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渭河三阳川盆地最高级阶地的年代厘定及其对河谷发育的指示意义

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摘 要：青藏高原东缘水系的演化历史长期存在着重大争议，鉴于任一水系的形成演化都是通过主要河谷的发育及其不断延展与整合完成的，因此确定河谷发育的起始时代是研究水系演化的关键。本文针对渭河上游三阳川盆地最高级阶地形成时代的研究，发现李家小湾河流阶地砾石层的 ESR 年代为 1.26 ±0.15 Ma 和 1.32 ±0.19 Ma，$^{26}Al/^{10}Be$埋藏年代为 1.45 ±0.70 Ma 和 1.04 ±0.43 Ma，说明该段河谷形成于早更新世晚期。综合青藏高原东缘夷平面、剥蚀面与河流阶地的研究成果，推断该区现代河谷系列主要形成于 1.2 Ma 以后，河流平均下切速率较高，为 0.1 ~0.32 m/ka，指示了中更新世以来该区快速的地表抬升与河谷发育过程；而其前少数地段的先成河谷下切速率介于 0.04 ~0.29 m/ka 之间，说明区域地势总体低平，地表过程以剥蚀夷平为主，即高原东缘的现今水系格局主要是第四纪期间构造和气候共同作用下河流侵蚀的产物。

关键词：ESR；$^{26}Al/^{10}Be$ 埋藏测年；阶地；河谷发育；三阳川盆地
中图分类号：P931.1 **文献标志码**：A

新生代期间青藏高原的构造隆升导致了东亚原来西倾的地势发生倒转[1]，在构造活动与气候变化相互作用下，河流通过不断的整合与重组，方才形成了当今以高原为中心的巨大辐射状水系格局[2]。围绕该区水系演化与河谷发育研究已产出了大量的学术成果[3-4]，但针对同一水系乃至同一河段演化历史的学术观点差异较大。以黄河中上游水系为例，其形成时代主要有早成说和晚成说两种认识，前者认为三趾马红土之下的砾石层是古黄河的沉积物，故晋陕峡谷段黄河在上新世或中新世晚期即已形成[5]；而后者认为黄河现代水系格局在早更新世中晚期[6-7]，甚至晚更新世[8-9]才得以形成。另外，就水系形成演化的形式而言，又可分为河湖共存说与溯源袭夺说，前者认为黄河中上游自古就存在着诸多断陷湖盆，如若尔盖、青东、河套、三门古湖等，黄河与这些古湖泊呈串珠状相连，且时代较老[10]；而后者认为这一系列湖泊是孤立的，时空异殊彼此之间不存在水系联系，是黄河后期的溯源侵蚀、袭夺贯通才形成了今天的流域格局[6-7]。作为黄河的第一大支流，渭河的形成演化也备受学术界关注，但学术观点也存在着分歧，如渭河曾是黄河故道，且自始新世已存在[11-12]；或形成于早更新世[13-14]。

究其原因，主要与学者们采用的研究载体和理论依据不同有关。鉴于河流阶地是水系演化和河谷

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发育过程中遗留下的直接证据[15]，因此对区域最老/最高级阶地进行研究，可以获取现代河谷形成发育的明确时限。如渭河地堑段最高级阶地形成于2.6 Ma[13]，而宝鸡段最高级阶地形成于1.2 Ma[16]，上游陇西段最高级阶地形成于1.11 Ma[14]，这说明渭河下游河谷的形成时代可能相对较老，与汾渭地堑的形成密切相关[13]，而上游河谷形成的时代相对较晚，可能是渭河下游河谷不断扩展和溯源侵蚀的结果。通过对宝鸡与陇西之间三阳川盆地的调研，曾发现该区渭河共发育13级河流阶地[17]，但是由于测年技术与野外采样的限制，未得到最高级阶地即李家小湾阶地的精确年代。本文基于电子自旋共振（Electron Spin Resonance, ESR）和宇生核素$^{26}Al/^{10}Be$埋藏测年方法，对该级阶地的堆积年代进行研究，并综合分析了青藏高原东部层状地貌面的研究成果，进而探讨了该区现代水系与河谷发育的问题。

