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青藏高原东南缘金沙江下游新生代构造与地貌演化

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Cenozoic tectonics and geomorphic evolution of the lower Jinsha River on the southeastern margin of the Tibetan Plateau

Abstract: The southeastern margin of the Tibetan Plateau is distinguished by a vast transition zone with hundreds of thousands of square kilometers of low-relief surfaces, which provides an ideal window for unraveling the timing, process, and mechanisms of the tectonic propagation and surface uplift. In order to reveal the Cenozoic tectonic response and geomorphic evolution of the southeastern margin of the Tibetan Plateau, a comprehensive study in the lower Jinsha River was conducted with a tectonic investigation, tectonic-landform and low-temperature thermochronological data analysis. The results show that the southeastern margin of the Tibetan Plateau remained in NW-shortening as early as the Eocene, forming widespread folds. However, we suggest that in the Paleogene, the lower Jinsha River of the southeastern margin of the Tibetan Plateau was marked by a low hilly topography with rather limited surface uplift. In the Late Oligocene–Early Miocene, the study area was characterized by a long-term stage with low denudation rates, which promoted the formation of widespread low-relief surfaces. Since the late Neogene, the southeastern margin of the Tibetan Plateau has undergone regional shortening deformation and significant surface uplift with a simultaneous incision along large rivers, forming the present landforms characterized by high-elevation low-relief surfaces and deep gorges. The late Neogene surface uplift across the southeastern margin of the Tibetan Plateau is suggested to be closely related to the shortening deformation and associated crustal thickening. In contrast, the mid-lower crustal thickening by channel flow might not be indispensable.

Keywords: southeastern margin of the Tibetan Plateau; tectonic analysis; thermochronology; tectonic landform; fission track

摘 要: 青藏高原东南缘发育数十万平方千米的广阔地貌过渡带与大面积低起伏地貌面, 独特的地貌提供了了解高原构造拓展与地表隆升时间、过程以及机制的理想窗口。为揭示青藏高原东南缘新生代构造变形响应和地貌演化过程, 通过构造解析、构造地貌以及低温热年代学数据分析对金沙江下游流域进行综合研究。结果表明青藏高原东南缘早在始新世即已处于北西向为主的区域性挤压条件下而发生广泛褶皱变形。尽管始新世存在区域性变形响应, 但青藏高原东南缘金沙江下游地区在古近纪为低海拔丘陵地貌, 地表隆升幅度极为有限。晚渐新世—早中新世研究区总体处于长期的低剥蚀速率环境, 促进了低海

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拔平缓地貌的形成。晚新近纪以来,青藏高原东南缘发生区域性缩短变形与显著地表隆升,大型水系同步下蚀,共同塑造形成现今较高海拔的低起伏地貌面与深切峡谷并存的特征性地貌。研究结果支持青藏高原东南缘晚新近纪以来的隆升与地壳构造缩短及增厚密切相关,而中下地壳塑性流动增厚机制并非必不可少。

关键词: 青藏高原东南缘; 构造解析; 热年代学; 构造地貌; 裂变径迹

中图分类号: P542 **文献标识码:** A **文章编号:** 1006-6616 (2023) 04-0453-12

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0 引言

青藏高原作为地球的第三极,晚新生代以来其一体化高海拔地貌的形成是亚洲乃至全球最具深远影响的地质事件。青藏高原独特的地貌过程,以地表作用为纽带,最终影响和驱动区域乃至全球气候变化、环境变迁以及生态多样性发展与演化(Royden et al., 2008; An et al., 2015)。

不同于青藏高原南缘(喜马拉雅山)和东缘(龙门山)陡峻突变的高原边缘地貌,青藏高原东南缘发育面积高达数十万平方千米的广阔过渡地貌带(图1),海拔高度多介于4000~1500 m之间,并且残留了大量的早期平缓地貌面。青藏高原东南缘独特的地貌提供了揭示高原边缘构造拓展、大型水系演变以及深部动力机制的理想窗口,然而其新生代以来的形成过程仍然备受争议。以Clark为代表的诸多研究者基于热年代学揭示的13~9 Ma以来快速河谷下切时间,认为青藏高原东南缘地表隆升始于晚中新世以来,并且依据地壳构造缩短的缺失,提出中下地壳塑性流动增厚是区域性地表隆升的主要驱动力(Clark and Royden, 2000; Clark et al., 2005a, 2005b)。尽管青藏高原东南缘及邻区进一步的热年代学研究(Ouimet et al., 2010; Tian et al., 2015; Zhang et al., 2016; Gournbet et al., 2020)揭示了中晚中新世以来的快速冷却的证据,但构造分析表明青藏高原东南缘在古近纪就已经发生构造变形(Wang et al., 1998; Tapponnier, 2001; Zhang et al., 2022),暗示青藏高原东南缘在中新世之前可能已经隆升。不少研究强调青藏高原东南缘在古近纪已经隆升至显著高度,甚至接近现今高程(Tapponnier, 2001; Liu-Zeng et al., 2008; Hoke et al., 2014; Su et al., 2018; Hoke, 2018; Xiong et al., 2020; He et al., 2022)。而最近的一些研究则强调青藏高原东南缘的隆升存在阶段性,例如Zhang et al. (2022)通过楚雄盆地的热年代

