青藏高原隆升阶段性

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摘要 青藏高原的隆升不仅是印度板块与亚洲板块碰撞导致的地球内部岩石圈地球动力学作用过程的结果,并且对全球和亚洲气候变化、亚洲地貌和地表环境过程及大量地内和地表矿产资源的形成分布产生了深刻影响。因而研究高原隆升的历史不仅对解决上述重大科学问题提供重要途径,而且可为高原区域资源环境的开发和可持续发展提供理论依据。简要回顾和梳理了国内外近年来,围绕青藏高原隆升所取得的主要进展。研究表明新生代青藏高原经历了多阶段、多幕次、准同步异幅且高原南北后期加速隆升的演化过程。具体可划分为55~30、25~10及8~0 Ma 3个主要生长隆升期次。其中55~30 Ma的高原早期隆升,主要集中在高原中南部的拉萨地块和羌塘地块,并且可能隆升到接近3 km高度,或甚至更高,有人称之为“原西藏高原”,但其周缘存在准同步异幅的变形隆升响应;25~10 Ma的中期隆升,“原西藏高原”南北缘的喜马拉雅山和可可西里—昆仑山开始强烈隆升,“原西藏高原”率先隆升到目前高度并开始向东西两侧挤出物质、拉张形成南北向裂谷,高原北缘普遍产生广泛变形隆升但幅度有限;从约8 Ma开始的晚期隆升,高原南、北部边缘的喜马拉雅山和昆仑山—西秦岭以北的高原东北部隆升显著加速,经历一系列短暂快速的多幕次构造变形和生长隆升,最终形成现今高原面貌。

关键词 青藏高原;隆升;阶段性

印度板块与欧亚板块碰撞导致的青藏高原隆升是固体地球形成以来最重要的地质事件之一,青藏高原的隆升不仅伴随着大规模的地内成矿作用、表生盐类和水资源等资源效应,而且对亚洲大气环流、季风和干旱环境的形成演化、动植物演替,乃至全球气候变化都产生了深刻影响。更为重要的是,青藏高原现今异常活跃的构造运动和地表过程变化,强烈地影响着本身及周边地区人类赖以生存发展的自然环境、资源和能源的配置及各种地质灾害的发生。因此,青藏高原隆升历史的研究既对解决岩石圈地球动力学、全球气候和亚洲环境变化有重要意义,也可为高原资源开发和区域可持续发展的广阔应用前景提供理论依据。

青藏高原隆升历史研究的早期有以施雅风、李吉均及徐仁为代表的中国地理学家,在中国科学院组织的对青藏高原几次大规模科学考察和地理植被环境资料分析总结基础上,认为青藏高原在上新世作为一个广阔的夷平面处于大约1 km高度,上新世末—第四纪初才开始大幅度整体差异性隆升,经过第四纪期间阶段性并且后期加速的隆升达到目前的高度[1-3]。随后,国外地质学家主要以喜马拉雅山和高原南部一些地段的地质证据为主,提出青藏高原的整体隆升可能主要开始于中新世,并在距今约8 Ma时就已经隆升到最大高度,然后高原岩石圈下部折沉,顶部开始拉张塌陷,形成南北向裂谷盆地,印度季风随之形成[4-7],后来有人依据更老的裂谷年龄或相伴的火山喷发年龄,认为距今约14 Ma高原就达到了最高高度[8]。综合集成后来更多的岩浆火山活动、盆地和地震地质资料,2001年Tapponnier等[9]提出高原的隆升是一个由南向北逐步生长隆升过程,首先是青藏高原南部在始新世隆起,然后向北到渐新世—中新世可可西里—昆仑山隆起,最后是柴达木—阿尔金山—祁连山组成的高原东北部在上新世—第四纪的隆起。最近,越来越多的地质证据显示青藏高原拉萨地块和羌塘地块组成的高原中南部,可能在始新世就隆升到接近现代的高度,王成善等称之为“原西藏高原”,然后高原再向南北两侧扩展,最后扩展到高原东北部[10-11]。但古生物地理证据认定这个“原西藏高原”当时的高度不会超过2~3 km,还不足以明显阻挡高原南北大型哺乳动物的交往和高原上适应低地环境的动植物生长[12]。而高原东北部本身可能是一个碰撞初期就开始响应,多阶段、多幕次、后期明显加速的变形隆升过程[13-15]。

