[22]及沉积记录^[23]

对比揭示了青藏高原东南缘印支地块与羌塘地块之间的强烈构造亲缘关系,且在后碰撞初期(> 32 Ma)二者古纬度相似^[24]。然而,由于缺乏对青藏高原东南缘隆升过程的详细刻画,目前仍无法全面理解青藏高原东南缘明显不同于高原腹地的高海拔,低起伏地貌成因^[11, 25]。

埃达克岩对于理解地壳演化具有重要意义。它们被认为代表了在现代弧环境中,由年轻的(≤ 25 Ma)俯冲玄武质洋壳在榴辉岩相的条件下熔融形成的一类富钠、富铝质强烈亏损重稀土元素(HREE,如 $Yb \leq 1.90 \times 10^{-6}$)与 Y ($\leq 18 \times 10^{-6}$)、富 Sr(一般 $\geq 400 \times 10^{-6}$)、高 La/Yb (≥ 20)与 Sr/Y (≥ 40)比值的中酸性($SiO_2 \geq 56\%$)钙碱性岩浆岩^[26–27]。这类钠质埃达克岩还有以下几种成因机制:(1)岛弧或陆缘弧环境中,以玄武岩—安山岩—英安岩—流纹岩岩浆系列为特征的基性岩浆经历同化混染与分离结晶(AFC)作用形成^[28–31];(2)陆内岩石圈地幔中拆沉下地壳的部分熔融形成^[32–35];(3)俯冲

带大陆边缘增厚下地壳的部分熔融形成^[37-38]。随着研究的深入,青藏高原内部和中国东部识别出了C型埃达克质岩石。这类埃达克岩具有钾质富铝的特征,属于钾玄岩系列或高钾钙碱性系列,具有类似钠质埃达克岩的轻重稀土元素分异特征,但 K_2O/Na_2O 比值更高(约为1)^[39]。它们通常被认为来源于富钾基性增厚下地壳的部分熔融^[40-43]或拆沉下地壳的部分熔融^[34, 36, 39]。无论是哪种类型的埃达克岩,其高Sr、低Y和显著轻重稀土元素分异特征均表明石榴石作为残余相或分离结晶相的作用,即高压熔融,暗示其与青藏高原后碰撞背景下的隆升过程密切相关。

维西地区位于青藏高原东南缘印支地块北端,该区发育的一系列C型埃达克岩记录了区域地壳加厚及隆升的关键信息。本研究以维西地区典型的C型埃达克质花岗岩和石英二长岩为对象,通过系统的锆石U-Pb年代学及Hf同位素,以及全岩地球化学及Nd同位素研究揭示其岩石成因,并计算区域地壳厚度和古高程,为青藏高原东南缘后碰撞阶段的隆升历史提供约束。

1 地质概况和岩相学特征

现今青藏高原东南缘由印支地块、Sibumasu地块及其他微陆块组成。这些地块在古生代至中生代期间从冈瓦纳陆缘分离,因一系列特提斯洋盆的发育(包括原特提斯洋、古特提斯洋和新特提斯洋)向东北漂移并最终拼合^[23, 45-52]。印支地块位于青藏高原东南缘,其东侧以哀牢山构造带为界与扬子板块相邻,西侧以澜沧江构造带为界与Sibumasu地块相接。两条构造带向北延伸,分别与金沙江缝合带和龙木措一双湖缝合带相连,构成青藏高原中部地区羌塘地块的边界。前人对印支地块与青藏高原中部地区羌塘地块之间的构造^[21]、岩浆^[22]以及沉积记录^[23, 48]的对比,揭示了二者之间强烈的构造亲缘性。不仅如此,在新生代后碰撞初期(> 32 Ma)二者具有相似的古纬度^[24]。

作为对印度—欧亚大陆碰撞的响应,沿着哀牢山构造带发育的一系列花岗闪长岩、二长斑岩、正长斑岩、二长花岗斑岩从南部的越南境内向北西延伸到羌塘北部,距离达到2000 km^[1, 53-54]。部分滇西地区的长英质碱性岩显示出C型埃达克质岩石的特征,岩石类型有二长斑

岩、正长斑岩、二长花岗斑岩和花岗闪长岩,主要分布在剑川、维西、巍山、宾川、北衙、永胜等地区,这些埃达克岩向西延伸至思茅地块内部50 km,向东延伸至扬子克拉通内部150 km的范围内^[55-58]。

本研究所采集的24件样品来自维西地区的桃花岩体和四家村岩体。该地区由四个大的侵入体和数个小岩株、岩枝等组成,呈不规则状分别侵位于古元古界羊坡岩组(Pty)、古近系宝相组(E₂b)、金丝厂组地层(E₃j)中,沿接触带角岩化、褪色现象明显(图1c)。所采集样品的岩性主要为花岗岩和石英二长岩。花岗岩样品野外呈现浅灰白色,呈花岗斑状结构,块状构造,手标本中可见明显的长石和石英斑晶,主要矿物有钾长石(40%, 0.5~3.0 mm)、斜长石(30%, 0.5~3.0 mm)、石英(15%, 1~5 mm)、黑云母(10%, 0.2~0.5 mm)和角闪石(5%, 0.2~0.3 mm)。石英二长岩样品野外呈深灰色,斑状结构,块状构造,手标本中可见暗色矿物含量明显更多,主要矿物组成为钾长石(25%, 0.5~2.0 mm)、斜长石(50%, 0.7~5.0 mm)、石英(5%, 0.8~3.0 mm)、黑云母(15%, 0.4~1.0 mm)、角闪石(10%, 0.3~2.0 mm)等。值得注意的是,在石英二长岩崖壁上可见发育有约10 cm的镁铁质包体。镜下鉴定显示,钾长石多呈自形至半自形;斜长石为他形粒状,多见聚片双晶和卡钠复合双晶;石英呈他形粒状,颗粒细小;黑云母呈片状,无定向性;角闪石发育特征解理,多呈自形。

2 分析方法

样品的锆石U-Pb定年在中国地质调查局天津地质调查中心实验测试室的LA-ICP-MS上完成。采用常规的重选和磁选技术,从样品中分选出无裂隙且晶形较好的锆石。将选出来的锆石颗粒与粘贴在环氧树脂靶上,并对它们进行抛光至露出一半晶面。根据锆石的透反射和阴极发光图像,选择合适的测试点位。详细的分析方法和流程可见Geng等^[59]和侯可军等^[60]。测点的U-Th-Pb同位素比值用标准锆石GJ-1(609 Ma, 230×10^{-6} U, 15×10^{-6} Th)^[61]获得。测点的Th和U元素含量用标准锆石91500^[62]校正获得。锆石Plesovice以及NIST610作为外标分别进行同位素和微量元素分馏校正。锆石Plesovice作为盲控样,其测定

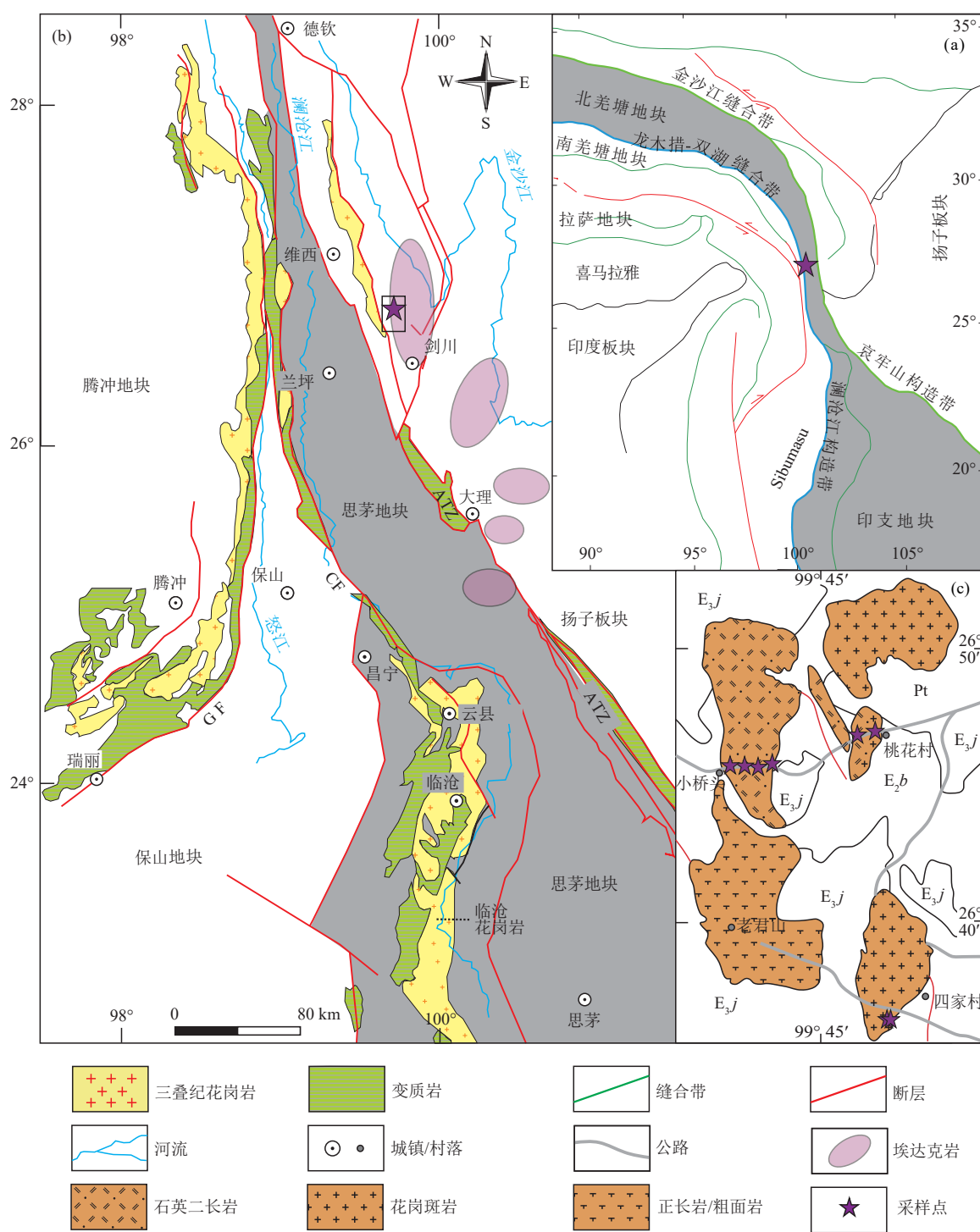


图1 研究区域地质背景图与采样位置图

Fig. 1 Geological background and sampling locations of the study region

(a) 青藏高原及东南缘所在位置及主要构造格架^[21]; (b) 滇西三江地区构造格架及样品位置^[44]; (c) 滇西维西地区的桃花岩体和四家村岩体区域地质简图和采样点位置(据 1:25 × 10⁴ 维西、兰坪幅地质图)