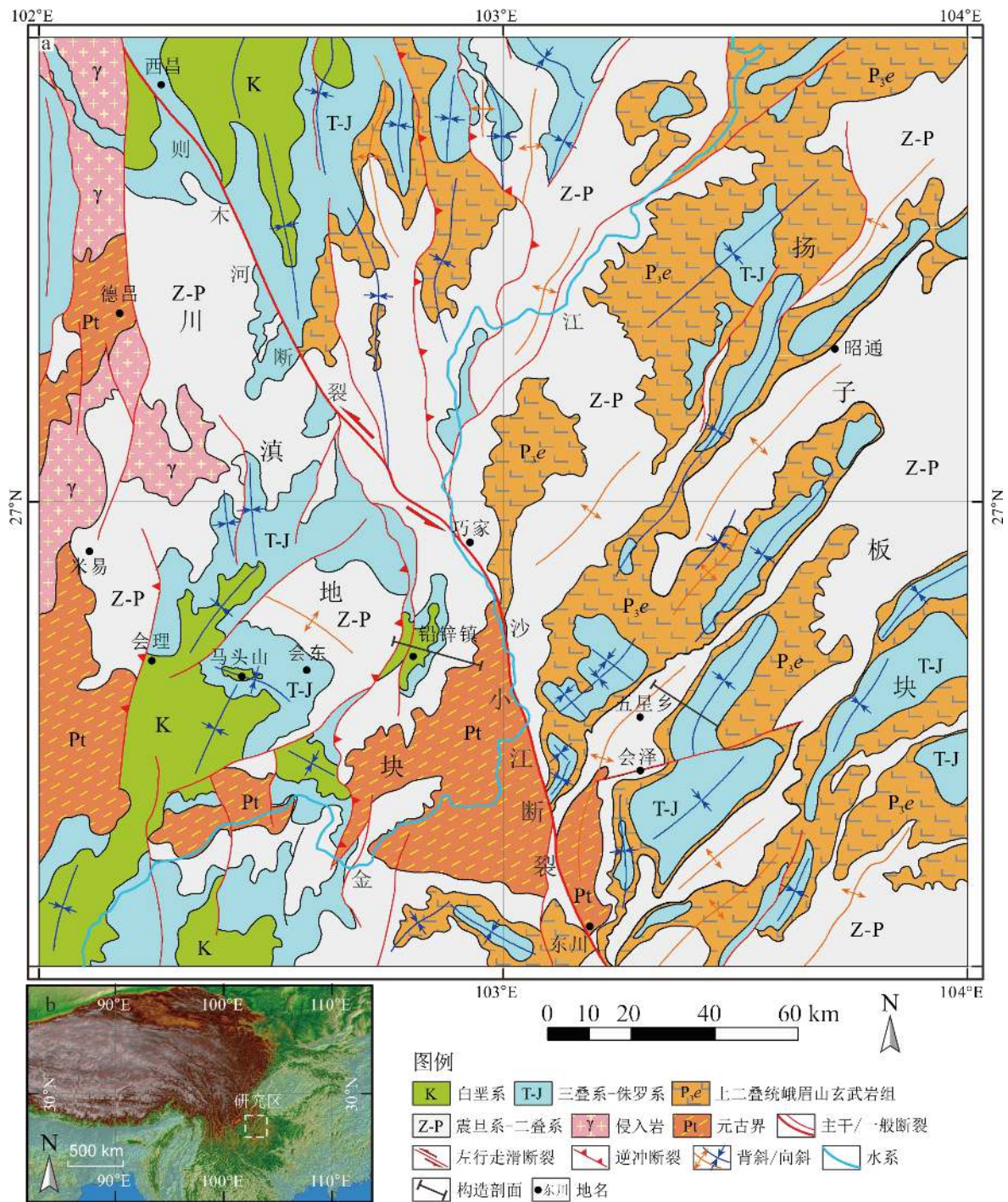
学研究认为青藏高原东南缘经历古近纪和新近纪2个阶段的隆升。虽然现有的研究揭示出青藏高原东南缘古近纪与新近纪2个主要阶段的构造与隆升作用信息,但古近纪与新近纪阶段地表隆升的具体幅度仍存分歧,新生代构造与地表隆升以及高原拓展之间的确切关系仍然比较模糊。此次研究通过金沙江下游地区的构造解析、地貌分析以及热年代学研究,揭示了青藏高原东南缘阶段性的构造与地貌响应历程,支持现今青藏高原东南缘外围金沙江下游地区的地貌主要形成于晚新近纪以来。

1 新生代构造

研究区主要位于金沙江下游会理-昭通地区,则木河-小江断裂呈北北西-南南东向贯穿研究区(图1),将其划分为东西构造单元,西侧为川滇地块,东侧为扬子板块,二者实际上均属于扬子克拉通的一部分。金沙江在研究区内总体呈北东向穿越,局部受小江断裂走滑作用控制形成数十千米的左行断错(Wang et al., 1998; Yan and Lin, 2015)。野外构造调查与解析表明研究区新生代变形主要表现为3组构造,分别为北西向、北东向和近南北向构造。

1.1 北西向构造

北西向构造在研究区主要表现为以中生界地层为载体的褶皱(图1),野外调查在小江断裂两侧川滇地块和扬子板块内部多处均有识别。会理盆地马头山地区发育以白垩系小坝组为核部的舒缓向斜,枢纽总体延伸方向为北西西向,两翼分别低角度倾向北北东和南南西。在金沙江以南东川以东,北西走向褶皱亦有较为完整的发育(图1),出露以中生代地层为核部的完整向斜,两翼对称出露震旦系灯影组至二叠纪地层,向斜核部中心地层为侏罗系益门组红色砂岩。在小江断裂以东会泽附近可见北西向褶皱被后期北东向褶皱构造叠加,使得中生代地层出露形成格状构造(图1)。总体而言,



a—地质构造简图; b—研究区地理位置

图1 青藏高原东南缘金沙江下游会理-昭通地区地质构造简图

Fig. 1 Simplified geologic and structural map of the Huili-Zhaotong area in the lower Jinsha River of the southeastern margin of the Tibetan Plateau

(a) Simplified geologic and structural map; (b) Location of the study area on the southeastern margin of the Tibetan Plateau