与青藏高原隆升相伴的环境效应研究表明约25~22 Ma中国气候经历了行星风系瓦解到东亚季风和干旱粉尘系统形成的重大调整[16-18],展示与上述高原隆升过程的认识不完全匹配。而现代大气环流数值模拟结果也与上述地质记录不完全吻合,因而呈现高原不同区域隆升可能对气候系统有

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不同影响,如Licht等[19]认为亚洲季风早在40 Ma已经形成;Boos等[20]认为只需要喜马拉雅山的隆升,而无需青藏高原的隆升,就可以形成亚洲季风;而Liu等[21]认为喜马拉雅山隆升可能主要仅仅影响南亚季风,青藏高原的隆升,尤其高原北部的隆升对东亚季风的形成发展更为重要。

综上所述,青藏高原现今面貌到底何时、以什么方式形成?高原隆升与环境变化如何耦合,对季风和干旱气候环境的形成演化又有如何影响?尽管进展很大,但是仍然存在很大分歧,而有关青藏高原隆升阶段性的研究显然对澄清和解答上述争议与问题极为重要。本文就近年来取得的众多地质证据对高原隆升的阶段性问题做一简要概述。

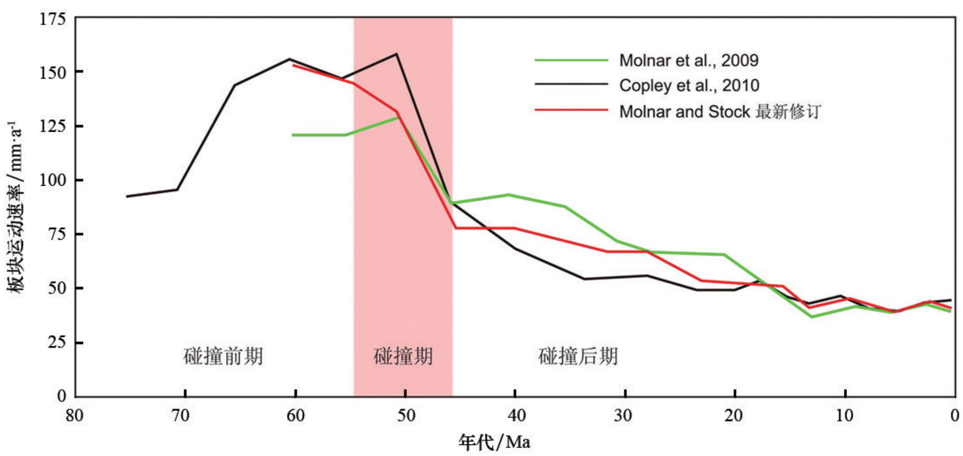
1 青藏高原隆升的阶段性

1.1 印度板块与欧亚板块初始碰撞时间

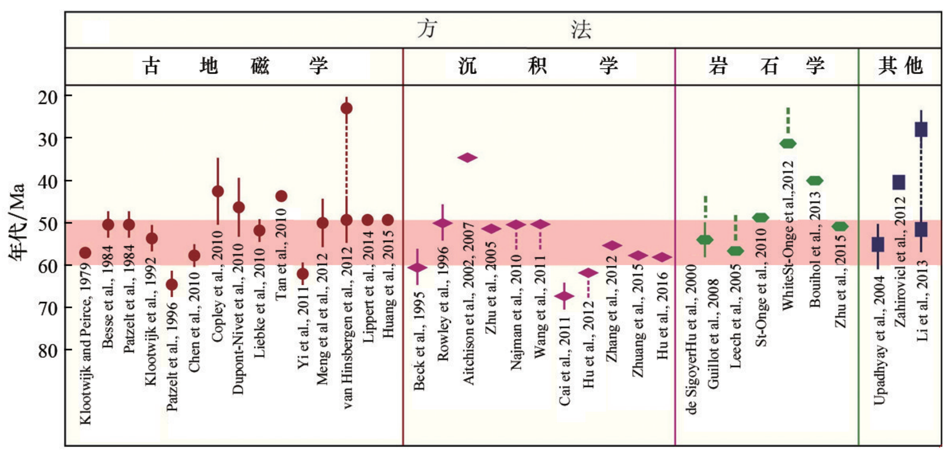
印度—欧亚板块的碰撞是青藏高原隆升的原动力,其初始碰撞时限是理解青藏高原形成与演化的起点。然而印度—欧亚板块的初始碰撞时间是一个争论很激烈的问题[22-27],大多数研究者认为初始碰撞时间大致在(55±5) Ma,理由如下:1)从洋底古地磁资料重建的印度板块相对欧亚板块的运动速度随时间变化可见(图1(a)),印度板块相对欧亚板块的运动速度在约55 Ma前一直很快,约为150 mm/a,但在55~50 Ma期间,运动速度突然下降至之前的近1/2,为70~80 mm/a(图1(a)),普遍认为是印度板块与欧亚板块发生陆—陆碰撞受阻而使速度降低[28-29]。2)大量基于高压—超高压变质作用、古地磁视极移曲线、最高海相层位年代、沉积物物源转变、陆生生物迁移及岩浆作用特征等研究结果,尽管对印度—欧亚板块的初始碰撞时代限制在较大的70~20 Ma范围,但碰撞主要发生年限都集中于55±5 Ma(图1(b))。