的²⁰⁶Pb/²³⁸U 加权平均年龄为(337 ± 2) Ma (2σ, n = 10), 与推荐值(337.13 ± 0.37) Ma 在误差范围内一致(2σ)^[63]。锆石 U-Pb 数据结果采用 Isoplot 软件进行处理^[64]。样品的锆石 Lu-Hf 同位素测试在中国地质调查局天津地质调查中心实验测试室的激光-多

接收等离子体质谱仪(LA-MC-ICP-MS)完成。为了保证样品来源的一致性和可对比性, 我们选择在已完成锆石 U-Pb 定年的相同结构域上进行了锆石 Lu-Hf 同位素测试。在测定时, 使用了锆石国际标样 GJ-1 作为外部标样, GJ-1 为(0.282009 ±



图2 维西地区的花岗岩和石英二长岩剖面

Fig. 2 Profiles of the granite and quartz monzonite in the Weixi area

(a)(b)野外照片;(c)含镁铁质包体(MME)的石英二长岩;(d)不含镁铁质包体的花岗岩;(e)石英二长岩手标本;(f)花岗岩手标本

0.000025)(1σ , $n = 30$), 与国际推荐值相一致^[65]。

样品的全岩主量元素和微量元素分别在广州澳实公司的X射线荧光光谱仪(XRF)和南京聚普科技有限公司的电感耦合等离子体质谱(ICP-MS)上完成。使用原地质矿产部岩石类GSR、水系沉积物GSD标物作为主量元素的质控盲样;美国地质调查局USGS岩石类标物(玄武岩BHVO-2、BCR-2、安山岩AGV-2、流纹岩RGM-2、花岗闪长岩GSP-2)作为微量元素的质控盲样。这些地质标物的实测值与德国马普学会地质与环境标物数据库GeoReM进行对比^[66](<http://geo-rem.mpg-mainz.gwdg.de>), 主量元素的分析误

差1%~5%之间, 而微量元素的分析误差在5%~10%之间。样品的全岩Nd同位素化学前处理和测试工作均在南京聚普科技有限公司利用多接收电感耦合等离子质谱仪(MC-ICP-MS)完成。Nd同位素的质量分馏校正参数为 $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ 。分析测试过程中, 标样JNdi-1和LaJolla用于监测仪器的运行状态。结果显示, 标样LaJolla的 $^{143}\text{Nd}/^{144}\text{Nd}$ 值为 $(0.511842 \pm 6)(2\sigma, n = 6)$, 标样JNdi-1的 $^{143}\text{Nd}/^{144}\text{Nd}$ 值为 $(0.512105 \pm 12)(2\sigma, n = 9)$ 。上述标样的测试结果均与推荐值吻合^[67]。

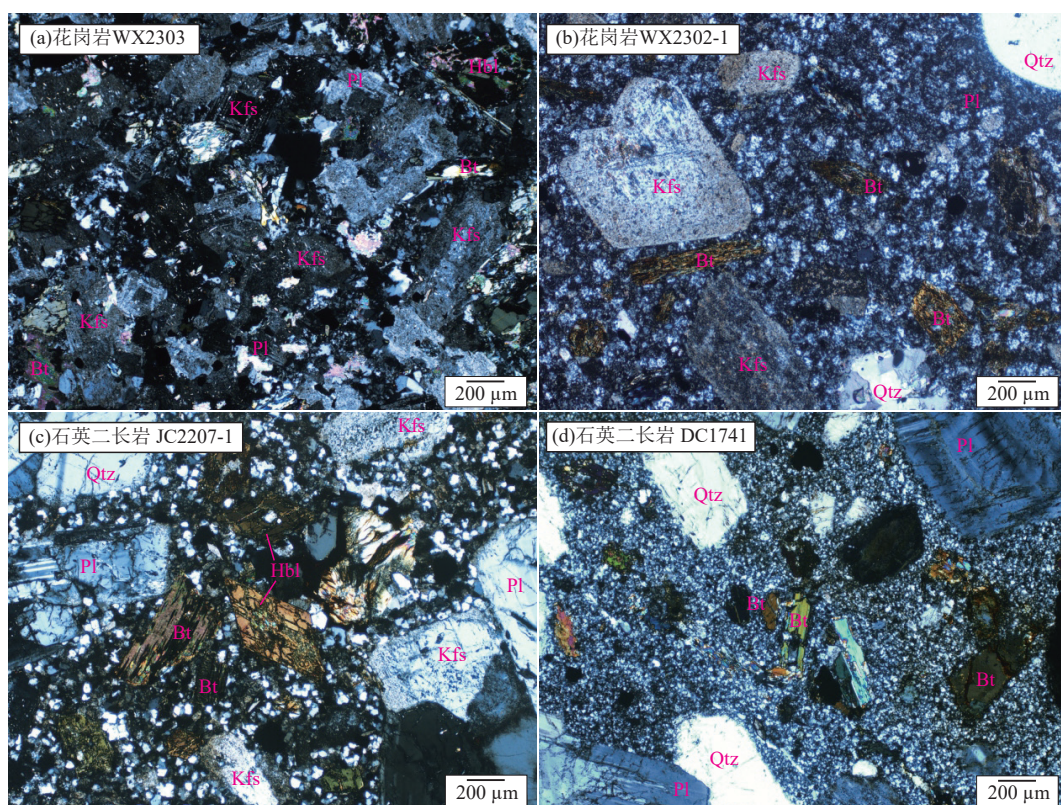


图3 滇西维西地区的花岗岩(a, b)及石英二长岩(c, d)的显微镜下照片(正交偏光)

Fig. 3 Photomicrographs under crossed polarized light of granite (a, b) and quartz monzonite (c, d) from the Weixi area
Kfs. 钾长石; Pl. 斜长石; Qtz. 石英; Hbl. 角闪石; Bt. 黑云母

3 分析测试结果

3.1 锆石 U-Pb 年龄

对花岗岩样品 WX2302 和两件石英二长岩样品(JC2207 和 WX2301)分别选取 35 颗、20 颗锆石, 开展了 LA-ICP-MS 锆石 U-Pb 测年分析, 结果见表 1。锆石阴极发光(CL)图像显示, 用于定年的锆石自形程度较好, 均呈自形-半自形, 长宽比 1:1 ~ 3:1, 发育清晰的振荡环带, 并且锆石 Th/U 值 > 0.1, 具有典型岩浆锆石的稀土元素配分模式, 表明这些锆石为岩浆锆石成因(图 4) [68]。

花岗岩 WX2302 样品 35 个锆石测点的谐和度均较高, 数据点均落在谐和线上或其附近(图 4a), 12 颗岩浆锆石加权平均年龄为 (40 ± 1) Ma (MSWD = 1.07; 图 4b), 可以代表该花岗岩的结晶年龄。老于这个年龄的, 均为捕获或继承锆石。值得注意的是, 有 5 颗锆石组成了一个年龄群, 加权平均年龄为 (227 ± 2) Ma (MSWD = 1.2), 结合其核边结构特征和测点位置(位于核部), 这些锆石可能为继承锆石, 代表了继承锆石的年龄。

石英二长岩(JC2207)获得 16 个谐和度(90% ~

110%)较高的测点, 其 $^{206}\text{Pb}/^{238}\text{U}$ 年龄范围为 $(31 \pm 1) \sim (754 \pm 10)$ Ma, 数据点分布在谐和线上或其附近(图 4a)。其中, 5 颗最年轻的岩浆锆石的加权平均年龄为 (33 ± 1) Ma (MSWD = 1.6; 图 4c), 代表该样品的结晶年龄。老于这个年龄的, 均为捕获或继承锆石。值得注意的是, 有 7 颗最老锆石形成年龄群, 加权平均年龄为 (751 ± 7) Ma (MSWD = 0.12), 结合核边结构特征及位于核部的测点位置, 可能代表继承锆石的年龄。

石英二长岩 WX2301 获得 19 个谐和度(90% ~ 110%)较高的测点, 其 $^{206}\text{Pb}/^{238}\text{U}$ 年龄值为 $(36 \pm 1) \sim (799 \pm 10)$ Ma (另有一颗为 (2338 ± 27) Ma)。数据点均落在谐和线上或附近(图 4a)。其中, 5 颗最年轻岩浆锆石加权平均年龄为 (37 ± 1) Ma (MSWD = 0.5, 图 4d), 代表该样品的结晶年龄。

3.2 锆石 Hf 同位素

根据维西地区 1 件花岗岩和 1 件石英二长岩样品中锆石的 Hf 同位素组成分析结果(表 2), 花岗岩的 $^{176}\text{Lu}/^{177}\text{Hf}$ 比值在 0.000967 ~ 0.001800 之间, 具有由负到正变化的 $\varepsilon_{\text{Hf}}(t)$ 值(-2.66 ~ +5.76), 对应两阶段 Hf 模式年龄分别为 $T_{\text{DM1}} = 0.48 \sim 0.82$ Ga,

表1 维西地区新生代花岗岩-石英二长岩锆石 U-Pb 同位素分析结果

Table 1 Zircon U-Pb isotopic data for the Cenozoic granites and quartz monzonites in the Weixi region