研究区北西向构造以舒缓褶皱为代表, 其空间发育和变形程度均相对较弱。

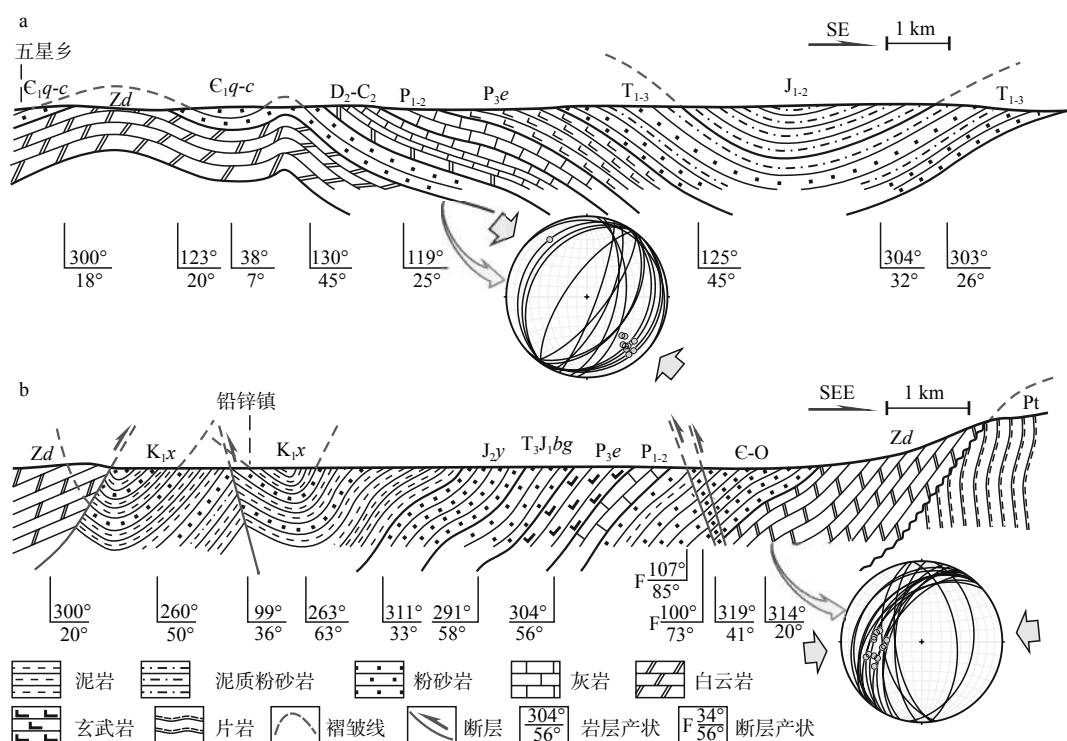
1.2 北东向构造

北东向构造在小江断裂以东的扬子板块有广

泛发育和保存, 主要以褶皱为表现形式。在较高海拔区普遍形成以古生代地层为背斜核部、中生代地层为向斜核部的一系列连续褶皱(图1)。会泽以北五星乡地区的野外构造调查在北东向褶皱翼部古

生代地层层面识别出该期褶皱变形弯滑线理, 赤平投影显示其平均方向为 $320.5^{\circ} \pm 2.6^{\circ}$, 指示北东向区域性褶皱构造的主应力方向为北西—南东向(图 2a)。北东向与北西向褶皱构造的叠加在研究区东川以西清晰可见, 北东向向斜与北西向向斜高角度横向叠加在二叠系地层中形成典型的勾状叠加褶皱特征(图 1)。在小江断裂以东, 北东向会泽背斜褶皱轴线受小江断裂压性牵引而形成北北东走向, 在背

斜核部出露扬子克拉通褶皱基底(图 1), 说明克拉通基底物质卷入了该期褶皱构造变形。总体而言, 研究区北东走向的构造空间分布广泛, 以连续的褶皱变形为典型特征, 根据构造剖面与地层产状数据估算北东走向褶皱的总体水平缩短量约为 10% 左右, 代表北西—南东向区域性挤压背景下的构造变形响应。



Pt—会理群变质褶皱基底; Zd—震旦系灯影组; C_1q-c —下寒武统筇竹寺组—沧浪铺组; C-O—寒武系—奥陶系; D_2-C_2 —中泥盆统一中石炭统; P_{1-2} —下二叠统一中二叠统; P_3e —上二叠统峨眉山玄武岩组; T_{1-3} —下三叠统一上三叠统; T_3J_1bg —上三叠统一下侏罗统白果湾组; J_{1-2} —下侏罗统一中侏罗统; J_2y —中侏罗统益门组; K_1x —下白垩统小坝组; 其他岩石地层单元未细分。

图中赤平投影显示褶皱翼部岩层产状与弯滑线理, 箭头代表区域性主应力方向。

a—会泽五星乡褶皱构造剖面; b—铅锌镇褶皱逆冲构造剖面

图 2 金沙江下游北东向与近南北向构造(剖面位置见图 1)及其赤平投影

Fig. 2 NE-trending and near SN-trending structures in the lower Jinsha River (See Fig. 1 for section locations) and their stereographic projections

(a) Fold section across Wuxing Village in Huize; (b) Fold-thrust section across Qianxin Town

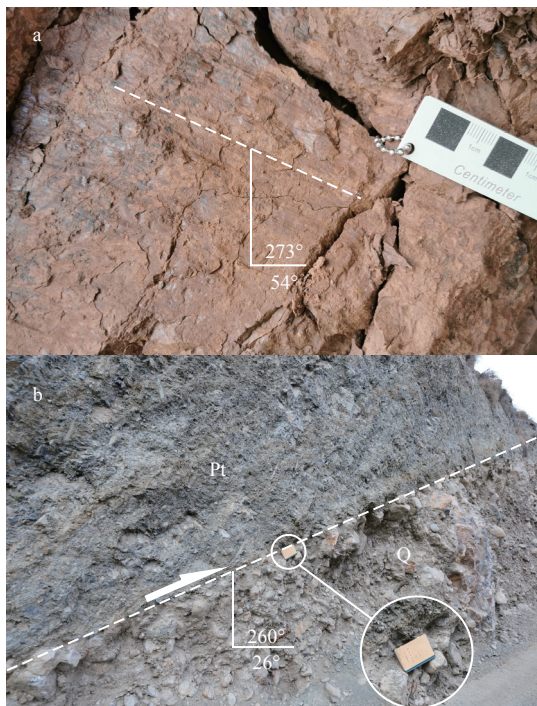
Pt—Folded basement of the Huili Group; Zd—Sinian Dengying Formation; C_1q-c —Lower Cambrian Qiongzhusi Formation—Canglangpu Formation; C-O—Cambrian—Ordovician; D_2-C_2 —Middle Devonian—Middle Carboniferous; P_{1-2} —Lower—Middle Permian; P_3e —Upper Permian Emeishan Basalt Formation; T_{1-3} —Lower—Upper Triassic; T_3J_1bg —Upper Triassic—Lower Jurassic Baiguowan Formation; J_{1-2} —Lower—Middle Jurassic; J_2y —Middle Jurassic Yimen Formation; K_1x —Lower Cretaceous Xiaoba Formation; Alternative lithostratigraphic units are undivided. The stereographic projections show attitudes of limb beddings and fold-slip lineations, and arrows indicate regional principal stresses.