1.2 高原陆内阶段性变形与生长隆升

印度板块自约55±5 Ma与欧亚板块碰撞以来,继续向北推进了约2000 km,导致亚洲板块内部强烈变形和生长隆升。越来越多的地质证据表明,青藏高原的隆升不是一蹴而就的,而是经历了多个阶段、多幕次隆升,高原主体边缘还呈现为后期显著加速的隆升,在空间上大致表现为高原中南部的主体部分在始新世率先隆起,然后在渐新世末和中新世初开始逐渐向南北两侧扩展,中新世晚期以来高原东北部最后



(a) 印度板块相对于欧亚板块的运动速度

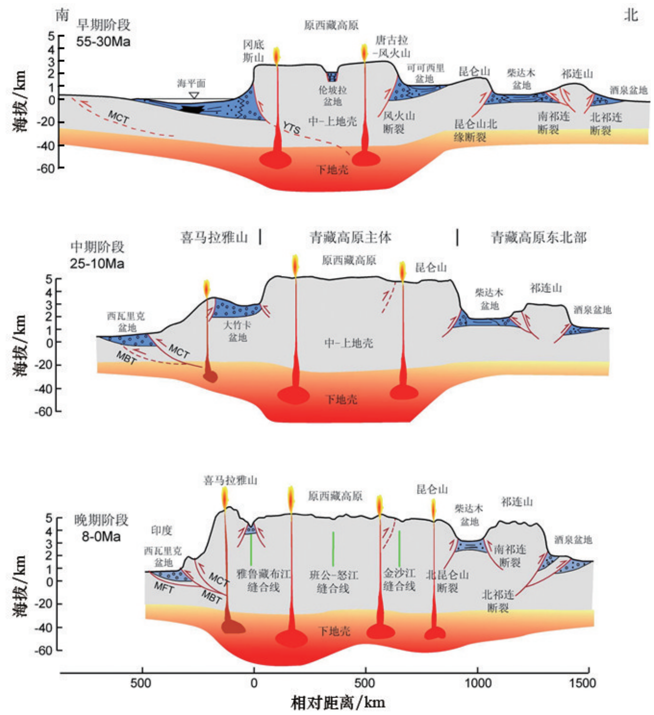


(b) 不同方法揭示的印度—欧亚板块初始碰撞时代

图1 地质证据限定的印度板块与欧亚板块的碰撞时间[30]

Fig. 1 Time of collision of India Plate with Eurasian Plate constrained by geological evidence[30]

强烈隆起，高原各部分大致表现为准同步但幅度不同的变形响应与隆升过程(图2)[11]，大致可划分为以下3个阶段。



YZS—雅鲁藏布江缝合带；MCT—主中央断裂；MBT—主边界断裂；MFT—主前沿断裂

图2　青藏高原新生代阶段性隆升示意[11]

Fig. 2　Sketch map showing the Cenozoic uplift of the Tibetan Plateau[11]

1.2.1　碰撞早期(55~30 Ma)