点号	Th(10^{-6})	U(10^{-6})	Th/U	同位素比值				年龄(Ma)			
				$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ
WX2302.01	110	371	0.30	0.248	0.005	0.0356	0.0003	225	4	226	2
WX2302.02	68	228	0.30	0.253	0.024	0.0354	0.0008	229	19	224	5
WX2302.03	179	1337	0.13	0.044	0.002	0.0063	0.0001	43	2	40	1
WX2302.04	238	1198	0.20	0.067	0.002	0.0103	0.0001	66	1	66	1
WX2302.05	57	587	0.10	1.138	0.016	0.1211	0.0008	771	8	737	5
WX2302.06	147	1032	0.14	0.039	0.002	0.0062	0.0001	39	2	40	0
WX2302.07	627	1111	0.56	1.836	0.036	0.1760	0.0029	1059	13	1045	16
WX2302.08	148	499	0.30	1.238	0.020	0.1242	0.0011	818	9	755	7
WX2302.09	33	1437	0.02	0.442	0.010	0.0610	0.0007	372	7	382	4
WX2302.10	318	1503	0.21	0.040	0.001	0.0062	0.0001	40	1	40	0
WX2302.11	51	359	0.14	0.053	0.008	0.0077	0.0003	52	7	49	2
WX2302.12	92	836	0.11	0.037	0.002	0.0063	0.0001	37	2	40	0
WX2302.13	79	358	0.22	0.257	0.012	0.0359	0.0007	232	10	227	4
WX2302.14	103	1070	0.10	0.044	0.002	0.0063	0.0001	43	2	41	0
WX2302.15	122	671	0.18	1.390	0.035	0.1474	0.0028	885	6	886	16
WX2302.16	43	141	0.31	0.040	0.006	0.0064	0.0002	40	6	41	1
WX2302.17	313	1312	0.24	0.067	0.001	0.0104	0.0001	66	1	67	1
WX2302.18	80	270	0.30	0.258	0.008	0.0369	0.0006	233	7	234	4
WX2302.19	184	1685	0.11	0.042	0.005	0.0063	0.0001	42	4	40	1
WX2302.20	147	848	0.17	0.043	0.002	0.0065	0.0001	43	2	41	1
WX2302.21	116	836	0.14	0.041	0.002	0.0065	0.0002	40	2	42	1
WX2302.22	47	241	0.19	0.965	0.021	0.1038	0.0009	686	11	636	5
WX2302.23	152	845	0.18	0.049	0.003	0.0073	0.0002	48	3	47	1
WX2302.24	42	81	0.53	0.308	0.014	0.0426	0.0006	272	11	269	3
WX2302.25	112	526	0.21	1.331	0.017	0.1413	0.0010	859	7	852	6
WX2302.26	377	354	1.07	1.624	0.020	0.1631	0.0013	980	8	974	7
WX2302.27	636	789	0.81	1.478	0.023	0.1533	0.0018	921	9	920	10
WX2302.28	117	1053	0.11	0.040	0.002	0.0062	0.0001	40	2	40	1
WX2302.29	85	182	0.47	0.240	0.015	0.0342	0.0010	218	13	217	6
WX2302.30	121	1246	0.10	0.041	0.004	0.0063	0.0001	40	4	40	1
WX2302.31	133	1283	0.10	0.037	0.001	0.0062	0.0001	37	1	40	0
WX2302.32	109	222	0.49	0.257	0.007	0.0357	0.0004	232	6	226	2
WX2302.33	830	1105	0.75	0.063	0.002	0.0095	0.0002	62	2	61	1
WX2302.34	443	1435	0.31	1.857	0.029	0.1664	0.0017	1066	10	992	9
WX2302.35	378	498	0.76	1.177	0.021	0.1304	0.0011	790	10	790	6
JC2207.01	188	429	0.44	0.034	0.001	0.0051	0.0001	34	1	33	1
JC2207.02	139	417	0.33	0.033	0.002	0.0051	0.0001	33	2	33	1
JC2207.03	81	241	0.34	0.247	0.005	0.0354	0.0004	224	4	224	2
JC2207.04	82	241	0.34	1.084	0.017	0.1174	0.0012	746	8	716	7
JC2207.05	46	782	0.06	0.883	0.014	0.0984	0.0013	643	8	605	8
JC2207.06	61	441	0.14	1.142	0.017	0.1239	0.0016	773	8	753	9
JC2207.07	62	424	0.15	1.138	0.019	0.1222	0.0018	771	9	743	10
JC2207.08	92	248	0.37	0.058	0.003	0.0072	0.0005	57	3	46	3
JC2207.09	66	217	0.31	1.107	0.016	0.1235	0.0011	757	8	751	6
JC2207.10	171	390	0.44	1.110	0.017	0.1240	0.0017	758	8	754	10
JC2207.11	30	259	0.11	1.056	0.026	0.1236	0.0027	732	13	751	15
JC2207.12	48	355	0.14	0.906	0.016	0.1039	0.0008	655	9	637	5
JC2207.13	242	675	0.36	0.033	0.001	0.0050	0.0001	33	1	32	1
JC2207.14	128	367	0.35	0.036	0.001	0.0052	0.0001	36	1	33	1
JC2207.15	121	214	0.56	0.085	0.006	0.0107	0.0003	83	5	69	2

(续)表1 维西地区新生代花岗岩-石英二长岩锆石U-Pb同位素分析结果
(Continued) Table 1 Zircon U-Pb isotopic data for the Cenozoic granites and quartz monzonites
in the Weixi region

点号	Th(10^{-6})	U(10^{-6})	Th/U	同位素比值				年龄(Ma)			
				$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ
JC2207.16	65	382	0.17	1.118	0.021	0.1236	0.0019	762	10	751	11
JC2207.17	181	473	0.38	0.035	0.002	0.0049	0.0001	35	2	31	1
JC2207.18	196	357	0.55	0.039	0.000	0.0050	0.0001	39	0	32	1
JC2207.19	55	261	0.21	1.120	0.021	0.1234	0.0023	763	10	750	13
JC2207.20	181	867	0.21	0.034	0.001	0.0052	0.0001	34	1	34	1
WX2301.01	410	862	0.48	0.043	0.002	0.0062	0.0001	43	2	40	1
WX2301.02	153	254	0.60	1.196	0.018	0.1320	0.0010	799	8	799	6
WX2301.03	267	830	0.32	0.041	0.002	0.0061	0.0001	40	2	39	0
WX2301.04	315	946	0.33	0.063	0.005	0.0060	0.0001	62	5	39	1
WX2301.05	374	622	0.60	0.036	0.002	0.0057	0.0001	36	2	37	0
WX2301.06	138	167	0.82	0.704	0.024	0.0818	0.0021	541	14	507	12
WX2301.07	150	460	0.33	0.229	0.008	0.0320	0.0009	210	7	203	6
WX2301.08	256	420	0.61	1.199	0.018	0.1298	0.0012	800	8	787	7
WX2301.09	201	583	0.34	0.038	0.003	0.0058	0.0001	38	3	37	1
WX2301.10	235	509	0.46	0.038	0.002	0.0058	0.0001	38	2	37	0
WX2301.11	178	592	0.30	0.824	0.010	0.0974	0.0006	610	5	599	4
WX2301.12	252	672	0.38	0.039	0.002	0.0057	0.0001	39	2	37	0
WX2301.13	253	700	0.36	0.040	0.002	0.0058	0.0001	40	2	37	0
WX2301.14	293	977	0.30	0.253	0.004	0.0361	0.0003	229	3	229	2
WX2301.15	692	1460	0.47	0.040	0.002	0.0062	0.0001	40	2	40	0
WX2301.16	231	535	0.43	0.042	0.002	0.0060	0.0001	41	2	38	1
WX2301.17	365	521	0.70	0.040	0.002	0.0060	0.0001	40	2	38	0
WX2301.18	105	297	0.35	9.479	0.131	0.4372	0.0061	2386	13	2338	27
WX2301.19	333	550	0.61	0.035	0.002	0.0059	0.0001	35	2	38	0
WX2301.20	295	723	0.41	0.037	0.005	0.0057	0.0002	37	5	36	1

注: 岩浆锆石的 $\varepsilon_{\text{Hf}}(t)$ 值由岩浆锆石U-Pb的加权平均年龄计算获得, 捕获或继承锆石的 $\varepsilon_{\text{Hf}}(t)$ 值由单点锆石的U-Pb数据校正获得。

$T_{\text{DM2}} = 0.77 \sim 1.31$ Ga(表1)。石英二长岩的 $^{176}\text{Yb}/^{177}\text{Hf}$ 比值在0.001932~0.003914之间, $^{176}\text{Lu}/^{177}\text{Hf}$ 比值在0.000918~0.001691之间。石英二长岩较于花岗岩具有更亏损的锆石Hf同位素组成(图5), $\varepsilon_{\text{Hf}}(t)$ 值在+0.04~+6.89之间,对应两阶段Hf模式年龄分别为 $T_{\text{DM1}} = 0.44 \sim 0.72$ Ga, $T_{\text{DM2}} = 0.69 \sim 1.13$ Ga。

3.3 全岩主微量元素

本研究对11件花岗岩和13件石英二长岩共24件样品进行了全岩主微量元素测试,并对其中2件花岗岩和1件石英二长岩开展了全岩Nd同位素分析(表3)。

维西花岗岩有高 SiO_2 (69.5%~72.29%)含量, K_2O (3.93%~4.90%)和 NaO (4.58%~5.32%)含量较高,呈现从碱性到亚碱性特征,在TAS图中落入花岗岩区域(图6a),显示出钾玄岩-高钾钙碱性系列的特征(图6b),铝饱和度(A/CNK)范围为0.94~1.10,属于准铝质至弱过铝质(图6c)。花

岗岩有高 K_2O (3.92%~4.90%)和 Al_2O_3 (15.22%~15.78%)含量,但 TiO_2 (0.20%~0.32%), $\text{Fe}_2\text{O}_3^{\text{T}}$ (1.53%~2.22%), CaO (0.89%~2.06%), MgO (0.37%~0.88%)含量较低, $\text{Mg}^\#$ 值为32~45。稀土元素球粒陨石标准化图解显示轻、重稀土元素分异显著,轻稀土元素富集且重稀土元素平坦分布,并且存在轻微Eu异常($\text{Eu}/\text{Eu}^* = 0.81 \sim 0.93$), $(\text{La}/\text{Yb})_{\text{N}}$ 比值为17.84~30.48(图7a)。值得注意的是,花岗岩具有高 $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 比值(0.75~1.04),低Yb(0.53~1.16 $\mu\text{g/g}$)和Y(7.19~13.78 $\mu\text{g/g}$)含量,高Sr(852~1409 $\mu\text{g/g}$)含量,以及较高的Sr/Y比值(71~143),显示出C型埃达克岩的地球化学亲缘性(图7)。在原始地幔标准化图解上,花岗岩表现出富集大离子亲石元素(如Rb, Ba, K),亏损高场强元素(如Nb, Ta, Ti, P)的特征(图7b)。

相较于花岗岩,石英二长岩 SiO_2 (67.20%~69.15%)含量稍低, K_2O (3.93%~7.20%)和 NaO (3.34%~5.25%)含量变化较大,呈现出碱性到