1.3 近南北向构造

近南北向构造在则木河—小江断裂两侧的会理地区以及西昌以东地区均有广泛发育, 主要表现为

近南北向的断裂与伴生褶皱构造(图 1)。近南北向构造明显切割和改造早期北东向褶皱, 说明其变形时间相对较晚。需要强调的是, 虽然近南北向构造

与小江断裂大致平行,但其运动学性质以逆冲变形为主。在会理以东,近南北向断裂普遍将以会理群为代表的克拉通褶皱基底以及震旦系白云岩系逆冲至中生代地层之上(图2b),指示近东西向的逆冲变形和挤压应力。研究区铅锌镇发育以侏罗系和白垩系为核心的北北东走向的向斜,在其翼部白垩系小坝组地层层面上发育一系列褶皱顺层弯滑线理,赤平投影显示其平均倾伏方向为 $264.5^{\circ} \pm 7.6^{\circ}$ (图2b,图3a),指示近东西向的挤压应力背景。



a—铅锌镇北北东向向斜翼部小坝组近东西向顺层弯滑线理; b—侵入会理群的变质闪长岩向东低角度逆冲至金沙江河道砾石层之上

图3 研究区近东西向挤压变形

Fig. 3 Near EW-trending shortening deformation observed in the study area

(a) Fold-slip lineations developed on the Xiaoba Formation in the limb of the NNE-trending syncline across Qianxin Town; (b) The metamorphosed diorite intruded in the Huili Group being thrust eastward above the fluvial gravels of the Jinsha River

在西昌以东,近南北向的逆冲断裂构造同样广泛发育(Deng et al., 2018b),早期 Burchfiel et al. (1995) 和 Wang et al. (1998) 在金沙江下游地区的构造调查也表明近南北向的构造主要以逆冲变形为特征。近南北走向逆冲构造的普遍发育说明近东西向挤压变形并非局部构造,而是区域性的变形响应。野外调查在金沙江左岸发现侵入会理群基底中的变质闪长岩沿近南北向断裂低角度向东逆冲

至第四系金沙江河道砾石层之上(图3b),说明研究区东西向的挤压变形在第四纪仍然持续。Deng et al. (2018b) 基于西昌盆地地区的平衡剖面构造分析估算近东西向的缩短量约为10%~20%,尽管近东西向逆冲缩短量仍然有待进一步工作的约束,但近东西向的褶皱变形明显强于早期北东向以褶皱为代表的变形缩短。研究区近东西向的缩短变形可能是宏观上东构造结地区向青藏高原东南缘斜向汇聚挤压和青藏高原东南缘向南东方向顺时针旋转挤出构造共同派生的结果,同时也可能与则木河—小江走滑断裂较高的活动性(韩明明等, 2022)所反映的较低的黏滞力有关。

2 流域地貌与构造地貌

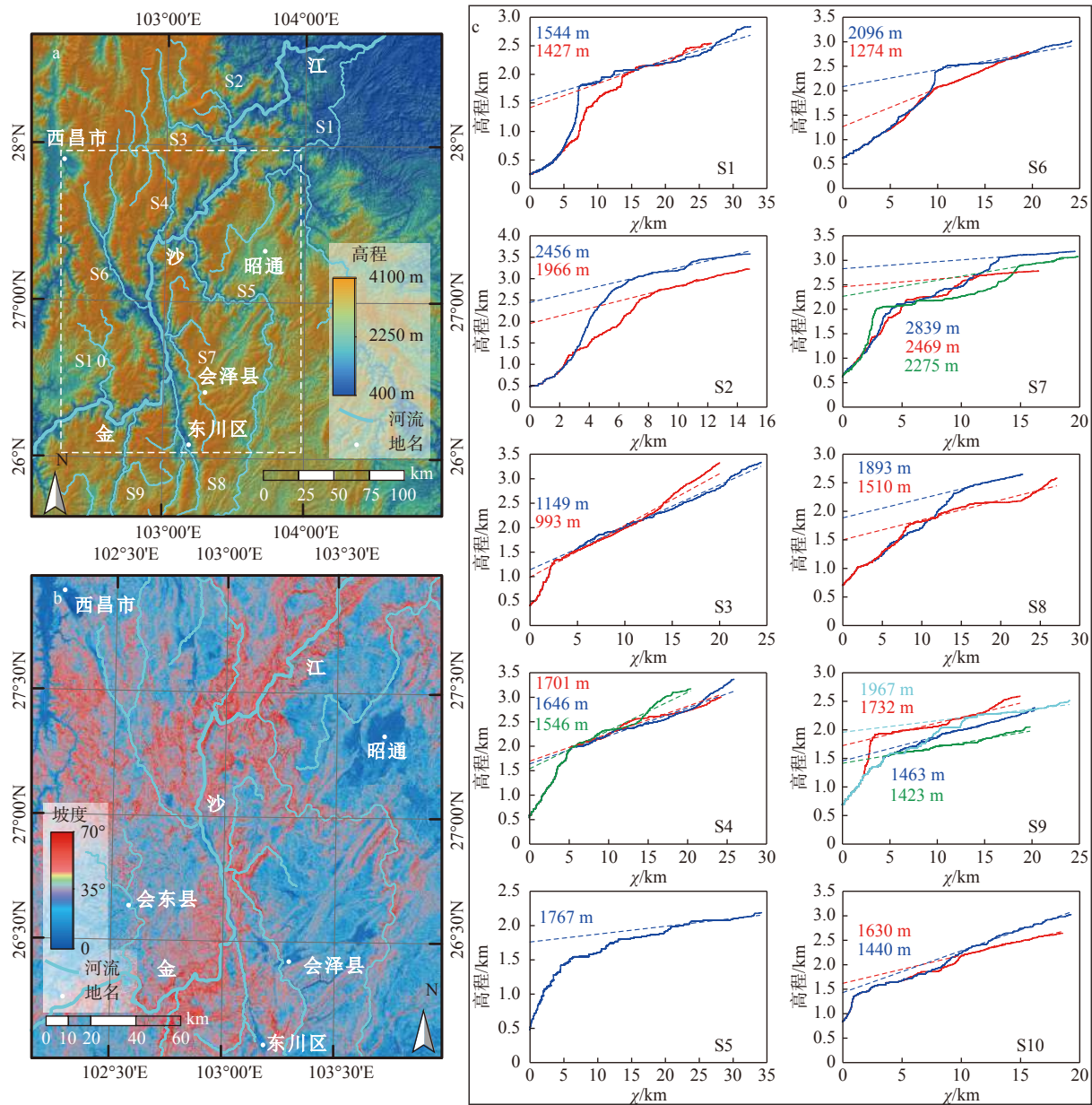
流域地貌是构造内动力与地表外动力过程共同作用的结果,也是定性甚至定量恢复内、外动力作用的重要媒介(曹鹏举等, 2021)。为量化揭示研究区构造与地表隆升信息,此次研究对金沙江下游的主干支流进行了流域地貌和河流纵剖面分析。