1 研究区概况

三阳川盆地位于陇中盆地东南隅，为一小型山间河谷盆地（图1a），构造上受西秦岭北缘断裂带、渭河断陷、六盘山断裂带等的控制[18]。第四纪以来，秦岭的抬升速率加快，从早更新世的0.11 m/ka增加到中晚更新世的0.16 m/ka[19]。同时，该区受东亚季风的影响，夏季炎热多雨，冬季寒冷干燥。第四纪期间气候变化强烈而显著，堆积了巨厚的黄土沉积。

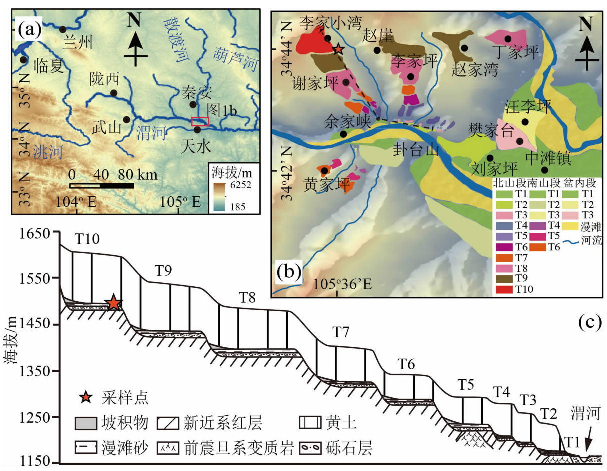

图1 三阳川盆地渭河阶地空间展布及断面图

（a）三阳川盆地构造及断裂分布；（b）三阳川盆地阶地空间展布；（c）渭河北岸阶地序列断面

Fig. 1 Schematic cross-section and spatial distribution along the Weihe River in the Sanyangchuan Basin, China

(a) location of the Sanyangchuan Basin tectonic settings in the northeastern Tibetan Plateau; (b) the space distribution of terraces in the Sanyangchuan Basin; (c) terraces sequences on Beishan

在三阳川盆地渭河共发育和保存了13级河流阶地[17]，其中卦台山北侧发育10级阶地（图1b，c），南侧发育6级阶地，盆地内葫芦河与渭河交汇处又发育了3级堆积阶地。李家小湾阶地（T10）为该区最高级阶地（图1，2），基座为新近系红层，基座拔河315 m，砾石层厚约3 m，砾径大多在2～5 cm，分选较差，砾石磨圆度较好，岩性与组构与现代河床砾石相似。砾石层之上为厚约1.3 m的细粒漫滩砂，上覆为120 m厚的风成黄土。先前对阶地上覆黄土进行过磁性地层学的研究，但未发现地磁倒转事件[17]，可能是由于砾石层中泉水涌出，地下水导致黄土的淋溶淀积，形成大量的钙质结核，破坏了黄土的原生磁性。

图2 李家小湾阶地砾石层与上覆黄土景观照片

Fig. 2 Photos of the Lijiaxiaowan terrace gravel layer and overlying loess

2 研究方法及结果

2.1 ESR测年方法及结果

在遮光条件下，我们在阶地砾石层的洞穴里对该粗砂成份进行了ESR样品的采集，编号为ZT－11和ZT－12。分析方法详见文献[20]，此处不再赘述。根据样品中所测ESR信号与辐照剂量，建立剂量响应曲线（表1，图3），采用指数拟合外推法[21]，求得古剂量为3508±412 Gy和3717±557 Gy，得到样品年代为1.26±0.15 Ma和1.32±0.19 Ma。