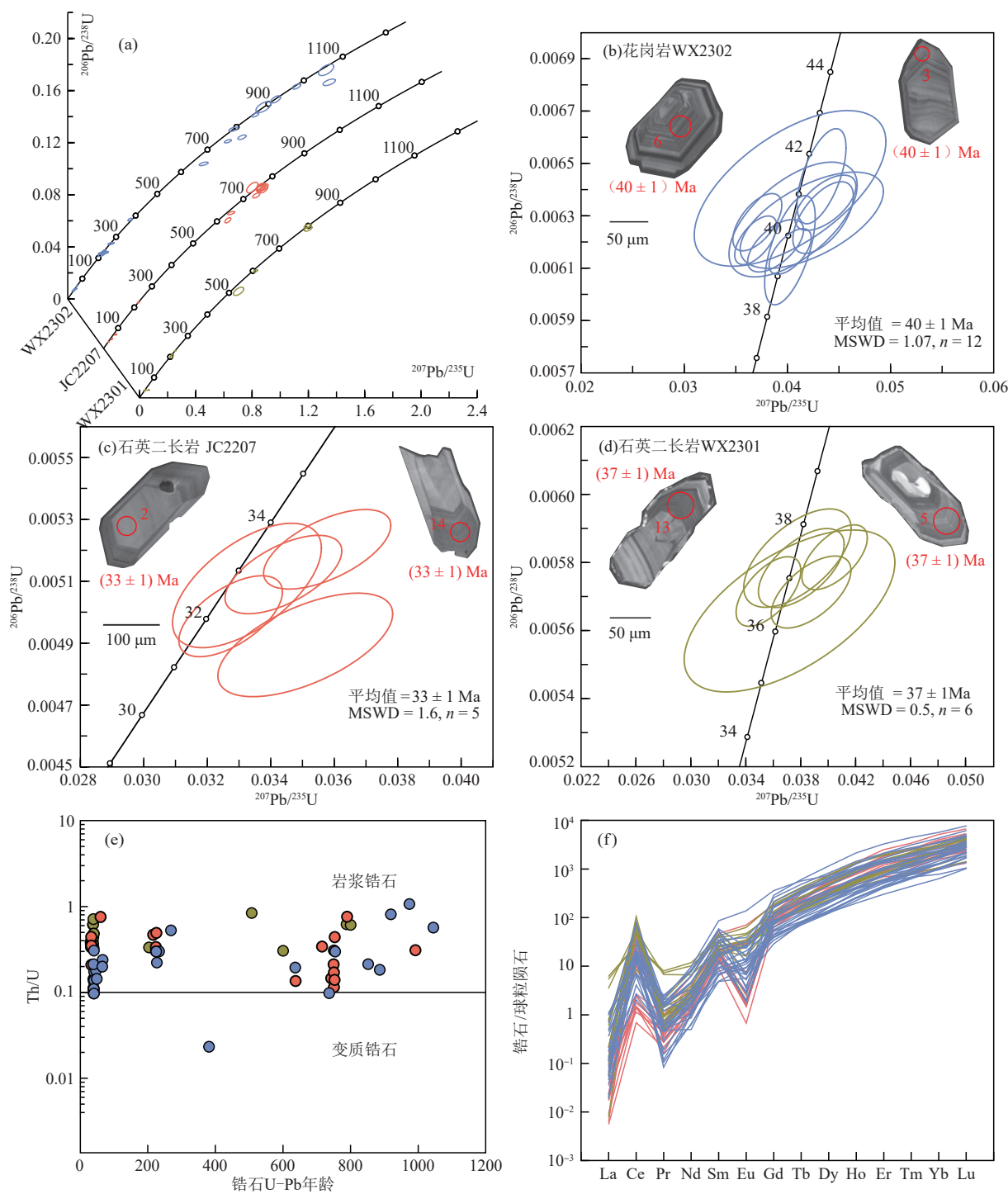


图4 维西地区花岗岩与石英二长岩中锆石的分析结果

Fig. 4 Analytical results of zircons from granites and quartz monzonites in the Weixi area

(a)–(d)维西地区花岗岩和石英二长岩U-Pb谐和图及锆石阴极发光图像;(e)锆石Th/U比值;(f)锆石稀土元素特征

亚碱性特征,在TAS图上落入石英二长岩区域(图6a),表现出高钾钙碱性-钾玄岩特征(图6b),其铝饱和指数(A/CNK)为0.84~1.06,属于准铝质至弱过铝质岩石(图6c)。石英二长岩K₂O(3.93%~7.2%)和Al₂O₃(15.13%~16.37%)含量都比较高,该特征与花岗岩相似,但TiO₂(0.35~

0.45%),Fe₂O₃^T(2.41%~3.59%),CaO(1.61%~3.2%)和MgO(0.63%~1.37%)含量相对更高,Mg#值为30~48。稀土元素分布表现为轻稀土元素富集、重稀土元素呈平坦分布的特征,轻微的负Eu异常(0.80~0.87),(La/Yb)_N比值为13.84~22.07(图7a)。在原始地幔标准化图解上显示富集

表2 维西地区新生代花岗岩-石英二长岩锆石 Lu-Hf 同位素分析结果

Table 2 Zircon Lu-Hf isotopic data for the Cenozoic granites and quartz monzonites in the Weixi region

点号	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	1σ	$\varepsilon_{\text{Hf}}(t)$	$\frac{T_{\text{DM2}}}{(\text{Ga})}$
WX2302.03	0.000636	0.282866	0.000019	4.21	0.83
WX2302.06	0.000749	0.282851	0.000019	3.65	0.90
WX2302.10	0.000884	0.282885	0.000018	4.85	0.83
WX2302.12	0.000512	0.282874	0.000020	4.48	0.85
WX2302.14	0.000550	0.282809	0.000019	2.18	1.00
WX2302.16	0.000772	0.282673	0.000020	15.65	1.31
WX2302.19	0.000550	0.282866	0.000016	4.20	0.87
WX2302.20	0.000806	0.282789	0.000023	1.46	1.05
WX2302.21	0.000577	0.282693	0.000022	-1.87	1.26
WX2302.28	0.000501	0.282864	0.000020	4.11	0.88
WX2302.30	0.000526	0.282847	0.000017	3.53	0.91
WX2302.31	0.000722	0.282901	0.000019	5.42	0.79
WX2301.05	0.001000	0.282872	0.000030	4.32	0.86
WX2301.09	0.001197	0.282809	0.000024	2.08	1.00
WX2301.10	0.001359	0.282945	0.000024	6.89	0.69
WX2301.12	0.001297	0.282751	0.000023	0.04	1.13
WX2301.13	0.001691	0.282916	0.000029	5.87	0.76
WX2301.20	0.001219	0.282813	0.000023	2.23	0.99

注: 岩浆锆石的 $\varepsilon_{\text{Hf}}(t)$ 值由岩浆锆石 U-Pb 的加权平均年龄计算获得, 捕获或继承锆石的 $\varepsilon_{\text{Hf}}(t)$ 值由单点锆石的 U-Pb 数据校正获得。

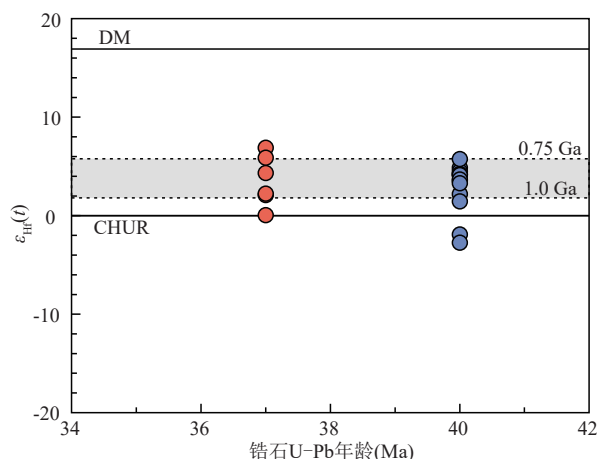


图5 维西地区花岗岩和石英二长岩岩浆锆石 Hf 同位素图

Fig. 5 Zircon Hf isotopic data of granites and quartz monzonites from the Weixi area

大离子亲石元素(如 Rb, Ba, K), 亏损高场强元素(如 Nb, Ta, Ti, P)特征(图 7b)。此外, 维西石英二长岩以低 Yb ($1.26 \sim 1.81 \mu\text{g/g}$)、Y ($14.82 \sim 21.22 \mu\text{g/g}$) 含量及高 Sr ($859 \sim 1725 \mu\text{g/g}$) 含量为特征, $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 比值在 $0.80 \sim 2.16$ 之间, Sr/Y 比值

为 $(42 \sim 109)$, 具有 C 型埃达克岩的地球化学亲缘性(图 7)。这些地球化学特征表明维西地区花岗岩和石英二长岩是典型的 C 型埃达克岩。

3.4 全岩 Nd 同位素

对维西地区 2 件花岗岩和 1 件石英二长岩进行了全岩 Nd 同位素组成分析, 结果见表 2。结合 3 件已有报道的维西花岗岩的全岩 Nd 同位素组成^[76], 维西花岗岩的 $^{143}\text{Nd}/^{144}\text{Nd}$ 值为 $0.512494 \sim 0.512578$, $\varepsilon_{\text{Nd}}(t)$ 值为 $-2.4 \sim -0.2$, 指示富集的源区性质(图 8a), 对应的 $T_{\text{DM}} = 0.89 \sim 1.04 \text{ Ga}$ 。石英二长岩样品的 $^{143}\text{Nd}/^{144}\text{Nd}$ 值为 0.512519 , $\varepsilon_{\text{Nd}}(t)$ 值为 -2.0 , 显示出富集特征(图 8a), 对应的 $T_{\text{DM}} = 0.94 \text{ Ga}$ 。

4 讨论

4.1 形成时代

采自维西桃花岩体的花岗岩和石英二长岩样品的锆石 U-Pb 定年结果表明结晶年龄约为 40 Ma 和 37 Ma(图 4), 形成于始新世中期。这一结果与前人对桃花岩体二长花岗斑岩(35.9 Ma)^[81] 和花岗斑岩(36.4 Ma)^[82] 的定年结果基本一致。采自剑川四家村剖面的石英二长岩的结晶年龄为 33 Ma(图 4), 形成于始新世晚期, 与前人得到的剑川盆地石鼓地区二长花岗斑岩年龄结果(35 Ma)^[83] 相匹配。因此, 滇西维西地区的花岗岩和石英二长岩形成于中-晚始新世期间。

4.2 C 型埃达克岩地球化学特征

埃达克岩的概念由 Defant 和 Drummond 和在 1990 年首次提出, 代表一类具有特定地球化学特征的中酸性岩石组合, 其标志是 $\text{SiO}_2 \geq 56\%$, 高铝 ($\text{Al}_2\text{O}_3 \geq 15\%$), $\text{MgO} < 3\%$, 贫 Y 和 Yb ($\text{Y} \leq 18 \times 10^{-6}$, $\text{Yb} \leq 1.9 \times 10^{-6}$), Sr 含量高(通常大于 400×10^{-6}), LREE 富集, 无 Eu 异常或轻微的负 Eu 异常^[26]。不同于钠质埃达克岩, C 型埃达克岩具有钾质富铝的特征, 属于钾玄岩系列或高钾钙碱性系列, 轻重稀土元素分异特征与钠质埃达克岩类似, 但 $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 比值通常更高 (> 0.6)^[39]。维西地区的花岗岩和石英二长岩具有高 SiO_2 ($67.2\% \sim 72.29\%$) 和 Al_2O_3 ($15.13\% \sim 16.37\%$) 含量。它们以高 $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 比值 ($0.75 \sim 2.16$), 高 Sr ($852 \times 10^{-6} \sim 1725 \times 10^{-6}$), 低 Y ($7.19 \times 10^{-6} \sim 21.22 \times 10^{-6}$) 和 Yb ($0.53 \times 10^{-6} \sim 1.81 \times 10^{-6}$) 含量为特征, Sr/Y 比值介于 $42 \sim 143$ 之间, 同时富集轻稀土元素, 亏损重稀土元素, 具有 C 型埃达克岩的特征^[39]。在 Sr/Y-Y 和 La/Yb-