2.1 流域地貌特征

金沙江是贯通青藏高原东南缘的大型水系,除局部河段异常(如受小江断裂控制区段)形成相对开阔的充填河谷之外,多数河段以深切基岩的峡谷地貌为特征,暗示现今青藏高原东南缘地表过程与地貌仍然受构造作用主导和维持。需要强调的是,峡谷地貌及其伴生的强侵蚀作用在空间上聚焦于金沙江主干河道及其大型支流沿线,而并未大面积扩散和辐射至整个流域空间。研究区较高海拔处大面积发育和保存有低起伏平缓地貌面,如普渡河、牛栏江等大型支流上游,平缓地貌面在数字地形与坡度空间分布上栩栩如生(图4)。金沙江下游地区特征性的高海拔低起伏地貌面与深切峡谷共存的二元地貌结构,说明青藏高原东南缘流域地貌在宏观上仍然处于构造驱动下的瞬态调整阶段,暗示地貌处于年轻的发展演化阶段。

2.2 地表隆升幅度

如果低起伏地貌面原始形成时期具有低海拔的侵蚀基准面(Clark et al., 2005b; Whipple et al., 2017),那么金沙江下游流域普遍发育的高海拔低起伏地貌面本身(高程下限)即提供了流域空间区域性地表隆升幅度的直接参考。另一方面,河流侵蚀与搬运动力过程对流域空间的构造隆升响应敏



a—研究区数字地形及主干水系；b—研究区坡度与主干水系分布，坡度分布显示研究区低起伏地貌面与陡边坡地貌的突变界线，坡度分析区域为图4a中白色虚线范围；c—主干支流 χ 纵剖面图解，河流纵剖面 χ 图解中不同颜色曲线代表不同的支流，数字表示相应河流纵剖面的投影高度，作为地表隆升幅度的指标，河流位置及编号详见图4a

图4 金沙江下游会理—昭通地区数字高程地形、坡度分布以及主干支流纵剖面 χ 图解

Fig. 4 Digital elevation topography, slope distribution in the Huili-Zhaotong area of the lower Jinsha River and χ plots of longitudinal profiles of the main tributaries

(a) Digital elevation topography and major tributaries of the study area; (b) Slope distribution with major tributaries. Note the abrupt boundary between the low-relief area and the steep hillslopes. See Fig. 4a for the analyzed area indicated by the white dashed box; (c) χ plots of the longitudinal profiles analyzed. Colors are used to distinguish distinctive tributaries, and the numbers marked indicate the projected stream heights, representing magnitudes of surface uplift. See Fig. 4a for tributary labels and locations.

感，河流纵剖面作为河流动力响应过程的集中体现，也详实提供了地表隆升的重要信息。河流 χ 纵剖面分析方法是约束流域地表隆升幅度的有效手段 (Kirby and Whipple, 2012; Perron and Royden,

2013)。

研究区流域数字地貌分析表明，金沙江下游流域低起伏地貌面的平均下限高程约为1.8 km，如果认为低起伏地貌面具有极低的侵蚀基准面，那么低

起伏面约 1.8 km 的平均下限高程可作为金沙江下游地区地表隆升幅度的参考。

对金沙江下游 10 条主干支流的河道纵剖面分析结果(图 4)表明,支流 χ 纵剖面均具有典型的两段式特点,上游为缓倾线性河段,代表早期低剥蚀速率的地形环境,而下游为陡坡段,对应构造隆升驱动河道快速切蚀响应下的河流裂点(带)地貌。金沙江下游河流纵剖面特征充分印证了流域早期为低剥蚀速率的平缓地貌,后期经历构造抬升形成深切峡谷的阶段性构造与地貌演化过程。如果认为早期低起伏地貌面的侵蚀基准面接近海平面,那么上游平缓河段在河口部位的投影高度即可作为隆升幅度。河流 χ 纵剖面的分析结果(图 4)表明金沙江下游流域地表抬升幅度介于 1.0~2.8 km, 平均值约为 1.75 km。需要强调的是,河流纵剖面揭示的隆升幅度与研究区低起伏地貌面的高度下限基本一致,而研究区数字地形分析表明现今流域平均高程约为 2.28 km,二者仅相差约 500 m。因此现今金沙江下游流域地貌主体由最近的地表隆升作用形成,而在隆升之前金沙江下游流域很可能处于低海拔的丘陵地貌环境。

