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冲积扇形态与沉积特征及其动力学 控制因素:进展与展望*

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摘要:冲积扇作为区域环境演变的敏感记录器,日益受到学界关注。通过文献调研,对冲积扇形态特征和动力学控制因素进行了总结梳理。首先对比分析了不同类型冲积扇的沉积学和地貌学特征。进而分别阐明了上游流域基岩岩性、构造运动和气候变化对冲积扇的形态、规模和沉积层序的影响。最后介绍了有助于冲积扇精细化研究的一系列新技术和新方法的应用以及未来研究的发展方向。主要提出重力流和牵引流沉积过程分别塑造碎屑流型和河控型冲积扇两类,并表明冲积扇是多种因素相互控制下的产物:流域基岩性质影响下游冲积扇规模和沉积物组成;构造活动提供山前沉积空间,影响冲积扇形态特征;气候变化决定着第四纪冲积扇沉积层序发育,特别是引发洪水事件的极端气象事件。进一步指出未来需要采用新的手段深入解读冲积扇所蕴含的环境信息。

关键词:碎屑流型冲积扇;河控型冲积扇;岩性;构造活动;气候变化

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1 引言

冲(洪)积扇是一种沉积地貌,其作用是储存上游山区流域内被搬运出流域范围的沉积物,是侵蚀与沉积等地表过程对地貌塑造的产物^[1]。冲积扇沉积层序富含区域构造变形与气候变化的历史信息,可作为重要的环境演变研究的载体,日益受到地貌学家和沉积学家的关注^[2-11]。1873年,Drew^[12]在印度河河谷上游的工作中最早提出了冲积扇的概念。20世纪60年代,Bull^[13]在加利福尼亚冲积扇研究中率先提出识别冲积扇的特点,随后关于冲积扇形态

特点的研究增长迅速,全球各个大陆都出现了对冲积扇的描述。冲积扇目前分布在世界各地不同的气候背景和构造环境中,从极度干旱(热带或极地)到湿润的温带和季节性/季风性热带地区,从构造活跃的沉积盆地边缘到冰川消退的山谷边缘等^[14-16]。最近10年,河流沉积为主的冲积扇对现代沉积盆地的地貌动力学和对古地层记录的解释逐渐得到重视^[14]。当前,对冲积扇的研究主要侧重于:①扇体沉积物与形态之间的关系^[17-20];②冲积扇形成的主要控制因素(流域形态、基岩的岩性、构造和长期地

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貌演化、气候控制及基准面等)的相互作用及其对环境变化的响应^[15,19,21-24]。

不同环境下形成的冲积扇除了形态、大小和沉积过程存在差异外,更重要的是具有明显不同的沉积相组合和地层结构^[18,25]。这些冲积扇受许多相互关联的因素影响,如上游流域的地形、水量和泥沙量,下游的基准面变化等,而这些因素最终受构造、气候和地貌过程的控制^[26-30]。因此,正确认识冲积扇自身特征和外部控制因素具有重要的沉积学、地貌学(如区域环境反演)以及社会经济学(如油气资源勘探)价值。鉴于此,本文在综合前人研究的基础上,详细阐述了不同类型的冲积扇形态和沉积学特征,并对其形成的动力学因素做了总结和评述。最后,对冲积扇研究的发展方向 and 趋势进行展望。

2 冲积扇形态特征与分类

冲积扇分类中一种较为流行的划分方案是按气候类型分为干旱型和湿润型冲积扇^[31]。这种分类依据干旱和半干旱气候条件下主要由碎屑流(debris flows)形成,而牵引水流(stream flows)在湿润气候条件下起主导作用,试图将冲积扇形成过程与干旱或湿润气候联系起来。但根据全球各地冲积扇目录表明,碎屑流可以在所有气候条件下形成,洪水泛滥形成的冲积扇在干旱和湿润的条件下均可形成^[32]。冲积扇环境可能受到一系列不同搬运过程的沉积作用,这些搬运过程动力来源为沉积物重力流和牵引流^[33-36]。碎屑流过程是最重要的沉积物重力过程类型,包括从黏土到砾石的沉积颗粒的混合物、夹杂水和空气。当碎屑流中颗粒粒径较小,形成高含沙流(hyperconcentrated flows),属于从重力流至牵引流的过渡阶段^[37]。