印度—欧亚板块在55±5 Ma汇聚后，巨大碰撞应力使得由拉萨块体和羌塘块体(即“原西藏高原”)组成的前缘地区率先隆升[11, 30]，进而引起该区古新统陆相地层直接不整合于下伏侏罗—白垩系地层之上[31]，“原西藏高原”地壳显著变形增厚至少达40 km，导致中下地壳局部熔融，岩浆侵入喷发形成一套51~38 Ma埃达克质岩石，指示该部分高原在此时应该有明显的地壳隆升[32-35]。地层氧氢同位素高度计及其他手段揭示，当时高原的高度已基本与现代高原高度相当[10-11,30]，但同样的研究揭示，拉萨地块当惹雍错地区在约46 Ma时的古高度仅为2590+730/−910 m[36]，Sun等[37]和Jia等[38]根据孢粉和叶蜡氢同位素研究结果甚至认为“原西藏高原”的伦坡拉盆地约26 Ma时海拔还未超过3.2 km，质疑了Rowley等[10]在同一地点获取的古高度结果。犀科化石恢复的约24~18 Ma伦坡拉盆地海拔高度也仅为约3 km[12,39]。印度—欧亚板块碰撞的应力不仅仅局限在“原西藏高原”地区，而是通过早期高原地区拼贴的刚性小块体向北几乎同步传递到高原东北部的祁连山及其邻近地区[13]，使得高原北部、东北部主要大型新生代盆地在晚白垩世长期剥蚀基础上，在约54~50 Ma时开始下陷接受沉积，如可可西里、柴达木、西宁—贵德和兰州盆地[11, 40-42]，盆地周缘断层开始明显逆冲或走滑活动[43-44]，东昆仑山、阿尔金山、祁连山等在55~50 Ma发生构造抬升作用[45-46]。随后，持续的变形在约45~41 Ma和约35~30 Ma呈现出2次快速隆升事件，共同组成一个大的早期高原变形隆升高峰期(图3)[13, 40, 47]，唐古拉山—昆仑山快速隆升，导致相邻的可可西里盆地急剧压陷变形[11]，柴达木盆地43.8~31.5 Ma地壳缩短明显加速，酒泉盆地最迟于40.2 Ma开始被压沉堆积含砾砂岩和泥岩[47](图3)，西宁盆地41 Ma发生25°顺时针旋转[48]，而更东缘的临夏地区则至少在30 Ma就已遭受压陷成盆[12, 49]。

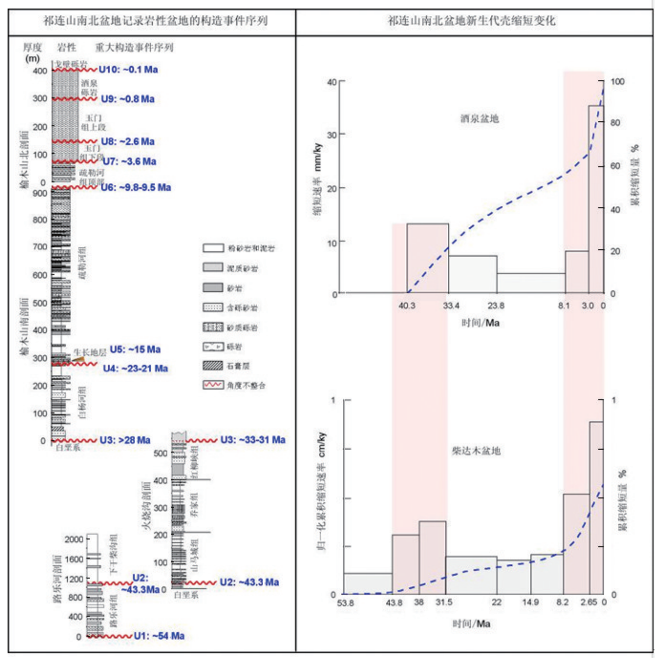


图3　祁连山南北盆地记录的重大构造事件序列

Fig. 3　Sequence of major tectonic events recorded by the basin sediments and tectonics in north and south sides of the Qilian Mountains

这期应力尽管引起“原西藏高原”外缘基本同步的变形隆升响应，但是隆升幅度可能有限。最近古高度研究结果揭示，沱沱河地区风火山群中湖相碳酸盐碳氧同位素与Mg/Ca比值指示该区在始新世—渐新世(52~30 Ma)古高度不超过2 km[50]；Miao等[51]根据孢粉组合特征分析也认为可可西里和高原东北部在晚始新世(40~37 Ma)的海拔高度不超过2 km。