3 新生代变形年代分析

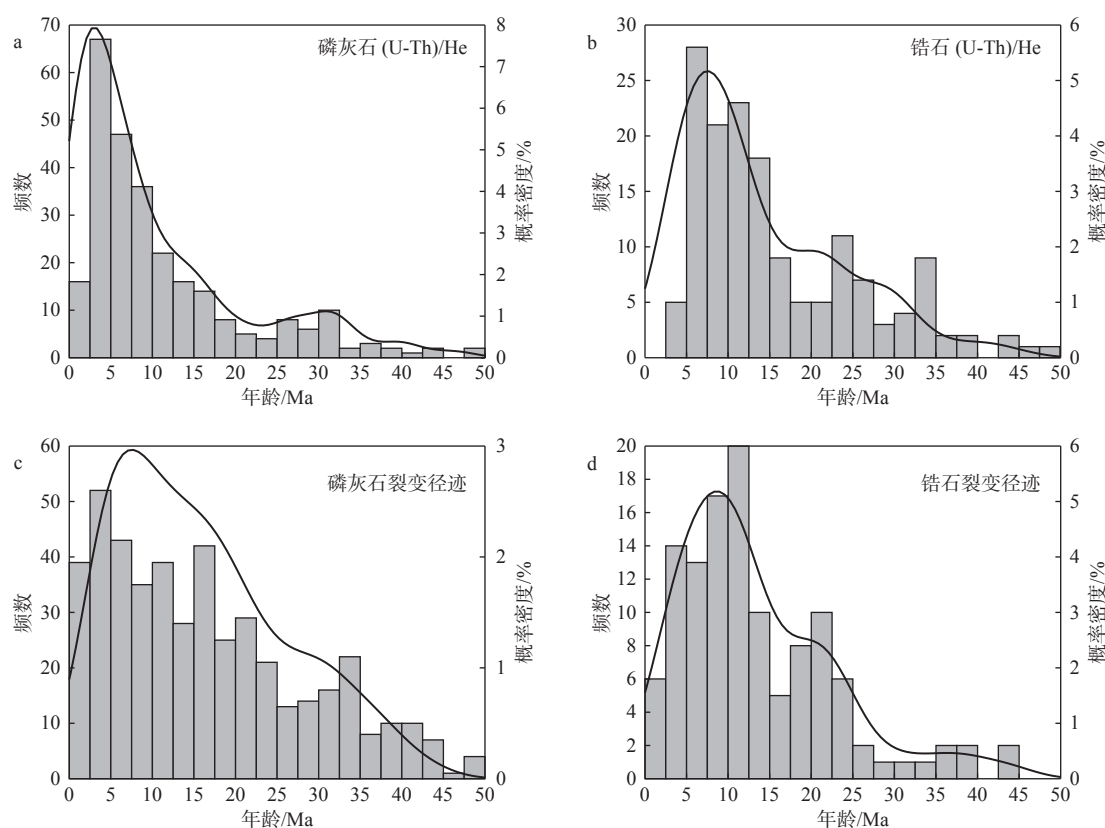
研究区所在的金沙江下游地区区域性褶皱变形以中生代地层为物质载体,而现今青藏高原东南缘广泛分布的中生代地层是扬子西缘中生代统一盆地的残留沉积(王鸿祯, 1985; 郭正吾等, 1996; Deng et al., 2018a)。王鸿祯(1985)早期将该大型盆地称为川滇盆地。川西南雅安地区古近系名山组和芦山组则被认为是川滇盆地最顶部的沉积(郭正吾等, 1996; 王二七和尹纪云, 2009; Wang et al., 2014; Deng et al., 2018a),因此研究区以中生界地层为物质载体的区域性褶皱均形成于新生代(Wang et al., 1998, 2014; Tapponnier et al., 2001; 王二七和尹纪云, 2009)。最近热年代学研究在金沙江乌东德峡谷近 1.3 km 的垂直剖面上获得的磷灰石裂变径迹年龄介于 34.5~20.7 Ma, 主体集中在 34.5~32.4 Ma 之间,揭示出晚始新世一早渐新世阶段(34.5~30 Ma)的快速剥露和晚渐新世一早中新世期间(30~20 Ma)的缓慢冷却,表明会理盆地最晚在始新世晚期之前开始遭受隆升剥露。而 Zhang et al. (2022)在研究区以西的攀枝花金沙江右岸约 1 km 的高程剖面上获得的磷灰石裂变径迹与 (U-Th)/He 年龄也

集中在 36~30 Ma。Wilson and Fowler (2011)在攀枝花附近的磷灰石裂变径迹长度热历史模拟研究也揭示出 40~35 Ma 的快速冷却,同样印证青藏高原东南缘晚始新世一早渐新世的区域性变形响应事件。据此此次研究认为青藏高原东南缘区域性褶皱变形时间约为晚始新世一早渐新世。

为进一步确认青藏高原东南缘区域上晚始新世一早渐新世的构造变形响应,此次研究统计了青藏高原东南缘川滇地块区已发表的包括裂变径迹和 (U-Th)/He 在内的热年代学数据(图 5)。结果显示除了锆石裂变径迹数据相对较少之外,磷灰石裂变径迹以及锆石和磷灰石 (U-Th)/He 都明确显示出约 35~30 Ma 期间的快速冷却剥露的峰值年龄信息,说明晚始新世一早渐新世阶段的区域性变形事件在整个川滇地块都有广泛响应,因而支持该地区存在晚始新世一早渐新世的区域性变形事件。