冲积扇地貌形状类似于一个锥形,根据沉积过程(从泥石流到片状水流和河道化的河流过程)和沉积尺度(从长度小于 50 m 的小碎石锥到长度最大可达 700 km 的以河流相为主的巨型扇)^[5,29,38-41],本文将冲积扇划分为 2 种类型:碎屑流型冲积扇(alluvial fan)和河控型冲积扇(fluvial fan)。碎屑流型冲积扇和河控型冲积扇的定义概念一直存在争议,它们要么是根本不同的沉积地貌,要么是陆上扇形堆积体的不同表现形式^[14]。碎屑流冲积扇是在重力流作用下形成的碎屑流沉积,与较短时间内发生的偶发性洪水和突发流有关^[40,42],若碎屑流体粒径较细缺乏大块砾石,含水量较高可形成高含沙流,而后者是在牵引水流搬运沉积作用下形成的,

特点是在山口的扇顶部分发育主河道,向扇缘方向形成以放射状散开且逐渐变浅的辫状分支河道,水流携带沉积物或漫溢出河道形成河流或片汜沉积^[14,29]。关于它们的主要特征与区别总结如图 1 所示。

2.1 碎屑流型冲积扇

碎屑流型冲积扇可能是陆相盆地边缘最重要的沉积环境^[18]。由于地势起伏较大,冲积扇主要是通过突发性碎屑流堆积而形成的^[18,40,42]。典型的碎屑流表现为单相混合物,其中固体重量占 70%~90%,质量密度在 1.8~2.5 g/cm³,水量占重量的 15%~60%^[37]。这类冲积扇的扇面坡度较陡(一般为 1°~25°)^[33,40],锥形表面的近端位于地形的高地边缘,最常见的是对应于一个高地流域的出口,受山地地形限制的径流在出山后变得无约束^[18]。冲积扇的辐射长度范围可能很广,一般从几百米到几公里不等,特别有利于泥沙水混合物的长距离运输^[44]。由碎屑流聚集的冲积扇往往形成于高地地形起伏的流域,基岩和崩积坡上有大量的原生碎屑或风化形成的次生黏土,可迅速输送大部分地表径流,从而引发短时间内的洪水事件,在水文曲线上达到峰值^[18,45]。由于在这类环境中典型的洪水事件具有高水沙比,但是缺乏有效分选和后期对地表沉积物的侵蚀,沉积物由母岩砾石和风化改造后砾石组成,棱角分明和磨圆度较好的砾石并存^[34,46,47]。碎屑流冲积扇沉积相具有一定的均一性,增强了垂向渗透率和内部连通性^[18]。现代冲积扇的观测结果表明,粗粒级碎石(卵石到块状)的形态粒径有下降的趋势,而从粗粉粒到细粒的粒径在下游无明显变化(图 2),这可能是由于高能泥流能够保持其搬运能力在近端与远端无明显差异^[44,48]。因此,该类冲积扇的沉积空间分布往往较为均匀。

碎屑流水沙比受流域形态的影响,在相对流域面积较大、地势较低的流域产生粒径较小的岩屑或砂质物质,形成中等至低砾石含量的高含沙流^[18],高含沙流固体占比为 40%~70%,具有中度分选和初始层理,质量密度在 1.3~1.8 g/cm³ 范围内,介于水流与碎屑流之间^[37]。这种情况下,冲积扇的主要沉积构造和结构主要由分选相对较好的砂质、砂砾质透镜体和薄片组成,伴生少量砾石层(图 2b),其形成的冲积扇沉积物的孔隙度和渗透性较差^[18]。