表3 维西地区新生代花岗岩-石英二长岩主量元素(%）、微量元素(10^{-6})和Nd同位素组成
Table 3 Major (%), trace (10^{-6}) element concentrations and Nd isotopic data for the Cenozoic granites and quartz monzonites from the Weixi area

样号	SiO ₂	TiO ₂	Al ₂ O ₃	TFeO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	MnO	烧失量	Cr	Ni	Rb	Sr
WX2301	67.20	0.42	15.59	2.65	1.00	3.10	4.37	5.34	0.28	0.04	0.71	10.51	3.71	127	1265
WX2301-1	67.38	0.42	15.13	3.59	0.95	1.70	3.34	7.20	0.29	0.01	1.99	11.00	7.47	194	890
WX2301-2	67.71	0.41	15.70	2.74	1.01	2.64	4.66	4.82	0.28	0.03	0.50	10.30	4.18	106	1312
WX2302	69.70	0.32	15.62	2.16	0.78	1.81	5.13	4.30	0.15	0.03	2.17	5.28	2.74	137	934
WX2302-1	69.67	0.31	15.60	2.10	0.76	2.06	4.94	4.38	0.14	0.03	2.34	4.98	2.87	136	1092
WX2302-2	69.15	0.35	15.78	2.41	0.91	1.61	5.25	4.30	0.21	0.04	2.10	4.63	3.01	134	859
WX2303	69.50	0.31	15.69	2.20	0.83	1.94	5.01	4.30	0.17	0.04	1.62	4.48	2.44	119	1229
WX2303-1	70.42	0.31	15.78	2.12	0.74	1.06	4.87	4.49	0.16	0.04	1.33	6.18	2.92	136	1253
WX2304	70.41	0.31	15.54	2.15	0.69	1.93	4.65	4.13	0.15	0.04	0.96	9.85	3.79	141	1391
WX2304-1	69.89	0.32	15.41	2.22	0.84	1.99	5.04	4.09	0.15	0.05	1.47	6.72	3.47	134	1409
WX2304-2	70.37	0.31	15.38	2.16	0.88	1.39	5.32	4.02	0.14	0.05	1.56	6.96	3.35	138	888
WX2305	68.98	0.37	15.83	2.60	1.08	2.02	4.94	3.93	0.16	0.08	1.15	12.60	5.71	125	1566
WX2305-1	70.68	0.32	15.22	2.21	0.85	1.56	5.03	3.92	0.15	0.05	1.48	8.58	3.85	135	1062
WX2306	71.91	0.21	15.58	1.55	0.38	0.89	4.81	4.55	0.10	0.01	1.12	1.77	1.03	165	1013
WX2306-1	72.29	0.20	15.50	1.53	0.37	0.96	4.58	4.48	0.08	0.01	1.09	1.77	1.04	161	1041
WX2306-2	71.05	0.21	15.60	1.99	0.52	0.94	4.70	4.90	0.08	0.01	1.75	1.71	5.45	177	852
JC2207	67.67	0.45	16.05	3.24	1.00	2.43	4.74	4.11	0.23	0.07	0.78	13.56	8.14	118	1725
JC2207-1	68.88	0.39	16.09	2.93	0.92	1.68	4.55	4.28	0.20	0.07	1.12	12.41	6.42	128	1326
JC2207-2	67.96	0.44	15.96	3.18	0.90	2.28	4.87	4.10	0.23	0.08	0.79	12.86	6.06	118	1671
JC2208	67.76	0.44	16.11	3.26	0.82	2.71	4.49	4.11	0.23	0.08	1.84	11.17	6.01	120	1549
JC2208-1	68.10	0.39	16.37	2.82	0.80	2.25	4.91	4.11	0.19	0.06	0.72	9.47	4.70	117	1634
JC2208-2	68.19	0.40	16.03	3.01	1.37	2.20	4.44	4.10	0.19	0.07	1.64	11.79	7.13	122	1465
JC2208-3	67.53	0.43	16.00	3.25	0.78	3.24	4.49	4.00	0.21	0.07	2.10	28.79	16.28	119	1649
JC2208-4	68.63	0.40	16.19	2.94	0.63	2.17	4.67	4.11	0.19	0.06	1.18	12.83	6.68	124	1636
样号	Ba	Pb	Th	U	Nb	Ta	Zr	Hf	La	Ce	Pr	Nd	Sm	Eu	Gd
WX2301	1688	27.7	13.89	3.22	13.23	0.817	208	5.45	34.8	71.4	8.85	32.7	6.36	1.600	5.27
WX2301-1	1426	18.7	15.00	3.72	13.10	0.804	206	5.50	34.7	71.5	8.79	33.5	6.47	1.580	5.32
WX2301-2	1609	21.9	13.90	3.33	12.50	0.819	200	5.31	36.5	71.7	8.61	31.7	5.98	1.530	4.85
WX2302	1709	31.1	9.38	3.64	8.13	0.532	158	4.62	27.8	51.0	6.21	23.0	4.37	1.120	3.49
WX2302-1	1754	34.0	9.41	3.62	8.16	0.535	151	4.42	26.8	50.1	6.04	22.4	4.35	1.100	3.26
WX2302-2	1704	26.1	10.60	4.13	8.50	0.549	170	4.81	29.2	55.3	6.84	25.8	4.83	1.240	4.20
WX2303	1680	24.9	9.03	3.21	7.54	0.505	144	4.22	26.7	49.5	5.88	21.9	4.14	1.100	3.24
WX2303-1	1908	27.2	9.87	3.48	8.15	0.547	159	4.61	29.3	53.8	6.21	23.0	4.18	1.120	3.30
WX2304	1682	47.7	10.80	3.02	8.44	0.580	156	4.63	29.1	52.2	6.49	23.9	4.59	1.200	3.67
WX2304-1	1688	43.9	9.89	3.03	7.99	0.533	164	4.74	28.8	53.9	6.52	24.7	4.63	1.170	3.65
WX2304-2	1489	45.7	8.96	2.27	7.98	0.546	151	4.33	26.0	47.8	5.98	22.1	4.21	1.090	3.29
WX2305	1770	52.4	10.20	2.89	8.73	0.576	158	4.55	29.9	55.5	6.66	25.2	4.84	1.270	3.77
WX2305-1	1513	32.0	9.49	3.42	8.28	0.578	156	4.49	28.2	51.2	6.18	23.0	4.33	1.150	3.41
WX2306	1616	33.2	6.91	2.69	6.96	0.474	129	3.99	18.5	30.9	3.79	13.7	2.58	0.709	1.96
WX2306-1	1560	31.4	6.83	2.49	6.92	0.466	126	3.90	18.9	31.9	3.81	14.0	2.72	0.745	2.02
WX2306-2	1530	43.8	6.99	5.31	6.53	0.460	126	3.97	24.6	43.4	5.23	19.2	3.58	0.847	2.62
JC2207	2024	46.9	15.55	3.86	11.53	0.757	248	5.99	43.6	80.3	9.25	35.0	6.42	1.620	5.02
JC2207-1	1656	69.4	12.44	5.01	9.42	0.649	191	5.10	34.1	61.1	7.74	30.3	5.69	1.470	4.54
JC2207-2	1969	43.0	15.70	3.83	11.26	0.755	245	6.01	42.9	79.5	9.13	34.8	6.41	1.630	5.10
JC2208	1925	47.1	15.40	3.56	11.19	0.759	239	5.94	44.3	80.1	9.41	36.0	6.45	1.640	5.07
JC2208-1	1960	36.8	14.83	3.93	10.56	0.732	228	5.76	38.7	72.1	8.09	30.8	5.42	1.400	4.12
JC2208-2	2092	36.9	16.55	3.64	10.87	0.709	234	5.78	42.4	80.8	9.29	35.2	6.47	1.630	5.17
JC2208-3	1981	48.7	16.21	3.53	10.93	0.723	237	5.85	42.9	75.9	9.00	34.6	6.14	1.570	5.04
JC2208-4	2137	57.3	17.10	3.97	10.91	0.716	237	5.88	40.2	73.5	8.33	31.9	5.79	1.480	4.65

(续)表3 维西地区新生代花岗岩-石英二长岩主量元素(%)、微量元素(10^{-6})和Nd同位素组成
(Continued) Table 3 Major (%), trace (10^{-6}) element concentrations and Nd isotopic data for the Cenozoic granites and quartz monzonites from the Weixi area

样号	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y	Sr/Y	(La/Yb) _N	Eu/Eu*	$^{143}\text{Nd}/^{144}\text{Nd}$	$\varepsilon_{\text{Nd}}(t)$	$T_{\text{DM}}(\text{Ga})$
WX2301	0.703	3.65	0.688	1.90	0.274	1.810	0.254	21.10	60	14	0.82		-2.4	1.04
WX2301-1	0.727	3.74	0.704	1.96	0.276	1.760	0.256	21.20	42	14	0.80	0.512494		
WX2301-2	0.656	3.49	0.643	1.82	0.259	1.660	0.256	20.00	66	16	0.84			
WX2302	0.437	2.23	0.407	1.15	0.161	1.070	0.164	13.00	72	19	0.85			
WX2302-1	0.425	2.22	0.390	1.13	0.160	0.994	0.156	12.60	87	19	0.85			
WX2302-2	0.500	2.65	0.524	1.36	0.195	1.320	0.198	14.80	58	16	0.82			
WX2303	0.422	2.16	0.402	1.12	0.160	1.030	0.155	12.30	100	19	0.89			
WX2303-1	0.434	2.18	0.393	1.12	0.156	1.040	0.145	12.10	103	20	0.89			
WX2304	0.472	2.47	0.444	1.21	0.183	1.160	0.177	13.80	101	18	0.86		-0.8	0.89
WX2304-1	0.460	2.34	0.442	1.19	0.168	1.090	0.161	13.40	105	19	0.84	0.512578		
WX2304-2	0.419	2.15	0.394	1.10	0.153	1.040	0.150	12.50	71	18	0.86			
WX2305	0.513	2.63	0.485	1.34	0.204	1.300	0.183	15.20	103	16	0.87			
WX2305-1	0.432	2.22	0.413	1.15	0.173	1.070	0.161	13.20	80	19	0.89			
WX2306	0.244	1.18	0.209	0.58	0.083	0.527	0.083	7.19	141	25	0.92			
WX2306-1	0.248	1.19	0.212	0.57	0.083	0.547	0.082	7.28	143	25	0.93			
WX2306-2	0.310	1.45	0.253	0.65	0.093	0.578	0.086	8.24	103	30	0.81			
JC2207	0.683	3.55	0.650	1.73	0.248	1.600	0.233	19.60	88	20	0.84		-2.0	0.94
JC2207-1	0.619	3.23	0.599	1.60	0.234	1.490	0.218	18.10	73	16	0.85	0.512519		
JC2207-2	0.691	3.58	0.657	1.74	0.248	1.580	0.229	18.90	88	19	0.84			
JC2208	0.688	3.57	0.649	1.72	0.250	1.600	0.236	19.20	81	20	0.85			
JC2208-1	0.565	2.87	0.513	1.38	0.197	1.260	0.187	15.00	109	22	0.87			
JC2208-2	0.701	3.60	0.641	1.72	0.237	1.510	0.218	19.60	75	20	0.84			
JC2208-3	0.678	3.45	0.633	1.73	0.240	1.560	0.231	19.40	85	20	0.84			
JC2208-4	0.615	3.17	0.571	1.53	0.217	1.390	0.203	17.80	92	21	0.85			