研究区以北东向褶皱为代表的区域性构造在低起伏地貌面上广泛发育出露,这意味着青藏高原东南缘低起伏地貌面的形成时间是在上述区域性褶皱变形之后,应为晚渐新世以来。会理盆地的磷灰石裂变径迹数据揭示在早渐新世之后长达 ~10 Ma 的缓慢剥露阶段,支持低起伏地貌面形成于早渐新世之后,并且至少持续至早中新世。晚渐新世一早中新世阶段的缓慢剥露事件在区域上也同样普遍存在。Zhang et al. (2016)在青藏高原东南缘九龙地区通过锆石和磷灰石 (U-Th)/He 年龄-高程剖面研究揭示出约 30~15 Ma 的缓慢剥露阶段,而前后阶段均为快速冷却。Liu-Zeng et al. (2018)在三江地区的热年代学研究表明约 40~20 Ma 期间为缓慢剥露阶段,最近 Zhang et al. (2022)在研究区以西楚雄盆地北部通过热史模拟也揭示出约 ~28 Ma 以来的缓慢剥露过程,均印证晚渐新世一早中新世阶段存在缓慢剥露。区域上磷灰石 (U-Th)/He 和裂变径迹冷却年龄直方图分别显示 30~20 Ma 和 30~25 Ma 为年龄波谷区间(图 5a、5c),锆石 (U-Th)/He 和裂变径迹冷却年龄在 ~30 Ma 之后亦与波谷对应(图 5b、5d)。由此可见,尽管青藏高原东南缘晚渐新世一早中新世可能存在局部构造响应,但区域上晚渐新世一早中新世总体为缓慢剥露作用无疑。

研究区近南北向构造以褶皱和逆冲构造为主要形式,并且明确截切和改造晚渐新世一早中新世形成的低起伏地貌面,因此其形成时间更晚,应在早中新世之后。如前所述,近南北向构造在成因上与小江断裂走滑变形相关,尽管在变形运动学方面



a—磷灰石 (U-Th)/He 年龄直方图; b—锆石 (U-Th)/He 年龄直方图; c—磷灰石裂变径迹年龄直方图; d—锆石裂变径迹年龄直方图

图5 青藏高原东南缘川滇地块区热年代学冷却年龄直方图(数据引自 Xu and Kamp, 2000; Clark et al., 2005b; 来庆洲等, 2006; 安艳芬等, 2008; 谭锡斌等, 2010; Ouimet et al., 2010; Wilson and Fowler, 2011; Wang et al., 2012, 2017, 2022; Tian et al., 2014, 2015; Tan et al., 2014; Deng et al., 2015, 2018b; Zhang et al., 2015, 2016, 2017, 2022; Meng et al., 2016; Yang et al., 2016, 2020; Shen et al., 2016, 2022; Liu-Zeng et al., 2018; Cao et al., 2019; Replumaz et al., 2020; Gourbet et al., 2020; Zhu et al., 2021; Pitard et al., 2021; Tao et al., 2022; Lei et al., 2022)

Fig. 5 Histogram of thermochronological cooling ages in the Sichuan–Yunnan Block area of the southeastern margin of the Tibetan Plateau (Data after Xu and Kamp, 2000; Clark et al., 2005b; Lai et al., 2006; An et al., 2008; Tan et al., 2010; Ouimet et al., 2010; Wilson and Fowler, 2011; Wang et al., 2012, 2017, 2022; Tian et al., 2014, 2015; Tan et al., 2014; Deng et al., 2015, 2018b; Zhang et al., 2015, 2016, 2017, 2022; Meng et al., 2016; Yang et al., 2016, 2020; Shen et al., 2016, 2022; Liu-Zeng et al., 2018; Cao et al., 2019; Replumaz et al., 2020; Gourbet et al., 2020; Zhu et al., 2021; Pitard et al., 2021; Tao et al., 2022; Lei et al., 2022)

(a) Apatite (U-Th)/He cooling-age histogram; (b) Zircon (U-Th)/He cooling-age histogram; (c) Apatite fission-track cooling-age histogram; (d) Zircon fission-track cooling-age histogram

存在差异,但其形成时间应与小江断裂变形时间总体一致。已有的研究表明鲜水河断裂左行变形启动时间约为 13~12 Ma (Roger et al., 1995; Zhang et al., 2017),小江断裂作为区域上鲜水河断裂南东向的延伸,其形成时间亦应为晚中新世以来。从区域热年代学统计结果(图5)来看,无论是较低封闭温度的磷灰石 (U-Th)/He 系统,还是较高封闭温度的锆石裂变径迹,都明确揭示出约 15 Ma 以来的冷却年龄峰值,并且伴随封闭体系温度的降低,相应年代学系统的峰值年龄呈现逐步年轻化的趋势,暗示青藏高

原东南缘~15 Ma 以来构造驱动下的岩石动态持续冷却剥露。因此青藏高原东南缘晚新近纪~15 Ma 以来,以东西向褶冲作用为代表的构造变形毋庸置疑。

4 青藏高原东南缘新生代构造与地貌演化

4.1 古近纪低海拔丘陵地貌

青藏高原东南缘古近纪区域性构造变形响应

早在20世纪90年代就已经被提出并得到关注(Wang et al., 1998),近年来大量的热年代学研究(Zhang et al., 2016, 2022; Liu-Zeng et al., 2018)进一步印证了青藏高原东南缘古近纪的冷却剥露事件,这也使得越来越多的研究认为青藏高原东南缘早在始新世就已经得到显著隆升。青藏高原东南缘诸多新生代盆地的古高程研究(Hoke et al., 2014; Li et al., 2015; Su et al., 2018; Hoke, 2018; Xiong et al., 2020; He et al., 2022)也对古近纪的地表隆升提供了广泛支持。例如芒康盆地的古植物焓变高程分析(Su et al., 2018)和贡觉盆地碳酸盐团簇氧同位素研究(Xiong et al., 2020)分别表明早渐新世和中始新世上述盆地已隆升达到和接近现今高度。最近雅砻江上游热鲁盆地的古高程研究(He et al., 2022)也显示始新世末已逐步隆升至约3.5 km,接近现今平均海拔。事实上这些盆地主要位于现今青藏高原东南缘邻近腹地一侧的高海拔地区,古近纪确实可能已经隆升至显著高度。然而研究区所在的金沙江下游地区位于青藏高原东南缘的外围较低海拔区域,虽然古近纪阶段存在区域性的变形响应,但实际的地表隆升幅度并不明显。