2.2 宇生核素$^{26}Al/^{10}Be$埋藏测年及结果

在阶地砾石层中挑选了数十个大小不等的石英

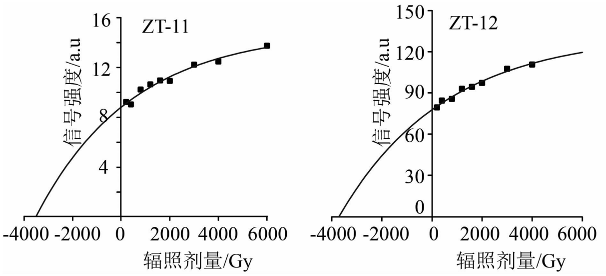

图 3　样品 ZT－11 和 ZT－12 中 E′芯的人工辐照剂量与 ESR 信号强度拟合曲线

Fig. 3　The dose response curve of E′ core in samples ZT－11 and ZT－12

砂岩砾石，分成两个样品，编号为 ZT13－1 和 ZT13－2，在美国 PRIME 实验室进行宇生核素埋藏测年的测试分析，结果见表 2。

青藏高原东北部的阶地序列分布广泛，发育完善即基岩面之上一般堆积着厚度约数米至数十米的冲积层，由河床相砾石层与漫滩相沙层组成，其上又被数十米乃至数百米的黄土地层所覆盖。当河流下切阶地形成后，即被黄土埋藏覆盖屏蔽了宇宙射线，使阶地砾石上的^{26}Al 和^{10}Be 浓度不再增加。在此情况下，依据样品中现存的^{10}Be 含量和^{26}Al/^{10}Be 比值，就可以在^{26}Al/^{10}Be－^{10}Be 的二维图上直观地求得埋藏年龄[22]。我们将样品 ZT13－1 和 ZT13－2 的^{26}Al/^{10}Be 和^{10}Be 浓度投影至埋藏测年曲线图上（图 4），得到样品的埋藏年代分别为 1.45±0.70 Ma和 1.04±0.43 Ma，其平均年代为 1.16±0.37 Ma，与上述 ESR 所测年代 1.26±0.15 Ma、1.32±0.19 Ma 及过去基于黄土与古土壤估算年代 1.19 Ma[17]相一致，因此可以推断李家小湾阶地

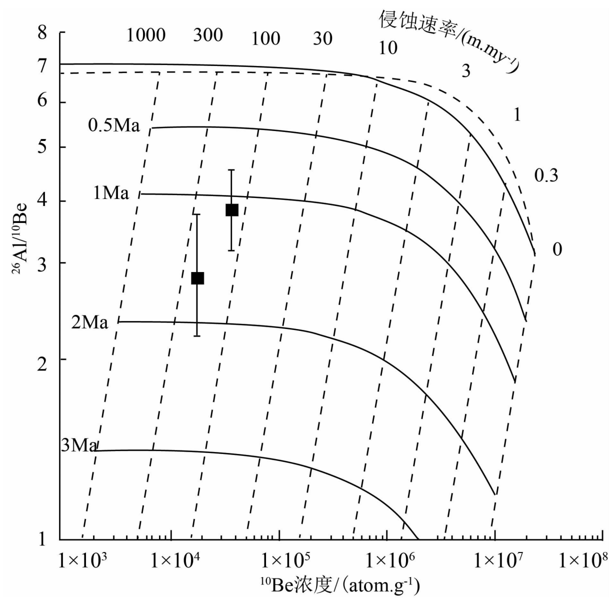

图 4　石英矿物中^{10}Be 浓度、^{26}Al/^{10}Be 与侵蚀速率及埋藏年代的关系[22]，其中黑色方块为李家小湾阶地样品 ZT13－1 和 ZT13－2 的埋藏年代

Fig. 4　The relation between ^{10}Be concentrations, ^{26}Al/^{10}Be ratios, and erosion rates and burial ages in quartz[22], the black square indicates the burial age of the samples ZT13－1 and ZT13－2 from Lijiaxiaowan terrace gravel layer

T10 形成年代为 1.2 Ma。

3　小湾阶地年代对区域河谷发育的指示意义

在传统地貌学中，夷平面、剥蚀面与河流阶地等层状地貌面是研究流域地貌演化与河谷发育历史的主要证据[23－25]。其中夷平面是侵蚀循环理论中地

表 1　李家小湾阶地样品的相关参数及 ESR 年代

Tab. 1　ESR age and related parameter of the samples from Lijiaxiaowan terrace gravel layer

样品编号	物质	U/(ug·g^{-1})	Th/(ug·g^{-1})	K_2O/%	含水量/%	年剂量/(Gy·ky^{-1})	古剂量/Gy	年代/Ma
ZT－11	粗砂	0.89	6.01	2.09	0.33	2.73	3506±412	1.26±0.15
ZT－12		1.49	7.03	1.97	0.36	2.79	3717±557	1.32±0.19

表 2　李家小湾阶地样品 ZT13－1 和 ZT13－2 的宇生核素^{26}Al/^{10}Be 测年结果

Tab. 2　Cosmogenic nuclide ^{26}Al/^{10}Be dating of the samples ZT13－1 和 ZT13－2 from Lijiaxiaowan terrace

