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如何定量评估构造和气候对造山带地貌演化的贡献?

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突出多圈层耦合作用的地球系统科学研究是当今地球科学发展的现实要求和必然结果.构造-气候-地表过程三者耦合是与人类宜居环境关系最为密切的近地表多圈层相互作用的体现,成为当今地球系统科学研究的重中之重.构造活动和气候变化通过不同的物理、化学和生物过程作用于地表,使地表不断发生隆升和沉降、剥蚀和沉积等过程,导致地貌的复杂演化;构造活动通过造山或成盆等地貌系统演化影响到区域或局部地区的气候变化或大洋环流,而气候则通过风化、剥蚀等地表过程引起的地应力场变化反馈促使构造活动.这些都凸显了构造-气候-地表过程三者之间的密切关联(图 1).然而,如何剥离构造和气候因素对地貌演化的相对贡献仍然是当今地球系统科学研究亟待解决的重大前沿科学问题.

地球上的山脉是人类文明发展和地球宜居环境的关键要素(Elsen and Tingley, 2015; Körner *et al.*, 2017),也是构造、气候和地表过程相互作用最为剧烈的区域(Kooi and Beaumont, 1996; Willett, 1999),是岩石圈、大气圈、水圈和生物圈相互作用和反馈的重要载体(图 1).造山带的形成和演化过程不仅记录了洋陆变迁和大陆演化历史(Molnar and Tapponnier, 1975;Cawood *et al.*, 2009),也对全球和区域气候、河流及生物多样性产生了重要影响(Molnar and England, 1990; An *et al.*, 2001; Guo *et al.*, 2002; Boos and Kuang, 2010; Hoorn *et al.*, 2010; Antonelli *et al.*, 2018; Ding *et al.*, 2020).在造山带内,构造内动力驱动岩石垂向运动

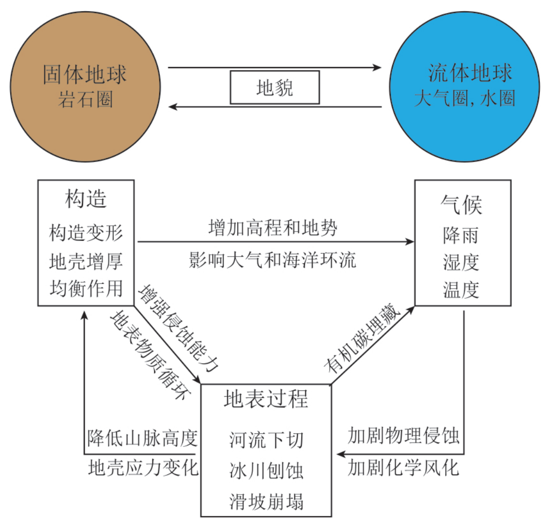

图 1 构造、气候和地表过程相互作用概念图(据 Willett *et al.*, 2006 修改)

形成地貌反差,而与气候因素直接相关的河流、冰川等外动力作用趋向于夷平地势,因此,造山带地貌是内、外动力竞争作用的最终结果(图 1)(Wolf *et al.*, 2022; Egholm *et al.*, 2013),但如何定量评估构造和气候对造山带地貌演化的贡献仍然是地学研究的难点和热点问题,也一直是构造地貌学和大陆动力学研究的前沿科学问题.