2.2 河控型冲积扇

河控型冲积扇通常比碎屑流型冲积扇大得多^[40],可以覆盖非常广泛的地区,如阿根廷和巴拉

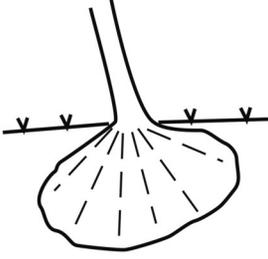
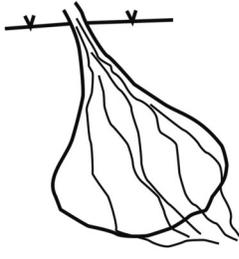
	碎屑流型冲击扇		河控型冲击扇
	流域坡度 ←————— 流域面积 —————→ 流域长度 —————→ 沉积体积 —————→ 冲积扇面积 —————→ 水分含量增加 —————→ 沉积物比重增加 ←—————		
地貌学	碎屑流	高含沙流	牵引流
	<ul style="list-style-type: none"> • 坡度较陡 • 加积为主 • 突发性泥石流 	<ul style="list-style-type: none"> • 中等坡度 • 加积和下切侵蚀 • 伴有砾石较少的泥流 	<ul style="list-style-type: none"> • 坡度较缓 • 河流冲刷明显 • 沙坝形式
			
沉积学	<ul style="list-style-type: none"> • 分选较差, 砾石混杂 • 含有近垂直碎屑 • 明显的流体结构 • 无冲刷 	<ul style="list-style-type: none"> • 含有砂质透镜体 • 叠瓦状碎屑 • 较弱的层理 • 含有近垂直碎屑 • 冲刷较弱 	<ul style="list-style-type: none"> • 砂质物质为主 • 层理现象 • 古土壤夹层 • 冲刷作用强

图 1 两种类型的冲积扇地貌学和沉积学特征对比(据参考文献[18, 19, 43]修改)

Fig.1 Comparison of geomorphology and sedimentology of fans (modified after references[18, 19, 43])

圭的 Pilcomayo 扇的最大长度可达 700 km, 扇区面积超过 $2.1 \times 10^5 \text{ km}^2$ [49], 这可能是现代地貌景观中最大的冲积扇 [50-53]。

河控型冲积扇通过分叉式河流系统的沉积物堆积形成 [1]。山地流域的河流到达出山口后, 径流会扩散为放射状, 由辫状或高弯曲度河道将沉积物堆积成扇形 [18]。相比碎屑流型冲积扇, 河控型冲积扇面坡度极低(一般小于 1° , 图 1, 图 2) [4, 54]。因为河道分散、蒸发和坡度的减小, 下游的径流能量逐渐耗散, 河控型冲积扇沉积物粒径随距离顶部距离的增大而逐渐减小。在长放射状距离上, 以牵引水流为主的输沙方式使得沉积物具有非常有效的分选和沉积结构, 沉积层序相对简单, 几乎全部由砂砾层和砂层组成, 夹有古土壤和湖泊沉积(图 2c) [18],

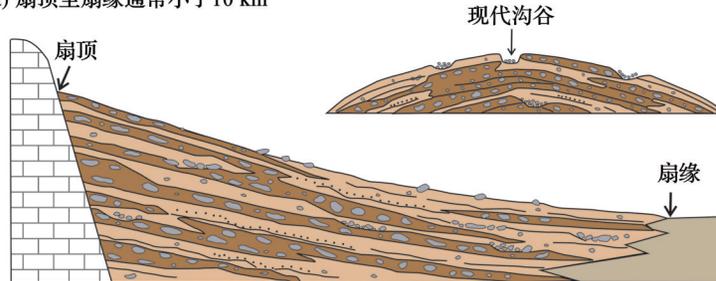
这与碎屑流型冲积扇层序形成了明显的对比。若现代和古代的河控型冲积扇相互叠加, 其沉积序列会变得复杂。

大型河控型冲积扇可能是现代大陆沉积盆地中最常见的中尺度沉积地貌, 尤其是在前陆盆地和克拉通盆地、造山带山前盆地和大陆裂谷中 [50]。最近研究人员认为, 河控型冲积扇的层序可能代表了古代地层记录中最大的河流沉积量, 这一假说迅速吸引了研究人员对河控型冲积扇的地质学和沉积学的关注 [1, 5]。目前, 世界多地报道了大型河控型冲积扇, 如伊朗中部的 Abarkoh 扇 [54]、尼泊尔和印度的 Kosi 扇 [55, 56]、非洲中南部的 Okavango 扇 [41]、阿根廷 Gastre 盆地扇 [57] 等。这些冲积扇显示了广泛地表水系的几何形状、下游河道弯曲度的横向变化、洪泛