“原西藏高原”南缘的喜马拉雅地区，大量生物地层学研究表明喜马拉雅地块发育古新世—始新世期间海相沉积[27, 29, 52]，特别是日喀则定日县附近发现了始新世末期最晚达38 Ma的朋曲组海相地层[29, 52]，这说明喜马拉雅地区至少在晚始新世以后海拔高度才超过海平面。同时，35~33 Ma冈底斯山早期侵入的大型花岗岩体被抬升剥露，印度河—雅鲁藏布江缝合带出现湖盆，开始2.5 km厚的冈底斯砾岩沉积，反映冈底斯山此时应有较强烈的隆升[53]。

而在青藏高原东南部的三江地区，以上两期强烈构造挤

压活动导致该区开始强烈挤出，主要块体边界深大断裂强烈走滑拉分，沿断裂形成一系列糜棱岩和地壳加厚局部熔融的高钾玄武岩、粗面岩喷发及相应的铜铅锌等多金属矿床[54,55]，同时结束和变形早期自白垩纪以来一直连续沉积细粒河湖相物质的大型盆地，致使盆地强烈大幅度顺时针旋转[56]，云贵高原主体形成。

1.2.2 碰撞中期(25~10 Ma)

印度板块持续向北挤压导致的渐新世末—中新世初开始的又一期强烈构造变形隆升，除了使得“原西藏高原”再次强烈隆升并可能达到目前海拔高度，最醒目的特征就是使“原西藏高原”向南、北两侧显著扩展，生长隆升形成喜马拉雅山和可可西里—昆仑山组成的高原北部地区，并且变形应力继续向北传播而使青藏高原东北缘甚至天山地区也发生准同步异幅的构造变形(图2、图3)，同时也使得印度板块本身的运动速率进一步受阻，在25~10 Ma与欧亚大陆汇聚速率减小了40%(图1(a))。

青藏高原隆升到最大高度的重要地质特征是高原顶部因重力作用和挤压诱发的拉张作用，包括可能的下地壳流动引起的上部物质拉张或岩石圈折沉导致的地壳垮塌，都可能共同作用促使了高原顶部一系列醒目的南北向裂谷的形成[57-58]。这些裂谷集中出现在约18.3~13.5 Ma [30,58-59]，主要分布在高原中南部，而喜马拉雅山上的裂谷则普遍年轻，主要形成于约7~8 Ma。

岩浆、热年代、沉积和地貌发育等其他地质证据也同样明显地记录了这期构造变形隆升。“原青藏高原”的东延部分被一系列近水平分布的来自增厚地壳局部熔融的23~22 Ma碱性火山岩层覆盖[60]，拉萨地块广泛发育一套26~10 Ma由于岩石圈下部增厚进而重力失稳引发拆沉作用所形成碱性超钾质火山岩和埃达克岩[58]。岩体冷却事件揭示“原西藏高原”在约26~15 Ma有显著的快速冷却剥露，如Harrison等[61]揭示拉萨曲水岩体在20~18 Ma发生快速冷却剥露；Copeland等[62]通过冈底斯基岩在26~20 Ma 处于快速冷却剥露期，且在20 Ma冷却速率加快；袁万明等[63]对拉萨—羊八井一带岩体磷灰石裂变径迹研究同样揭示21~15 Ma间存在快速冷却剥露事件。三江地区约22~15 Ma形成新的一期断裂走滑活动高潮和块体大幅度旋转[56]。同时，雅鲁藏布江周缘分布的大竹卡组(E_3-N_{1d})粗碎屑沉积[61,64]及羌塘地区以康托组(E_3-N_{1k})磨拉石堆积为代表的陆内盆地的发育，以及早、晚第三纪地层之间普遍存在的显著角度不整合面，正是对“原西藏高原”这期构造隆升的沉积响应。地貌上约22 Ma也是现今雅鲁藏布江谷地雏形形成的重要时期[65]，此时金沙江可能被长江袭夺，形成当代长江东流入海[66]。