Yb判别图解中(图9), 维西花岗岩样品全部落入埃达克质岩区域。石英二长岩样品在La/Yb-Yb图解中也基本落入埃达克岩区域(图9b), 但在Sr/Y-Y图解中, 部分投影在云南基性岩范围与埃达克岩区域之间(图9a), 可能反映了石英二长岩与花岗岩岩石成因的差异。综上所述, 维西花岗岩和石英二长岩均为典型的C型埃达克岩。

4.3 维西地区埃达克岩的成因

滇西维西地区的C型埃达克质花岗岩形成于印度-欧亚板块碰撞之后, 区域上并没有同时期的洋壳俯冲的地球动力学证据。通常情况下, 俯冲洋壳发生部分熔融形成的埃达克质岩浆会与上覆地幔橄榄岩相互作用, 产生高MgO含量(或Mg[#]值>60)、高Cr(>100×10⁻⁶)和Ni含量(>100×10⁻⁶)的特征^[32]。维西埃达克质花岗岩的Mg[#]值(32.3~44.8)、Cr(1.71×10⁻⁶~9.85×10⁻⁶)和Ni(1.03×10⁻⁶~5.45×10⁻⁶)含量明显更低, 与典型俯冲洋壳熔融产生的钠质埃达克岩不同(图10)。

此外, 这些岩石的 $\varepsilon_{\text{Nd}}(t)$ 值(-2.4~-0.8), 显著低于新生代洋壳部分熔融产生的MORB型钠质埃达克岩(+5.5~+6.9^[32])。此外, 维西埃达克质花岗岩Nb/Zr=0.049~0.55, Th/Nb=0.99~1.28, Ta/Hf=0.11~0.13, 显示大陆地壳的特征。基于以上证据, 维西地区埃达克质花岗岩不太可能是俯冲洋壳部分熔融的产物。拆沉下地壳岩石(榴辉岩或者石榴石辉石岩)的熔点低于地幔橄榄岩, 在同样压力条件下发生部分熔融会形成富钾的埃达克岩。尽管维西埃达克质花岗岩K₂O含量较高(3.92%~4.90%), 但是拆沉下地壳岩石不可避免地会与地幔的橄榄岩发生相互作用, 呈现出高的MgO(或Mg[#]值), 以及更高的Ni和Cr含量^[35], 明显区别于维西埃达克质花岗岩的地球化学特征(图10), 因此拆沉下地壳部分熔融不能解释该区花岗岩的成因。

维西地区C型埃达克质花岗岩的最可能来源是增厚的富钾基性下地壳的部分熔融, 支持这一观点的证据如下: (1)这些岩石Mg[#]值、MgO、Ni

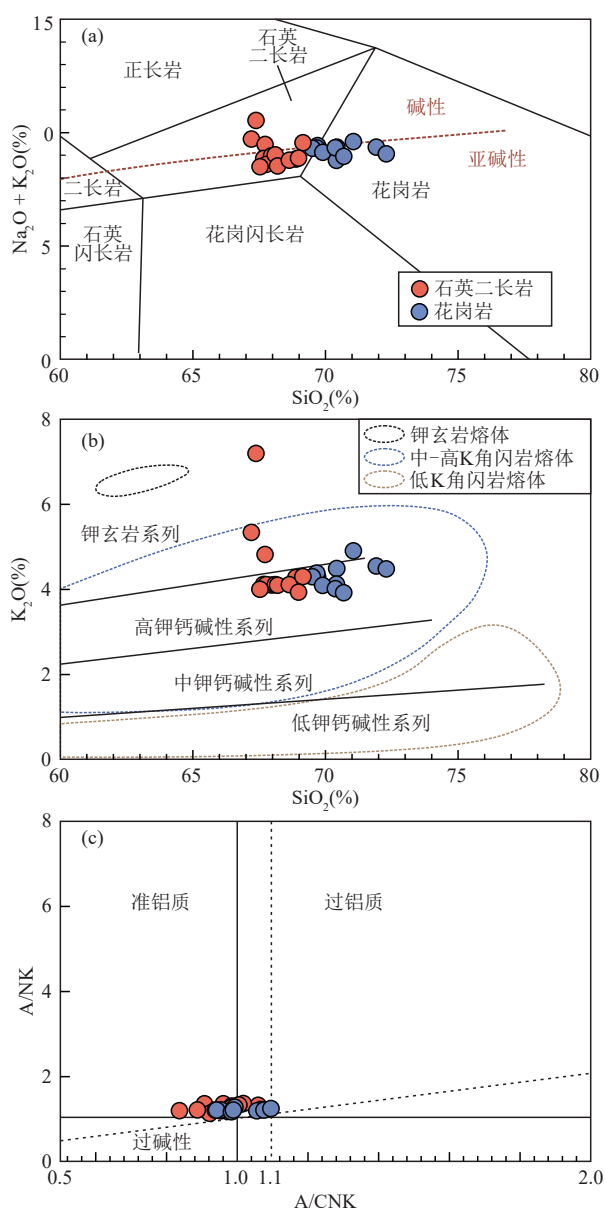


图6 维西地区花岗岩和石英二长岩地球化学分类图解
Fig. 6 Geochemical classification diagrams for the granites and quartz monzonites from the Weixi area

(a) $\text{SiO}_2 - (\text{K}_2\text{O} + \text{Na}_2\text{O})$ 图解^[69]; (b) $\text{SiO}_2 - \text{K}_2\text{O}$ 图解^[70]; (c) $\text{A/CNK} - \text{A/NK}$ 图解^[71]

和Cr含量与增厚下地壳来源的埃达克质岩石及变质玄武岩和榴辉岩实验熔体(1–4 GPa)的特征一致(图10a)^[35]; (2)主量元素成分与中-高钾和钾玄质角闪岩实验熔体一致(图6)^[39, 85–91]; (3)维西埃达克质花岗岩的稀土元素和微量元素分布与青藏高原南部增厚下地壳成因的埃达克岩相似(图7)^[1]; (4)由负到正的岩浆锆石 $\varepsilon_{\text{Hf}}(t)$ 值(–2.66 ~ +5.76)、负的 $\varepsilon_{\text{Nd}}(t)$ 值(–2.4 ~ –0.2)和锆石Hf同位素 $T_{\text{DM}2}$ 为0.77 ~ 1.31 Ga, 指向扬子克拉通古老地壳的熔融成因, 与扬子克拉通主要的

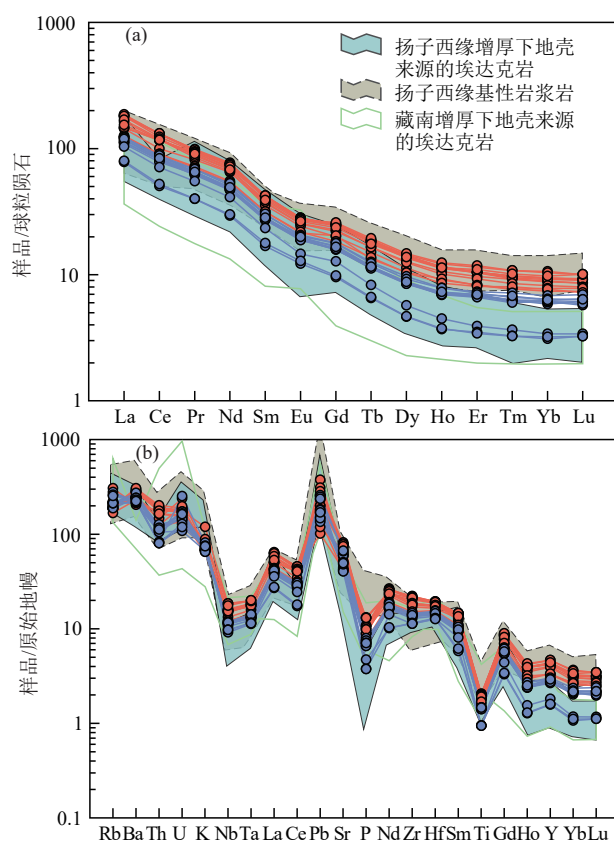


图7 维西地区花岗岩与石英二长岩的稀土及微量元素标准化图解
Fig. 7 Chondrite- and primitive mantle-normalized diagrams of rare earth and trace elements for granites and quartz monzonites from the Weixi area

(a) 稀土元素球粒陨石标准化分布图; (b) 微量元素原始地幔标准化蛛网图; 球粒陨石、原始地幔数据来自Sun和McDonough^[72]; 浅蓝色区域代表扬子板块西缘增厚下地壳来源的埃达克岩^[57]; 棕色区域代表扬子西缘基性火山岩^[73–75]; 绿色框线代表藏南增厚下地壳来源的埃达克岩^[40]

地壳增长期相匹配(图5); (5)样品中47 ~ 1045 Ma的继承锆石以及继承锆石年龄群(约227 Ma)的出现, 进一步表明大陆地壳的贡献。综上所述, 这些埃达克质花岗岩源自富钾增厚下地壳的部分熔融, 同时混染了大陆地壳物质。由于剑川埃达克质岩石侵位于古近纪砂岩地层中, 为了衡量大陆地壳物质混染对剑川埃达克质花岗岩全岩组分的影响, 我们应用古近纪砂岩JSC-1^[80]代表壳源物质端元与埃达克质岩浆(样品WX2304代表)进行简单二元混合计算。结果表明, 包括花岗岩和石英二长岩在内的维西埃达克质岩石的主要地球化学特征均偏离了二端元混合模拟趋势线, 进一步表明大陆地壳物质混染并没有明显改变这些岩石的全岩地球化学组成(图8)。