碎屑流型冲积扇

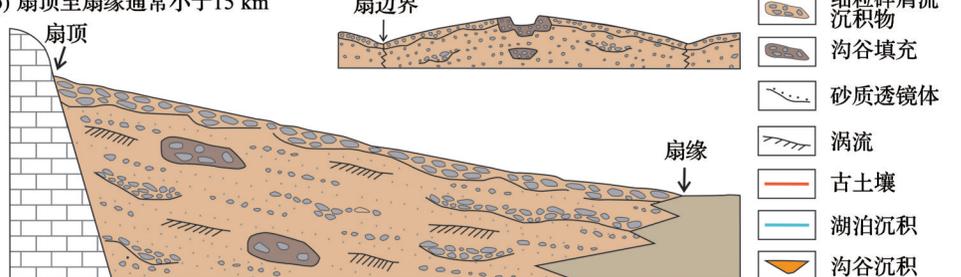
碎屑流

(a) 扇顶至扇缘通常小于 10 km



高含沙流

(b) 扇顶至扇缘通常小于 15 km



河控型冲积扇

牵引水流

(c) 扇顶至扇缘可达数百公里(最大 700 km)

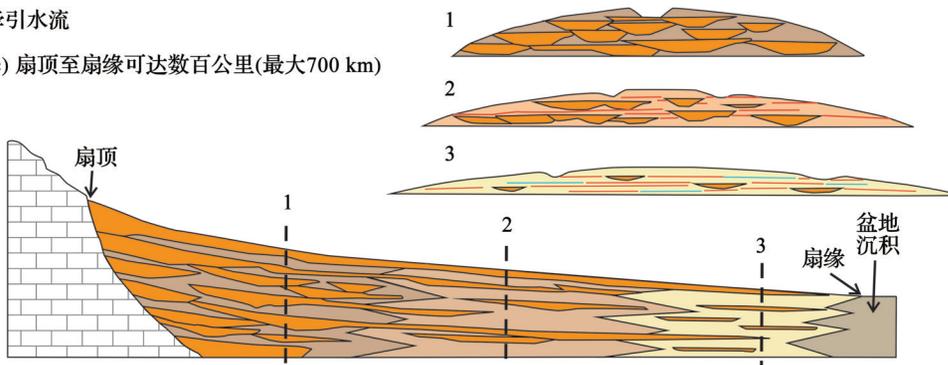


图 2 碎屑流型冲积扇和河控型冲积扇纵剖面概念图(据参考文献[18]修改)

Fig.2 Cross-sections through a generalized debris flow alluvial fan, a hyperconcentrated flow alluvial fan and a fluvial fan (modified after reference [18])

(a)由碎屑重力流形成的扇体,扇面坡度较陡,沉积物分选差,多含粒径较粗的砾石,夹杂砂质透镜体;(b)由高含沙重力流形成的扇体,沉积构造和结构主要由中度分选的砂质、砂砾质透镜体和薄片组成,伴生少量砾石层;(c)由牵引水流形成的河控型扇体,扇面坡度较低,沉积物分选较好,沉积层序相对简单,几乎全部由砂砾层和砂层组成,夹有古土壤和湖泊沉积;从扇顶至扇缘,不同位置的横剖面(编号:1,2,3)显示了河控型冲积扇的沉积结构

(a)The alluvial fan formed by the debris gravity flow has a steep slope, poor separation of sediments, and contains coarse gravel with sandy lens; (b)The sedimentary structure and structure of the alluvial fan formed by the hyperconcentrated gravity flow are mainly composed of moderately separated sand, sand and gravel lenses and thin sections, accompanied by a small amount of gravel layer; (c)The fluvial fan formed by the traction water flow has a low slope, a good separation of sediments, and a relatively simple sedimentary sequence.