样品编号	物质	上覆黄土厚度/m	^{10}Be/(atoms·g^{-1})	^{26}Al/(atoms·g^{-1})	^{26}Al/^{10}Be	Age/Ma
ZT13－1	砾石	120	$(0.23±0.05)×10^5$	$(0.60±0.19)×10^5$	2.65±0.2	1.45±0.70
ZT13－2			$(0.24±0.02)×10^5$	$(0.83±0.20)×10^5$	3.47±0.2	1.04±0.43

貌发育的终极产物,而剥蚀面主要有部分或区域夷平面,是地貌侵蚀旋回中河流达到壮年期开始侧蚀拓宽形成的阶梯状地形,表现为山足面或河流宽谷面[25],更有甚者 Bucher 认为基座阶地也可以归类于部分夷平面[26]。

众多研究表明,新生代早期我国广大地区构造活动进行平静期,地貌以剥蚀夷平为主从而在各大山系都形成了一期地势和缓的准平原,目前分布在主要山系山顶[27-29]。冈底斯运动之后的中新世至上新世期间,地表再次以长期的剥蚀夷平作用为主,形成了广泛分布的新一期准平原;3.4 Ma 前后强烈的青藏运动又导致了该级准平面的解体,但在青藏高原上其分布广泛且保存完整,被称为主夷平面[25,27,30],华北山地被称为唐县期夷平面[29,31];长江中上游也有分布,形成时代在3.1~3.47 Ma[32-33]。在这两级夷平面之下,诸多山地还分布有发育在早更新世期间的区域剥蚀面[25,27,34-35]。上述事实表明,新生代期间青藏高原及其周缘山地地貌的形成演化复杂而多期。而随着区域地貌侵蚀旋回的发生,夷平面发育前后的古水系必然发生了消亡与新生的全新演化,虽然我们可以从部分区域沉积地层中提供局地的古水流信息[4],但它们与现在水系之间的关系尚需探究。剥蚀面发育期间的水系可能是现代河谷形成的地貌基础,但区域性较强。兰州盆地剥蚀面之下黄河最高级阶地形成于1.7 Ma[27,34],黑山峡段最高级阶地的形成时代在1.57~2.4 Ma[36-37],指示该段黄河河谷形成于早更新世早期。而汾渭地堑自始新世即开始接受河湖相沉积[38],但随着区域宏观地貌格局的演化,古水系难觅其踪,目前渭河下游保存的最高级阶地约形成于2.6 Ma[13],说明该段河谷具有继承性属于先成河谷。

随着第四纪期间青藏高原东部构造运动的持续进行,地表加速隆升,河流快速侵蚀,促成了现代河谷的发育与水系格局的形成。综合高原东部主要水系干流河谷最高级阶地的年代数据(图5),可以发现其形成时代主要出现在1.2 Ma前后,如高原东北部石羊河水系上游的支流金塔河最高级阶地形成于1.24 Ma[39];中更新世早期,甘青一带的黄河发生强烈下切,致使区域水系重组如倒淌河流向发生倒转,青海湖封闭成为内陆盆地[40],湟水在西宁盆地内流向也由西偏南转为目前的东偏南[41];晋陕峡谷、三门峡段的最高级阶地形成[7,15];渭河上游陇西段[14]、三阳川盆地[17]以及下游宝鸡段最高级阶地亦形成于1.2 Ma[16]。另外,长江三峡段[33]、金沙江巧家段[42]最高级阶地的形成年代也为1.2 Ma;其支流大渡河泸定段[43]、雅砻江下游段[44]最高级阶地形成于1.1 Ma前后,这些地貌证据揭示早更新世以来河流的持续下切是青藏高原东部现代河谷形成发育的主要原因,即普莱费尔法则具有普世性[17],且该区水系格局的形成时代既不是早成说推断的如此古老,也绝非晚更新世才形成的如此年轻,前者具有自然神学的印迹,而后者又带着灾变的论调。