这些事件的出现，尤其裂谷的广泛发育，指示“原西藏高原”可能此时已经隆升到最大高度。古高度研究进一步认定拉萨地块在15 Ma之前已经隆升到目前海拔高度[67-68]。

在“原西藏高原”进一步变形隆升的同时，强烈的变形隆起主要发生在当时高原的南北两侧，向南扩展生长导致喜马拉雅山在26~20 Ma发生强烈的造山运动[66]，并促使主中央断裂(MCT)在25~22 Ma不断向前逆冲推覆扩展[69-71]，冲压印度板块北缘形成著名的中新世早中期的西瓦里克前陆盆地沉积[72]；喜马拉雅地区广泛分布的一套26~13 Ma淡色花岗岩，进一步佐证这时喜马拉雅山已经隆升到相当高度[73]。向北生长使得巴颜喀拉—松潘甘孜块体为基底的可可西里盆地经历了近10 Ma的地层变形和沉积间断后，盆地类型发生改变，在23 Ma开始接受近水平的五道梁群沉积[11,74]，并相伴发育一套18~16 Ma喷发的代表下地壳显著加厚局部熔融的埃达克岩[75]；东昆山地区同样在中新世早期发生强烈抬升[76]。

与此同时，构造应力持续向北传播，引起高原东北部的众多山体幕式隆升以及山前盆地，如柴达木、河西走廊、贵德、临夏盆地等挠曲下沉，冲断褶皱下部地层，形成显著的上、下第三系不整合面，并于其上大规模堆积厚层山麓砾岩[12,77-86]。低温热年代学和磁性地层学研究揭示中新世青藏高原东北部经历了快速剥露事件，如祁连山在约20~10 Ma发生快速隆升剥蚀事件[87-88]，柴达木盆地东缘的鄂拉山25 Ma开始发生快速剥露[84]，拉脊山和积石山也分别在约22 Ma和约13 Ma开始快速隆升[89]，其两侧的贵德—西宁盆地在中新世23~19 Ma和16~13 Ma发生两期构造变形和隆升事件[90-91]。

在天山地区，这次构造事件也有明显响应。天山山前的沉积记录揭示天山经历了25~20 Ma[92-93]和13.6~11 Ma[94-95]两期构造隆升活动；低温热年代学结果显示塔里木盆地南缘和西缘的山脉自25~20 Ma起发生了快速的剥露事件[96-98]。

尽管如此，青藏高原北部和东部地区此时的平均海拔高度可能为1~1.4 km[81,99]，局部地区甚至达到2.1 km[100]。

1.2.3 碰撞晚期(约8~0 Ma)

这一时期，随着高原主体的形成，印度—欧板块汇聚的应力主要被南向继续生长隆升及北向最剧烈的挤压缩短隆升所消解，以至于发生在高原周边山脉的构造与发生在中央高原的构造在性质上截然不同，但在时间上还是基本同步的，即高原主体主要发生伸展垮塌的表现，从造山转变成造高原，随着地形起伏的变小，地表的侵蚀营力如河流的下切幅度也开始减小，平坦的高原面可能就在这一阶段发展起来。Armijo等[101]和Molnar等[102]研究表明，“原西藏高原”地区在晚中新世以来开始出现显著的近南北(SN)向拉张，形成一系列SN向裂谷以及北西(NW)向右旋和北东(NE)向左旋的共轭走滑断裂系。而其边缘开始挤压隆升或向外扩展生长的造山作用，在各个方向又具有多幕次、后期加速、准同步异幅的特点。这期间的一系列构造事件，塑造了现今青藏高原的构造变形框架、山川地貌特征及气候—生态环境格局[14,103-106]。其中尤以青藏高原东北部的变形隆升最为强烈，多幕次并且明显后期加速(图3)。李吉均和方小敏等将这期青藏高原的隆升事件划分为4大阶段，早期8 Ma的构造隆升为“青藏运动序幕”；中期(3.6~1.7 Ma)为“青藏运动主幕”，包括A、B和C这3个阶段(3.6、2.6和1.7 Ma)；晚期(1.1~0.6 Ma)为“昆黄运动”，也包括3个阶段(1.1、0.8和0.6 Ma)；以及最近