It is almost entirely composed of sand and gravel layers, sandwiched by ancient soil and lake deposits. From the fan apex to the toe, cross-sections at different locations (No. 1, 2, 3) show the sedimentary structure of the fluvial fan

区发育、泥沙运移和沉积、植被覆盖和土壤改造等。另外,古河控型冲积扇沉积中记录了大量的沉积相组合、砂体几何形状和三维结构^[58-62],与现代河控型

冲积扇所处的构造和气候环境极为不同,地貌和沉积学特征变化较大,我们对这些冲积扇系统的认识仍有待完善。

3 冲积扇动力学

冲积扇的形态、大小和沉积过程受许多因素影响,如上游流域的特征、水量、泥沙含量和沉积空间等,这些因素最终受上游流域基岩的岩性、构造运动和气候变化的控制^[26-30]。

3.1 物源性质对冲积扇的影响

冲积扇源区基岩的岩性被认为是造成冲积扇规模和沉积相的关键因素,可直接影响冲积扇的沉积过程^[63-65]。

3.1.1 对冲积扇规模的影响

Bull^[66]和Hooke^[67]报告指出,抗侵蚀能力弱的流域往往比抗侵蚀能力强的流域所产生的冲积扇面积更大。这种观点认为,抗侵蚀能力弱的流域产沙较多(即产沙量),而且由于这种物质较细,可以输送得更远,因此会产生更大的冲积扇。相比之下,Lecce^[68]在加利福尼亚的White山脉发现下伏更耐侵蚀基岩的流域产生了更大的冲积扇,而较小的冲积扇上游流域下伏易受侵蚀的岩性单元。这是因为上游基岩耐侵蚀的流域,河谷陡峭狭窄,沉积的泥沙很少,所以大部分的泥沙最终都被输送到堆积的冲积扇面。而易受侵蚀的流域盆地具有更宽的谷底,较低的山谷斜坡,而且沿干流峡谷所储存的沉积物比由抗蚀岩石组成的流域要多得多。这些互相矛盾的效应可能在大多数流域内相互作用:一方面,基岩易蚀可能产生较多泥沙,使下游冲积扇面积变大;另一方面,岩石可蚀性可影响流域山谷的坡度和水文特征,使泥沙更多沉积在上游流域内,下游形成的冲积扇较小(图3)。

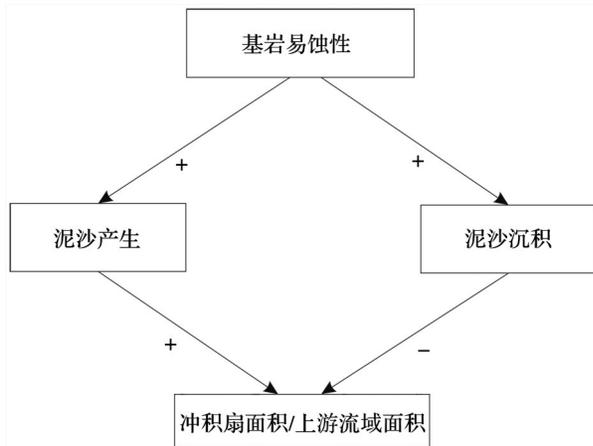


图3 流域基岩易蚀性与冲积扇规模的关系
(据参考文献[68]修改)

Fig.3 The relationship between the erodibility of bedrock and the area of alluvial fan(modified after reference[68])

3.1.2 对冲积扇沉积物组成的影响

不同岩性的基岩对风化的响应有所区别,产生不同的侵蚀和输沙模式。例如,在流域产生大量黏土和岩屑的地区,沉积物和水的混合物往往以碎屑流的形式到达冲积扇面,而不是松散的水流,这不仅影响了扇沉积的基本结构,而且会影响冲积扇系统的整体几何结构及其自生动力学^[63-65]。Wagreich等^[45]在阿尔卑斯山东部Fohnsdorf盆地中发现,源区岩性不同的冲积扇沉积物粒径存在显著区别,粗颗粒的沙子、卵石和大型砾石主要来自抗侵蚀能力强的角闪岩地区,而细粒的淤泥和较小的砾石则来自于以云母片岩和大理石为主的抗侵蚀能力弱的流域。意大利Valdarno流域基岩以长石质砂岩和灰粒砂岩为主,含有丰富的正长石和斜长石,碳酸盐颗粒相对稀少(包括岩屑和化石),有利于迅速崩解成砂质沉积物,导致其抗侵蚀能力弱,易于发生快速、强烈的风化和成土作用,有助于黏土矿物的形成^[69]。这些因素使得下游冲积扇沉积物富含砂质沉积物,且粒径较细。