金沙江下游地区古近纪区域性构造响应以褶皱变形为代表,研究区典型构造剖面的初步分析表明其总体缩短量约为10%,Zhang et al. (2022)对元谋盆地古近纪的缩短量估算也得到类似的结果。不妨以现今四川盆地地壳为参考,按40 km初始地壳厚度和始新世10%的地壳缩短量估算,地壳增厚贡献约为4.4 km。如果完全不考虑地表剥蚀,按地壳(2700 kg/m³)和软流圈(3200 kg/m³)典型岩石密度值进行均衡计算(Watts, 2001),表明地表隆升幅度约为700 m。而事实上,青藏高原东南缘古近纪阶段的剥蚀幅度是显著的。研究区广泛分布的低起伏地貌面上诸多部位的中生代地层已剥蚀殆尽,而大量的地质资料(王鸿祯, 1985; 何登发等, 2020)表明青藏高原东南缘中生界地层的厚度十分显著,普遍在6~10 km以上。尽管中生代地层在研究区众多向斜核部仍有广泛残留,但古近纪阶段的显著剥蚀作用是显而易见的。如前所述,会理地区中生界地层中的磷灰石裂变径迹冷却年龄集中在晚始新世一早渐新世,已有的热年代学数据也印证青藏高原东南缘低起伏地貌区的岩石普遍记录了古近纪(晚渐新世之前)的磷灰石裂变径迹冷却年龄(Wilson and Fowler, 2011; Zhang et al., 2022),而低起伏地貌面本

身遭受的后期剥蚀幅度非常有限,意味着现今低起伏地貌区的岩石在古近纪阶段就已经剥露至近地表,这也说明古近纪青藏高原东南缘区域性剥蚀幅度至少在3~4 km以上,超过磷灰石裂变径迹封闭温度对应的深度。由此可见,青藏高原东南缘古近纪地壳的实际增厚幅度不足1 km,区域性的地表剥蚀幅度甚至可能平衡了同期构造缩短对地壳增厚的贡献。因此尽管研究区古近纪存在区域性的变形响应,但青藏高原东南缘金沙江下游地区在古近纪并不存在明显的地表隆升,平均高程可能不足200 m。

4.2 早中新世平缓地貌

晚渐新世一早中新世阶段,青藏高原东南缘总体处于长期的低剥蚀速率环境,这进一步促进了青藏高原东南缘区域性平缓地貌面的形成,从而奠定了现今广泛发育的低起伏地貌面的雏形。晚渐新世一早中新世阶段的缓慢剥露同时也反映青藏高原东南缘川滇地块内部构造相对稳定,这可能与渐新世一早中新世青藏高原东南缘的主体变形被哀牢山-红河剪切带左行走滑(Leloup et al., 1995, 2001)以及印支地块向南挤出变形调节吸收有关。

4.3 晚新近纪区域性隆升

晚新近纪以来,伴随哀牢山-红河左行走滑变形的衰减和构造反转(Leloup et al., 1995, 2001),青藏高原东南缘发生区域性构造变形响应。以鲜水河-小江断裂为代表的大型断裂强烈走滑以及块体内部发生近东西向的缩短变形,使得晚渐新世一早中新世阶段形成的平缓地貌面隆升和解体,同时青藏高原东南缘大型水系快速发生下蚀响应而形成深切峡谷地貌。金沙江下游地区的构造地貌分析表明,区域性地表隆升幅度约为1.8 km,而现今研究区平均高程不足2.3 km,说明现今青藏高原东南缘外围金沙江下游地区地貌主体形成于晚新近纪以来,而晚新近纪之前则为低海拔的平缓地貌。构造分析表明,晚新近纪以来青藏高原东南缘地表隆升在机制上与区域性构造缩短及其驱动的地壳增厚密切相关,晚新近纪以来显著的构造缩短变形也意味着中下地壳塑性流动驱动的地壳增厚可能并非高原东南缘地表隆升的必要机制。研究成果支持即便青藏高原东南缘确实存在流变屈服的中下地壳,构造缩短作用仍然是青藏高原东南缘地表隆升的重要驱动力。

5 结论

构造、地貌以及热年代学数据分析表明,青藏高原东南缘金沙江下游地区新生代以来存在三阶段的构造与地貌演化过程,分别为始新世一早渐新世阶段区域性变形与低海拔丘陵地貌,晚渐新世一早中新世阶段的低剥蚀地貌环境以及晚中新世以来区域性地表隆升和低起伏地貌面的解体与深切。

尽管青藏高原东南缘金沙江下游地区古近纪存在区域性的构造变形响应,但同期地表剥蚀明显,显著消减甚至平衡了构造缩短对地壳增厚的贡献,因此青藏高原东南缘金沙江下游地区古近纪的地表隆升极为有限,可能为不足 200 m 的低海拔丘陵地貌。晚渐新世一早中新世阶段研究区长期处于低剥蚀速率环境,反映青藏高原东南缘块体内部总体相对稳定的构造环境。长期低剥蚀与相对稳定的构造环境最终奠定了现今青藏高原东南缘大面积较高海拔的低起伏地貌面的雏形。

晚渐新纪以来青藏高原东南缘发生区域性构造变形和隆升拓展,在金沙江下游地区近东西向的构造缩短变形显著,区域性地表隆升与大型水系快速下蚀耦合,共同塑造了青藏高原东南缘特征性的低起伏地貌面和深切峡谷并存的二元结构地貌。此研究虽然并不完全排除中下地壳塑性流动机制对地表隆升的贡献,但强调晚渐新纪以来的构造缩短是青藏高原东南缘隆升的重要动力。

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