在1.2 Ma之前确有部分地区已经发育了现代河谷的雏形,但综合青藏高原东缘层状地貌面的研究成果,尤其是利用阶地高程-年代数据获得的河流平均下切速率来看,其平均值绝大多数介于0.04~0.29 m/ka之间(图5c~o),如此低的河流侵蚀速率指示了当时区域地貌总体地势低平,起伏和缓,地表过程以剥蚀夷平为主。而在1.2 Ma之后,河流的下切速率总体升高,在0.1~0.32 m/ka之间。再通过对比各地河流阶地与阶地之间的下切速率(图5p),可以发现1.2 Ma后河流的下切速率迅速增加,也说明早更新世晚期以来,青藏高原东部地区存在着地表加速隆升的过程,促成了现代河谷发育与水系格局的形成。

4 结论

本文基于两种绝对测年方法,对渭河三阳川盆地李家小湾阶地的形成年代进行了研究,发现ESR年代为1.26±0.15 Ma、1.32±0.19 Ma(平均值约为1.29 Ma),宇生核素$^{26}Al/^{10}Be$的年代为1.45±0.70 Ma、1.04±0.43 Ma(平均值约为1.24 Ma),与先前[17]利用阶地上覆黄土气候地层估算的结果1.2 Ma一致,因此可以确定该级阶地形成于1.2 Ma,即早更新世晚期。综合青藏高原东部山地夷平面、剥蚀面与河流阶地等层状地貌面的研究,说明新生代期间该区流域地貌演化经历了多期隆升、夷平的复杂过程,目前的水系格局与河谷系统主要形成于1.2 Ma以后,是第四纪期间构造隆升与气候变化共同作用下河流逐渐侵蚀的结果。