3.2 构造活动对冲积扇发育的影响

冲积扇常常会在构造活动强烈的地区发育,因此常被用作研究构造变形的标志物^[70-74]。在以往的地质文献中,构造运动影响山地流域的风化作用、地形起伏,控制着下游冲积扇的位置、环境和总体几何形状,被认为是冲积扇序列变化的主要控制因素^[8,15]。

3.2.1 构造活动形成冲积扇沉积空间

造山带的构造活动形成并维持着地形的起伏,山前构造沉降有利于冲积扇沉积空间的形成(图4),决定着冲积扇沉积体的形态和体积,并在一定程度上影响了冲积扇系统的长期迁移速率^[24,76]。例如,位于断层下盘的流域构造抬升速率增大,会使下盘山前变陡,增加沟道的坡度,促使碎屑分离并输送到上盘冲积扇。当山内流域的输沙速率超过山前盆地的沉积速率,使得沉积空间不足以沉积山内泥沙物质,河道将被迫将其携带的泥沙向下分散,从而促进冲积扇进积。对希腊Corinth湾南部海岸41个冲积扇的聚类分析表明,它们的沉积空间受构造隆升相对速率控制,决定了冲积扇的空间分布,较小的碎屑流型冲积扇位于隆升速率较高的地方,较大的河控型冲积扇分布在隆升速率较低的地方^[77]。西班牙Almeria地区东南部的第三纪—第四纪晚期阶段的冲积扇在数百万年的时间尺度上受到复杂的挤压和转换历史的影

响,造成了其沉积位置、沉积空间和基准面的持续局部变化^[33]。

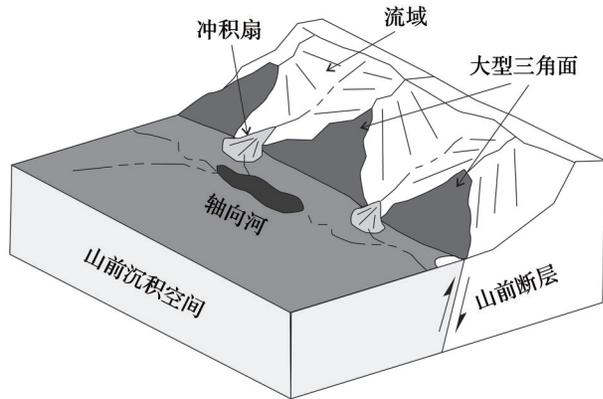


图4 山前沿正断层发育的典型冲积扇(据参考文献[75]修改)
Fig.4 Typical alluvial fans located along a normal fault at a range front(modified after reference [75])

山内流域位于断层下盘,冲积扇在断层上盘向山前轴向河进积
Sourcing drainage basins are entrenched in the mountainous footwall.
Triangular facets indicate the mountain front. The fans prograde
towards the axial river in the hanging wall basin

3.2.2 冲积扇对断层活动的响应

冲积扇沉积物和地层变形的识别是评价断层活动历史的关键^[78,79]。断层作用可通过影响主要山地流域出水口的位置来控制单个冲积扇的位置^[40]。山前的走滑断层可能会使冲积扇侧向移动,远离它们的补给河道。利用冲积扇上的偏转河道或其他地貌标志的偏移量可以确定水平滑动的累积量,结合沉积物测年数据可进一步推算断层活动速率。山前断层作用会造成扇面上的垂向变形,形成横穿冲积扇的线性地貌陡坎,这是观察和确定构造事件年代以及计算其滑动率的重要地貌标志^[37]。地表断裂的年龄可以根据最年轻的断层冲积物的年龄确定,也可以根据未被形成陡坎的断层切割的最古老的上覆沉积物的年龄来确定。

断层作用也会引起厚层沉积序列的变形或扭曲^[80]。长时间尺度内,构造活动总体上控制着冲积扇的空间演化和沉积相的一些微小变化,如盆地边缘的逆冲断层形成向斜构造。Leleu等^[79]研究了法国东南部 Provence 盆地边缘冲积扇沉积相组合和生长构造的分布,利用标志层和侵蚀面,探讨了盆地边缘构造—沉积演化。Provence 盆地冲积扇构造体系记录了流域的构造隆起与中生代地层褶皱之间的关系(图5)。盆地内向斜中保存的生长构造与向斜南翼向外逆冲造成的中生代地层倾斜和抬升有关。同时,地层楔入前生长地层表明构造抬升是