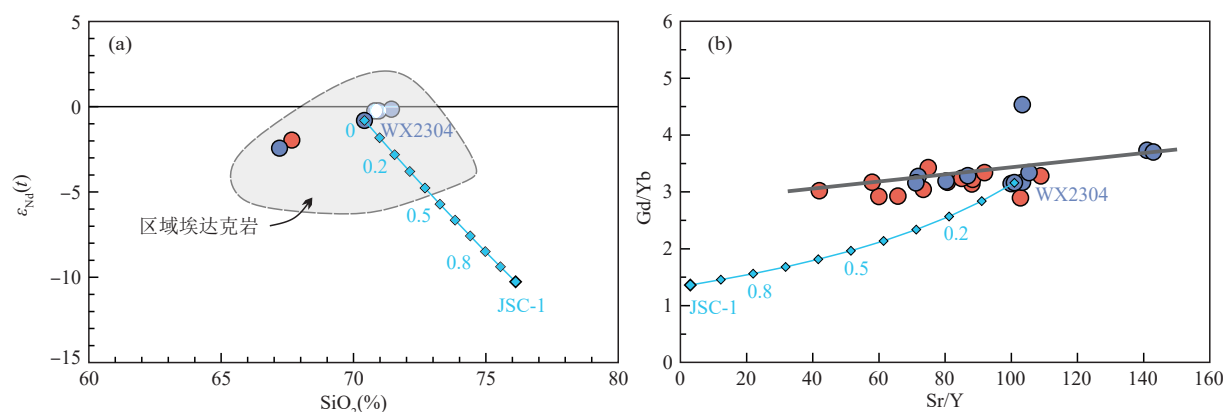
图8 维西地区花岗岩与石英二长岩的 $\varepsilon_{Nd}(t)$ - SiO_2 (a) 及 Gd/Yb - Sr/Y (b) 协变图

Fig. 8 Covariation of $\varepsilon_{Nd}(t)$ values with SiO_2 content (a) and Gd/Yb ratios with Sr/Y ratios (b) for Weixi granites and quartz monzonite

灰色填充区域代表区域上的C型埃达克岩据文献[57, 76-79]; 蓝色菱形线用以评估地壳物质贡献对埃达克质岩石成分变化的影响, 是使用古近纪砂岩JSC-1^[80]代表壳源物质端元与样品WX2304代表的埃达克质岩浆进行简单二元混合的结果

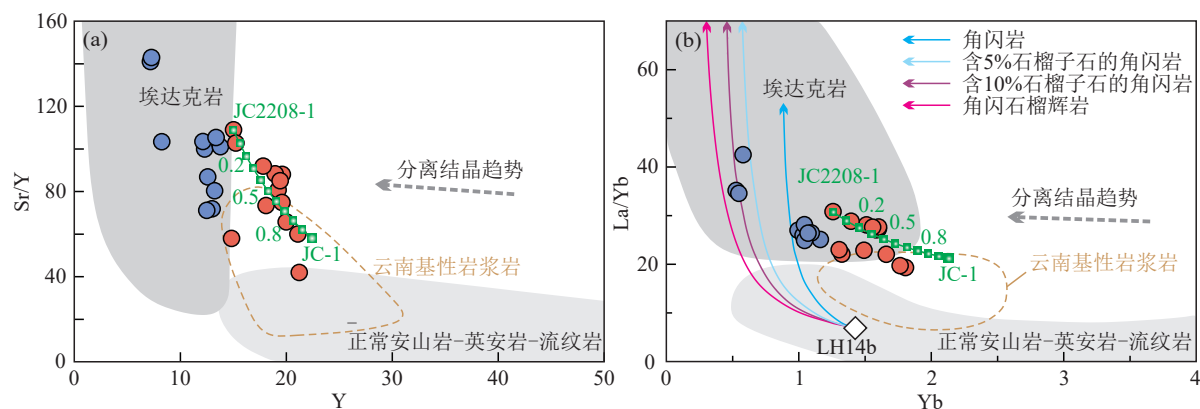
图9 维西地区花岗岩与石英二长岩的 Sr/Y 和 La/Yb 协变图((a) Sr/Y - Y 图解; (b) La/Yb - Yb 图解)

Fig. 9 Sr/Y and La/Yb covariation diagrams for granites and quartz monzonites from the Weixi area ((a) Variation of Sr/Y vs. Y ; (b) Variation of La/Yb vs. Yb)

图中箭头分别表示以滇西六合地区的角闪岩样品 LH14b^[84]作为初始成分发生部分熔融, 形成不同残余相的熔融曲线; 角闪辉长岩、含 10% 石榴石的角闪岩、含 5% 石榴石的角闪岩以及不含石榴石的角闪岩。绿色圆形组成的混合线代表基性端元 JC-1^[57]与酸性端元 JC2208-1 的混合; 线旁的数字表示混合物中基性端元的质量百分比 (F)。区域钾玄岩系列的分离结晶趋势以灰色虚线箭头表示。棕色虚线区域为滇西古近纪基性火山岩分布范围^[73-75]。埃达克质岩和正常安山岩-英安岩-流纹岩的范围参考 Richards 和 Kerrich^[31]

尽管石英二长岩与花岗岩具有相似的地球化学特征, 如明显的 Sr 正异常, 高 Sr/Y 和高 La/Yb 比值, 以及普遍亏损的 Nb、Ta、Ti 等, 表明其均来源于增厚下地壳熔融。然而, 以下证据表明石英二长岩可能经历了基性岩浆的混合过程: (1) 石英二长岩中出现镁铁质包体 (MMEs), 显示岩浆混合作用 (图 2c)^[92]; (2) 稀土元素和微量元素特征介于花岗岩与云南西部的钾质镁铁质岩浆之间 (图 7, 图 9); (3) 相较于增厚下地壳来源的埃达克岩和变质玄武岩实验熔体, 石英二长岩中 SiO_2 与 $Mg^{\#}$ 和 MgO 含量的负相关趋势更为显著, 表明存在镁铁质岩浆的输入 (图 10a, b)^[55]; (4) 在相同的

SiO_2 含量下, 石英二长岩样品中 Ni ($3.01 \times 10^{-6} \sim 16.28 \times 10^{-6}$) 和 Cr ($4.63 \times 10^{-6} \sim 28.79 \times 10^{-6}$) 含量相对更高, 因此可能存在高 Ni 和 Cr 成分 (如镁铁质熔体) 的输入 (图 10c, d)。此外, 用角闪正长岩 JC-1^[57] 作为基性端元与石英二长岩 JC2208-1 样品进行岩浆混合模拟, 模拟了 Sr/Y - Y 及 La/Yb - Yb 的变化趋势, 方法参考 Schwartz 等^[93]。结果表明, 维西石英二长岩的 Sr/Y 与 Y 及 La/Yb 与 Yb 的变化趋势与岩浆混合曲线高度吻合 (图 9)。因此, 维西石英二长岩样品 Sr/Y 变化范围受控于基性岩浆混合作用。

岩石成因分析表明维西地区埃达克质花岗岩是增厚下地壳部分熔融的产物, 石英二长岩熔体

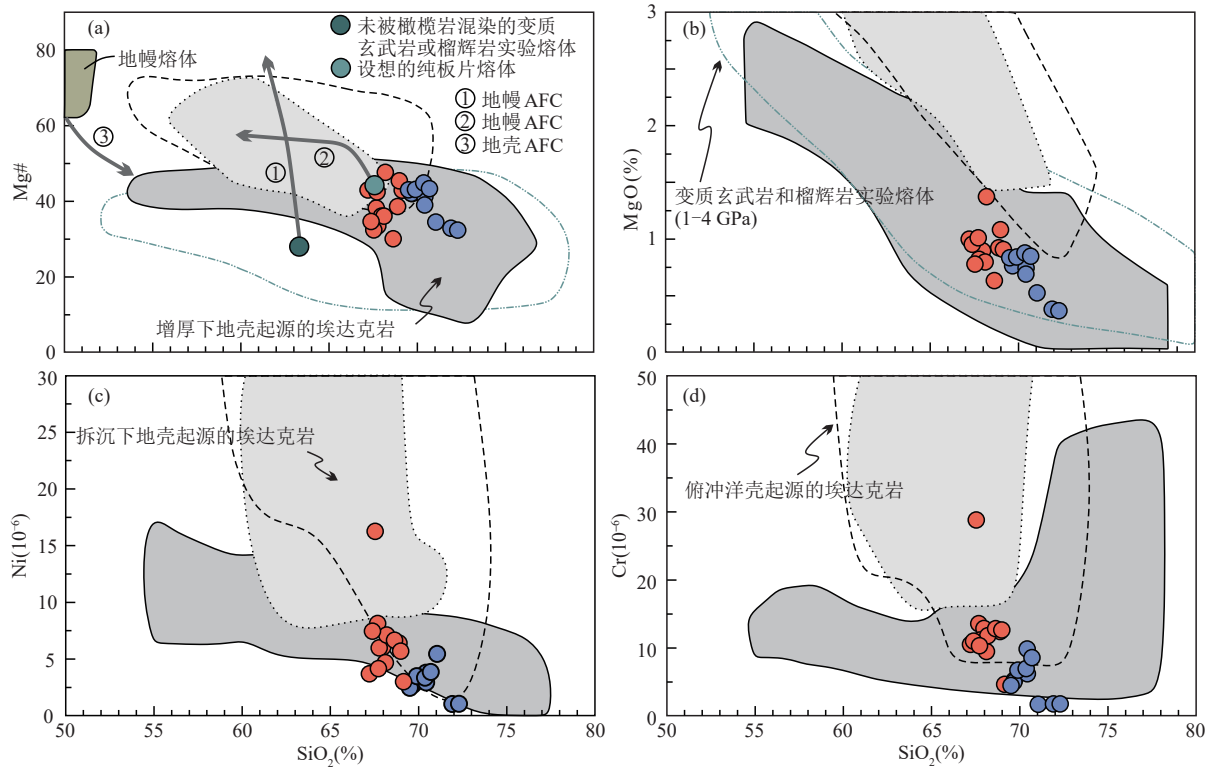


图 10 岩石成因判别协变图

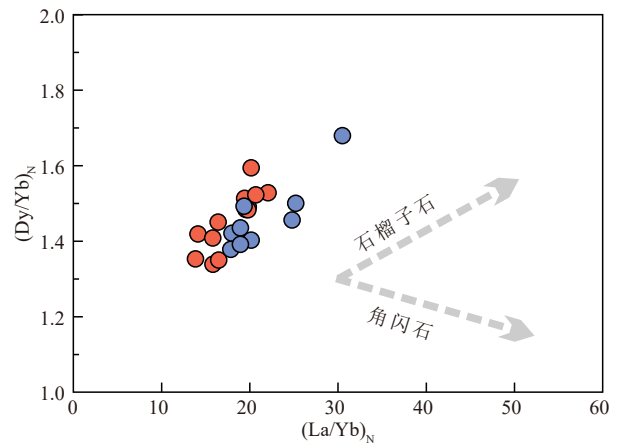
Fig. 10 Petrogenetic discrimination covariation diagrams