1 核心理念

造山带地貌的发育状态和控制因素一直是地质学家和地貌学家关注的核心科学问题.Davis

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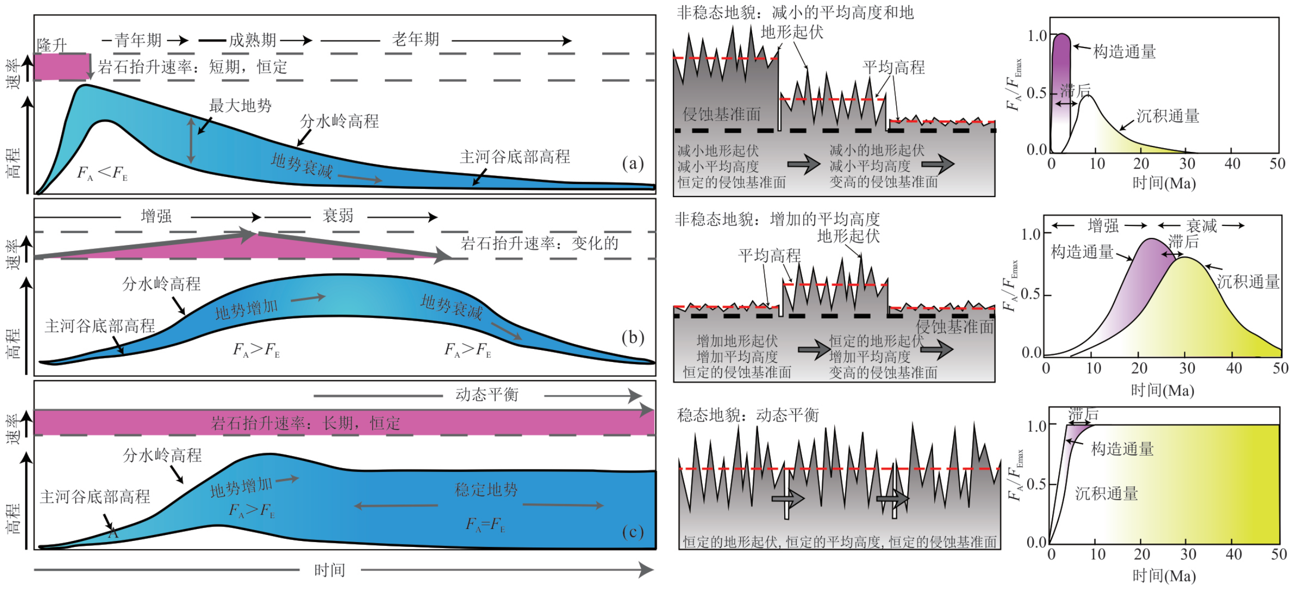

图 2 造山带地貌演化的 3 种代表性模型

a. Davis 的地貌"侵蚀循环"理论；b. Penck 修正的"侵蚀循环"理论；c. Hack 的地貌"动态平衡"理论 . 据 Burbank and Anderson（2011）修改 .F_A 和 F_E 分别为构造和侵蚀通量（Stolar *et al.*，2007），侵蚀引起沉积通量

（1899）的"侵蚀循环"理论系统阐述了造山带地貌演化的周期性，认为早期的构造变形奠定了山脉的结构和高度；构造作用停止后，山脉地貌表现为非稳态，地表侵蚀使地貌从青年期逐渐发展到成熟期、老年期，早期高耸的山脉会被夷平至海平面附近，最大沉积通量的时间明显滞后于构造隆升期（图 2a）.Penck（1954）发展了 Davis 的理论，提出地貌和地势会随着构造强度的增强而增加，山脉表现为非稳态，最大沉积通量的时间滞后于强构造隆升期（图 2b）. 随着 20 世纪 60 年代板块构造理论的兴起，地质学家和地貌学家开始从板块构造的视角重新思考造山带的地貌演化和控制因素（如，Kooi and Beaumont，1996；Willett，1999；Summerfield，2000；Beaumont *et al.*，2001；Pazzaglia and Brandon，2001）.Hack（1973，1975）基于基岩河流纵剖面形貌学的研究提出了地貌演化的"动态平衡"理论：当构造隆升和地表侵蚀同时发生时，造山带地貌可以处于平衡状态，即高程和地势不随时间变化，较高的沉积通量一直持续发生（图 2c）；另外，由于岩石强度有限，山脉不会无限隆升，当地形坡度达到临界角就会发生地貌垮塌 . 由此可见，造山带地貌的长期演化状态及控制因素一直是构造地貌学的基础科学问题，但理论上仍存在巨大争议 .

2 解决思路

高精度数字高程（SRTM、ASTER GDEM、Lidar 和无人机）、低温－超低温热年代学（裂变径迹、U-Th/He 和 ^{4}He/^{3}He）和宇宙核素等测试技术、古高度计、气候干湿指标，以及构造－地表过程数值模拟技术为定量刻画造山带的地貌状态、发育过程及其控制因素成为可能 . 定量评估构造和气候对造山带地貌演化的贡献，首先需要独立定量约束造山带的长期造山过程、古高度及变化、气候历史和地表侵蚀状态；其次，分析造山带构造、气候和地表侵蚀在长时间尺度上的耦合性 . 最后，利用上述多源数据集作为边界条件输入构造－地表过程数值模型，开展构造和气候对造山带地貌演化过程的贡献度分析，探索造山带地貌的发育状态及主控因素 .

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