同沉积过程,冲积扇的沉积过程记录了其褶皱变形作用。

3.3 气候因素对冲积扇沉积序列的影响

3.3.1 气候变化主导第四纪冲积扇发育

气候通过改变流域产沙量、洪水频率及其水动力之间的相互作用来驱动冲积扇沉积^[14]。冲积扇形态根据当时的沉积物供应和洪水情况而调整。如果气候变化改变了长期降水或/沉积物的供应,冲积扇会通过侵蚀或沉积状态的变化来响应,从而导致沉积环境的变化^[16]。一些研究表明,特别是对第四纪扇沉积和地貌序列变化中构造和气候的相对作用的研究表明,气候变化会导致冲积扇体系的变化。因此,气候可能是第四纪冲积扇沉积序列的主要控制因素。

在地中海东部的气候和地理环境中,希腊 Spartan 山麓更新世期间气候变化主要表现为冰期期间的干旱和植被覆盖的周期性变化,以及间冰期期间的湿度和落叶林地的变化。沉积作用发生在冰期,而深切作用则发生在间冰期和更长的间冰阶,大部分间冰期有少量沉积和间歇性侵蚀^[76](图6)。对塞浦路斯更新世冲积扇的层序研究表明,冲积扇沉积与岁差极小期吻合,具有晚更新世粗粒和细粒的层状构造,根据沉积相旋回的平均厚度与磁极层段内沉积厚度的对比,初步确定为米兰科维奇旋回^[81]。西班牙中部中新世冲积扇粗粒的远端扇层与细粒盆地剖面之间的地层交错分布。通过对其古气候和年代信息的详细研究,扇体中部清晰的层状结构表明其可能受到外部因素的影响,与 $10^4\sim 10^5$ a 时间尺度的气候变化相关,是流域对气候变化的响应^[14]。西班牙 Almeria 东南部地区的流域受到高频气候变化的影响,由此引发冲积扇下切、阶地形成和堆积阶段,这在第四纪冲积扇上表现最为明显^[33]。在更大的范围内, Macklin 等^[82]对 Peloponnese 半岛广泛的冲积扇沉积物进行了调查并得出结论:在间冰期和哈里因事件中发现的冷杉林表明晚更新世的沉积是气候驱动的。

另外,在那些朝向海岸或湖岸的冲积扇上,以及那些扇缘受到河流侵蚀的冲积扇,沉积基准面改变可能是触发末端冲积扇下切的有效机制^[83]。如果末端水面上升导致扇缘侵蚀和冲积扇轮廓的缩短和变陡,那么基准面上升可能会触发冲积扇的末端下切。基准面的变化,如海面升降变化或河流和洪积湖水位的变化,对冲积扇的影响取决于它对沉积物供应的影响,可能最终受到气候的控制^[15,16]。