(a) $Mg^{\#}$ - SiO_2 ; (b) MgO - SiO_2 ; (c) Ni - SiO_2 ; (d) Cr - SiO_2 ; 图 (a) 的地幔 AFC 曲线据文献[94]。起始点表示未与橄榄岩混合的变玄武岩或榴辉岩实验熔体的组成^[94]。图中代表来源于俯冲洋壳的埃达克岩、增厚下地壳起源的埃达克岩、拆沉下地壳起源的埃达克岩以及变质玄武岩和榴辉岩实验熔体(1~4 GPa)的数据^[35]

则是增厚下地壳部分熔融后与基性岩浆混合的产物。虽然花岗岩与石英二长岩的成因略有不同, 两者轻重稀土分异, 强烈亏损 HREE ($Yb = 0.53 \sim 1.81$) 的特征, 都显示其来自石榴子石残余的源区。尽管部分石英二长岩具有更高的 Y 和 Yb 含量, 根据前述讨论, 应该反映了基性岩浆混合的特征。不仅如此, 两类岩石的 MREE 相对 HREE 更加富集, $(Dy/Yb)_N$ 介于 1.34 ~ 1.68 之间, 且 $(La/Yb)_N$ 与 $(Dy/Yb)_N$ 表现出明显的正线性关系 (图 11), 进一步说明源区主要受石榴子石的控制, 而不是角闪石。岩浆起源过程中石榴子石作为残余相出现, 表明岩浆源区在高压下发生熔融, 暗示了维西地区的 C 型埃达克岩与青藏高原后碰撞隆升过程的密切联系。

5 对青藏高原后碰撞隆升过程的意义

前人对青藏高原腹地羌塘地块的隆升过程进行了大量研究, 全岩微量元素反演结果显示该地区地壳厚度在渐新世之前已经增厚至现今状态^[95], 同时古高程已达约 5000 m^[20, 95]。这一过

图 11 维西花岗岩和石英二长岩的 $(Dy/Yb)_N$ 与 $(La/Yb)_N$ 关系图解Fig. 11 Diagram of $(Dy/Yb)_N$ vs. $(La/Yb)_N$ for granites and quartz monzonites from the Weixi area

程与区域地壳缩短及快速剥蚀事件相匹配^[97-100], 记录了渐新世之前青藏高原中部的隆升历史。尽管构造^[96]、岩浆^[22]及沉积记录^[23, 48]对比揭示了青藏高原东南缘印支地块与羌塘地块存在强烈构造亲缘关系, 且两者在后碰撞初期(> 32 Ma)的古

纬度相似^[24]。但是二者地壳增厚及隆升历史是否类似目前仍不清楚。

近年来,地球化学参数(Sr/Y 和 La/Yb 比值)被广泛用于估算大陆弧和碰撞带中的 Moho 面深度和地壳厚度^[14-16, 101-102]。岩浆岩 Sr/Y 和 La/Yb 比值与原始岩浆产生过程以及分离结晶过程中斜长石、角闪石、石榴子石的出现密切相关,而这些矿物又受压力的控制^[26, 103-105]。因此,岩浆岩 Sr/Y 和 La/Yb 比值可以指示原始岩浆的熔融深度,被用于反演其就位时的地壳厚度和古高程^[13, 15, 18-20, 106-108]。其中,全岩 $(\text{La/Yb})_N$ 值对碰撞造山带中的地壳厚度的敏感性通常比 Sr/Y 值更高^[15, 19, 109-110],因此本研究使用 Hu 等^[15]提出的全岩 $(\text{La/Yb})_N$ 方法估计青藏高原东南缘剑川和维西两地中一晚始新世的古地壳厚度。仅使用 $\text{SiO}_2 = 55\% \sim 70\%$ 、 $\text{MgO} = 0.5\% \sim 6.0\%$ 、 $\text{Rb/Sr} = 0.05 \sim 0.35$ 、烧失量 < 4 的全岩样品来消除幔源、高度分异的岩石样品的影响^[15, 19, 111],并进一步剔除了受混合作用显著影响的样品后,共有 17 件符合条件的样品被用于反演古地壳厚度。结果显示,青藏高原东南缘维西—剑川地区在中—晚始新世期间的地壳厚度分别为 $(50 \pm 9) \text{ km}$ 和 $(53 \pm 17) \text{ km}$ (图 12a)。此外,我们使用 Airy^[112] 提出的方法用 $(\text{La/Yb})_N$ 比值计算剑川和维西地区的古高程,具体计算过程的参数选择与 Wang 等^[95] 相同。结果表明,青藏高原东南缘维西—剑川两地的古高程分别为 $(2678 \pm 1480) \text{ m}$ 和 $(2947 \pm 641) \text{ m}$ (图 12b)。将结果与前人计算得到的青藏高原中部和东南缘不同区域的古地壳厚度进行对比^[95] (图 12a),可知我们的结果与前人计算得到的维西和剑川两地的古地壳厚度 $((48 \pm 15) \text{ km}, (49 \pm 14) \text{ km})$ 和古高程 $((2424 \pm 850) \text{ m}, (2503 \pm 795) \text{ m})$ 结果一致,保证了结果的可信度。与青藏高原现今 Moho 面深度^[113] 和平均现今高程的对比表明,由 $(\text{La/Yb})_N$ 比值估算得到的青藏高原东南缘的地壳厚度和古高程结果与现今地壳厚度和现今高程基本一致,表明青藏高原东南缘维西—剑川地区的地壳厚度可能在古近纪之前就已经发生增厚和隆升。进一步,区域囊谦盆地、贡觉盆地地层分析揭示的古近纪地壳缩短^[114-120]、德钦—维西地区低温热年代学重现的白垩纪—早古近纪的快速冷却事件^[121-122] 所揭示的区域地壳增厚与本次应用 C 型埃达克质岩石的估算结果相匹配。与前人研究基于稳定同位素得

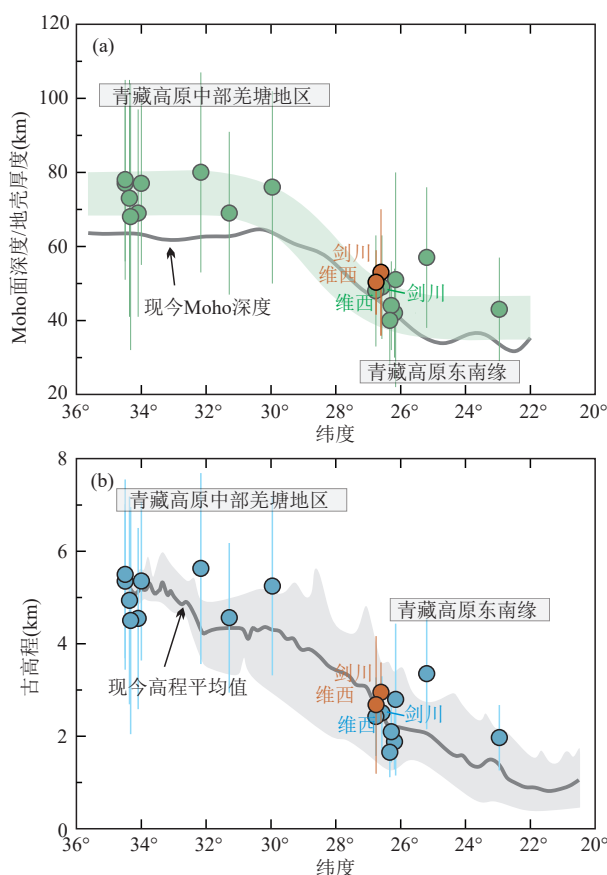


图 12 基于微量元素 $(\text{La/Yb})_N$ 比值反演计算得到的维西和剑川采样点的古 Moho 面深度(a)和古高程(b)

Fig. 12 Projection of Moho depth derived from the median $(\text{La/Yb})_N$ (a) and calculated paleo-elevation (b) based on $(\text{La/Yb})_N$ (b)

绿色圈和蓝色圈分别代表使用 $(\text{La/Yb})_N$ 比值反演得到青藏高原中部羌塘地区和青藏高原东南缘不同地区的地壳厚度和古高程^[95]; 现今 Moho 面深度据文献^[113]

到的古高程相比,所得到的古高程结果介于稳定同位素得到的古高程最低值与最高值之间,且接近现今平均高程^[123-124]。在不考虑较大误差的情况下,我们的研究结果支持青藏东南缘的地壳增厚和隆升主要发生在早渐新世(33 Ma)之前。综合地壳增厚和隆升历史,认为青藏高原东南缘与青藏高原中部的羌塘地块一样,在渐新世之前就已经发生了地壳增厚和地形隆升^[15, 19, 95, 111]。青藏高原中部羌塘地块在中—晚始新世期间的地壳厚度(68 ~ 80 km)和古高程(4500 ~ 5500 m)已经接近现今状态。与之相比,青藏高原东南缘的古地壳厚度更薄、古高程相对更低,两者的高差与现今状态基本一致,这可能受区域动力学机制的影响。

青藏高原东南缘低海拔、高起伏的地貌特征被认为与下地壳通道流^[125-126]或者岩石圈尺度的

块体挤出^[129]有关。下地壳通道流模型中,地壳流动引起的增厚和地表抬升始于中一晚中新世,并且被同时期的河流快速侵蚀所证明^[130-131]。相比之下,块体挤出模型认为青藏高原东南缘的地形在中新世之前就已经达到现今高度^[127-129]。因此,青藏高原东南缘在渐新世之前地壳隆升过程可能主要受到区域岩石圈尺度的块体挤出控制。在印度欧亚大陆碰撞早期阶段,碰撞过程传播到了青藏高原中部和东南缘并引起地壳增厚和隆升,与此同时,该过程导致了哀牢山构造带内部和周边地区47~32 Ma岩浆岩的形成和喷发^[1, 95-96]。

6 结 论

(1)维西地区花岗岩结晶年龄为40 Ma,石英二长岩结晶年龄为37~33 Ma,表明这些岩石形成于中一晚始新世期间。

(2)维西地区花岗岩和石英二长岩具有C型埃达克岩的地球化学特征。岩石成因分析表明维西花岗岩为增厚下地壳部分熔融的产物;石英二长岩同样源自增厚下地壳部分熔融,但下地壳熔体经受了与区域基性岩浆混合。

(3)基于维西C型埃达克岩的(La/Yb)_N比值对青藏高原东南缘的地壳厚度和古高程进行恢复,维西—剑川地区在中一晚始新世期间地壳厚度分别为(50±9) km和(53±17) km,古高程分别为(2678±1480) m和(2947±641) m,表明青藏高原东南缘的地壳厚度和古高程在渐新世之前就已经增厚和隆升至现今状态。

致谢:感谢野外工作中韩玉冰等课题组成员和样品分析测试中实验室工作人员提供的帮助,感谢主编的及时处理和两位匿名审稿人的审稿意见,这些意见显著提升了文章质量。

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