0.15 Ma以来的“共和运动”[3, 14, 107-109]。

喜马拉雅山此时继续向南扩展，主边界断层(MBT)开始强烈活动冲起，并逐步将应力和变形传递到更外侧的主前缘逆冲断裂带(MFT)，上新世和第四纪形成的著名厚层磨拉石建造“上西瓦里克群”砾岩也开始卷入强烈的构造变形，成为喜马拉雅碰撞造山带的组成部分，沉积速率减慢[110-111]。最近，Mishra等[112]通过对西瓦里克中发育的震积岩磁性地层学研究结果表明，在约5~4 Ma主边界断裂复苏，向南逆冲活动强烈。西瓦里克盆地的钻孔资料同样表明，1 Ma大量卵石砾岩沿逆冲断裂以背驮式盆地方式开始沉积于西瓦里克群之上[113]。喜马拉雅山再次产生强烈隆升，形成一系列南北向山间裂谷盆地[114-116]，山体产生强烈剥露[117]，动植物、冰川和同位素高度计研究表明喜马拉雅山在晚中新世以来至少隆升了3 km[2, 118-119]。

西昆仑山和天山山前大面积分布的西域砾岩也主要在这个时期形成，并且伴随找冲断褶皱带向盆内的显著扩展和山盆的急剧缩短[95, 120-124]。

2 结论

综上所述，印度板块与欧亚板块自55±5 Ma碰撞以来导致了青藏高原多阶段、多幕次、准同步异幅且后期加速的生长隆升演化历史，大致可划分为碰撞早期(55~30 Ma)、碰撞中期(25~10 Ma)及碰撞晚期(约8~0 Ma)3个主要时期(图2、图3)。其中，碰撞早期高原隆升主要集中在“原西藏高原”，但其周缘地区有所响应，“原西藏高原”呈现大致2~3 km高的雏形，云贵高原主体形成；25~10 Ma“原西藏高原”开始率先达到目前海拔高度。同时，高原的外围扩展生长不仅造成喜马拉雅山和可可西里—东昆仑地区强烈抬升，而且碰撞应力持续向北传播使得青藏高原东北缘甚至天山地区也发生准同步异幅的构造变形。8 Ma以来“原西藏高原”的构造性质由造山转为造高原，隆升幅度有限，而其东北部经历着由“青藏运动序幕”到“青藏运动主幕”再到“昆黄运动”以及“共和运动”的最剧烈、多幕次、后期显著加速的造山作用，并形成现今构造地貌特征。

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Phased uplift of the Tibetan Plateau

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Abstract The uplift of the Tibetan Plateau is the result of the collision of the India-Asia Plates with the result of the geodynamic process of the earth´s lithosphere, and has profound impacts on the global and Asian climate changes, the Asian geomorphology and surface environment, and the abundant surface and underground mineral resources. Thus, the study of the uplift history of the Tibetan Plateau can not only solve the major scientific problems mentioned above, but also provide a theoretical basis for the plateau regional environmental resource exploitation and sustainable development. In this paper, we briefly review the main progresses of recent studies concerning the uplift of the Tibetan Plateau. It is shown that the Tibetan Plateau has experienced uplift processes of multiple stages and episodes, quasi-synchronous but with different amplitudes, which are accelerated in a later period.

The uplift processes can be divided into three main uplift stages, those during 55~30 Ma, 25~30 Ma, and 8~0 Ma, respectively. The early uplift mainly happens in the Qiangtang and Lhasa terrains of the central-southern Tibetan Plateau during 55~30 Ma, which might be close to the modern plateau elevation and is called the "Proto-Tibetan Plateau"; they are deformation uplifts in the peripheral area, quasi-synchronous but with different amplitudes. The second stage uplift mainly occurs in the Himalaya and Hoh Xil-Kunlun Mountains in the north and south of the "Proto-Tibetan Plateau" during 25~10 Ma. The "Proto-Tibetan Plateau" may have first reached its present elevation and started to squeeze its materials out to both E-W sides, resulting in the N-S extensional rifts, accompanied by a widespread deformation and uplift of the northern part of the plateau, but with limited magnitudes. Since ~8 Ma, the Himalayas and NE Tibetan Plateau in the southern and northern margins of the major plateau begins to experience an accelerated uplift, manifesting as a set of episodic short intense tectonic deformation events, and finally develops into its present configuration.

Keywords Tibetan Plateau; uplift; episodic

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