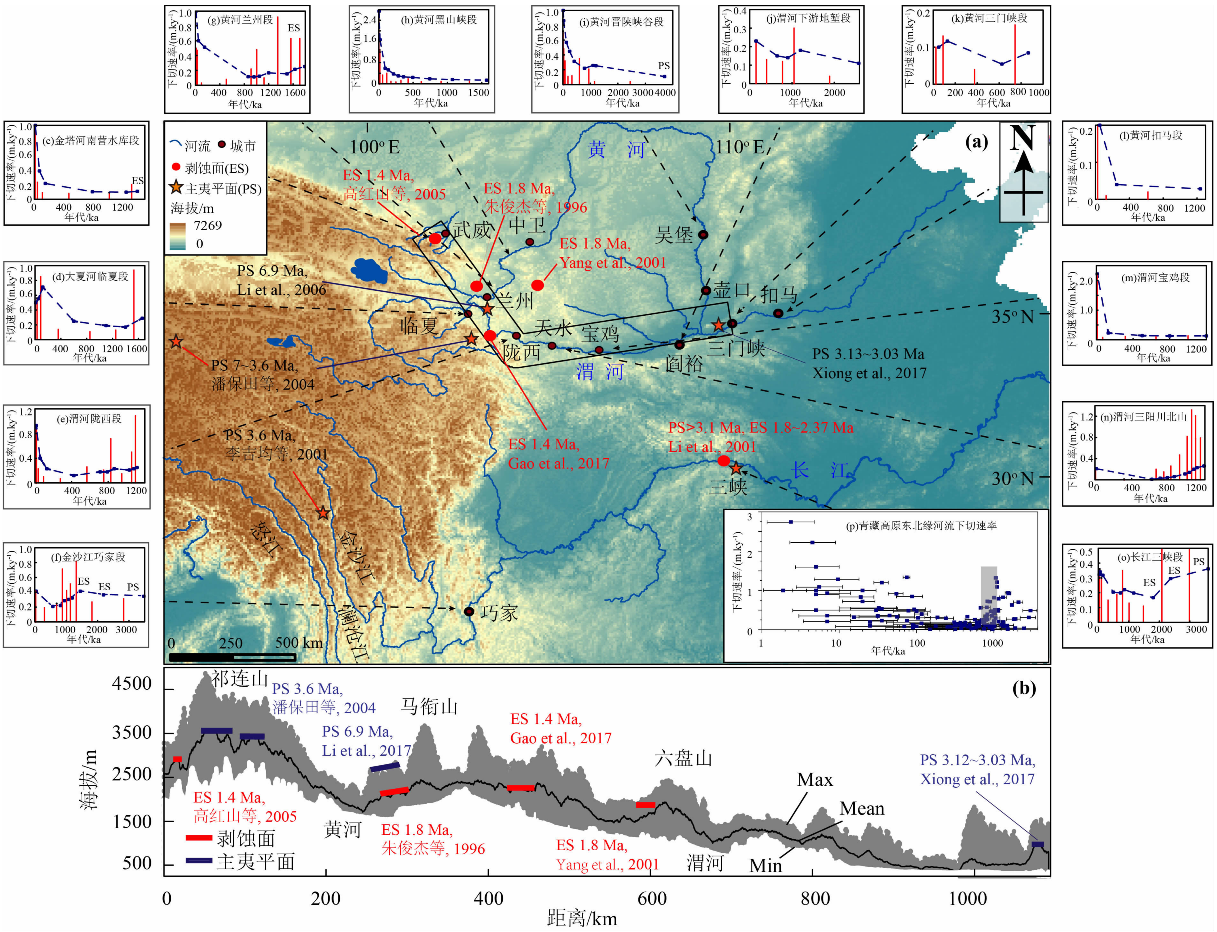

图 5　青藏高原东缘层状地貌面研究综合图

(a)夷平面、阶地研究点位分布；(b) Swath 剖面(宽度为 100 km)；(c－p)河流下切速率的时序分布图，其中红色竖线为研究河段相邻阶地间的平均下切速率，蓝色线段为每级阶地形成以来河流的平均下切速率(c. 金塔河南营水库[39]；d. 大夏河临夏段[45]；e. 渭河陇西段[14]；f. 金沙江巧家段[42]；g. 黄河兰州段[27,46]；h. 黑山峡[36]；i. 晋陕峡谷[7]；j. 渭河下游地堑段[13]；k. 三门峡[15]；l. 扣马段[15]；m. 宝鸡段[16]；n. 三阳川盆地[17]；o. 长江三峡[33]；p. 区域内河流断面相邻阶地间的下切速率)

Fig. 5　Comprehensive map of step－like geomorphic surfaces of the eastern margin of the Qinghai－Tibet Plateau: (a) Distribution of study sites of the planation surfaces and river terraces. (b) the swath profile of the 100 km wide. (c－p) the river incision rates around the eastern Tibetan Plateau. The red line implies incision rates calculated between adjacent terraces, and the blue line is the mean incision rates since the terrace formation (c. Jinta River near Nanying Reservoir[39]; d. Daxia River in Linxia[45]; e. Wei River in Longxi[14]; f. Jinsha River near Qiaojia[42]; g. Yellow River near Lanzhou[27,46]; h. Heishan Gorge[36]; i. Jinshaan Gorge[7]; j. Weihe Garben[13]; k. Sanmen Gorges[15]; l. Kouma[15]; m. Baoji[16]; n. Sanyangchuan[17]; o. Three Gorge of the Yangtze River[33]; p. Incision rates between adjacent terraces in the eastern Tibetan Plateau)

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Dating of the Highest Terrace of the Weihe River in the Sanyangchuan Basin and Its Implications to Valley Evolution

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Abstract: There has been a long-term debate on the evolution of the great river systems of the eastern Qinghai-Tibet Plateau. The formation and development of any drainage system is completed by the origin of the valley, with its continuous extension and integration, under the regional tectonic and climatic change. Therefore, it is the key to study of the issue in the beginning of the valley development. In this paper, the electron spin resonance (ESR) and the cosmogenic nuclide $^{26}Al/^{10}Be$ burial dating techniques were used to test and analyze the accumulation age of the gravel layer in the highest terrace of the upper Weihe River in the Sanyangchuan Basin. The ESR and $^{26}Al/^{10}Be$ burial ages of the gravel layer were 1.26 ± 0.15 Ma, 1.32 ± 0.19 Ma and 1.45 ± 0.70 Ma, 1.04 ± 0.43 Ma, respectively, indicating that the modern Weihe River valley was formed in the late Early Pleistocene. Combined with the researches of the planation, erosion surfaces and other fluvial landforms in central China, it could be found that a few valleys have been formed before 1.2 Ma, and the incision rate is between 0.04 ~ 0.29 m/ka, but the overall regional geomorphic process is still dominated by planation or partial planation. The modern river valley of the trunk stream was mainly formed after 1.2 Ma, and the average incision rate increase to 0.1 ~ 0.32 m/ka, indicating the rapid surface uplift process in the region since the Middle Pleistocene.

Key words: ESR; $^{26}Al/^{10}Be$ burial dating; terraces; valley evolution; Sanyangchuan Basin