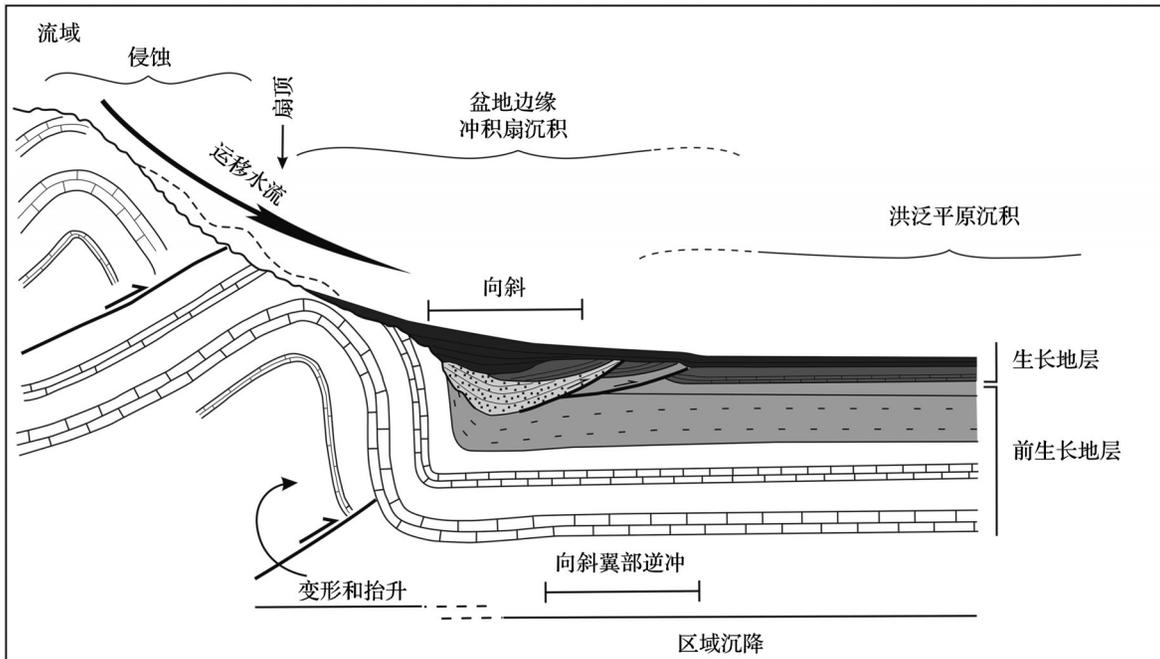


图 5 构造挤压作用对山前冲积扇发育的影响(据参考文献[79]修改)

Fig.5 Cross-section showing the influence of tectonic compress on the development of alluvial in the piedmont (modified after reference[79])

盆地冲积扇构造体系记录了流域的构造隆起与地层褶皱之间的关系;地层楔入前生长地层表明构造抬升是同沉积过程,冲积扇的沉积过程记录了其褶皱变形作用

The alluvial fan system records the relationship between tectonic uplift and stratigraphic fold in the basin. The formation wedge into the former growing strata indicates that the tectonic uplift is a syndepositional process and its folding deformation is recorded in the deposition process of alluvial fan

3.3.2 降水、温度和植被

影响冲积扇发育的3个相互关联的气候变量是降水、温度和植被^[32,84]。年平均降雨量会影响地表植被发育、流域水分入渗能力等。单个降水事件的强度和频率对于洪水的发生尤为重要,高强度的雷暴事件在干旱气候中强烈影响着冲积扇的发育^[85,86]。

值得注意的是,仅从气候角度对地质历史时期冲积扇沉积物进行解释尚存在潜在的缺陷,因为大多数冲积扇上的主要沉积过程是由偶发的、强烈的降水事件触发的洪水或碎屑流造成的,而这些气象事件不能被唯一和明确地归因于任何特定的气候状态^[40,87]。碎屑流是山地环境中分布最广的地貌过程之一,与其他陆上沉积物输送机制不同,在这种机制中,碎屑流中的泥沙被间隙水饱和,两种组分以黏塑性的流体向坡下运动^[88]。它们的出现与异常降水或长期降雨期间的含水饱和度有关^[89]。从最近和历史事件的研究以及第四纪地层记录来看,极端降水和碎屑流事件之间的关系已经得到很好的确定^[90-92]。极端气象事件还会引发基岩和崩积体滑坡,这些滑坡会在高地流域迅速改道,并大幅增

加产沙量^[93,94]。因此,短时间尺度的极端气象事件的影响似乎大于长时间尺度的气候变化。

在南美晚第四纪物质中可以清楚地识别出分布不规则、强度变化大的区域沉积活动^[95]。这些全新世沉积堆积覆盖了一大片区域,可能是由一种特殊的气候因素控制的,即厄尔尼诺—南方涛动(El Niño-Southern Oscillation, ENSO)的活动性^[96]。这种振荡的动态表明,非常强烈和随机分布的降雨可能导致洪水的不规则分布,使泥石流沉积物搬运可以显著分期。因此,Colombo^[96]认为短期的气象变化(如 ENSO)而不是气候变解释了阿根廷 1 000 km 地区内的几条大河冲积扇伸缩式结构的形成。在智利地区北部, Mather 等^[97]重建了 2001 年和古代的洪水范围,探讨了超干旱的流域内不同强度的洪水事件与由此产生的沉积物地层之间的关系,证明大洪水事件可以带来高含沙量,对冲积扇沉积具有重要影响。因此,在讨论气候对冲积扇的影响时,应重点关注极端气象事件带来的大洪水的影响,它们可能是气候因素中影响冲积扇沉积的主要因素。

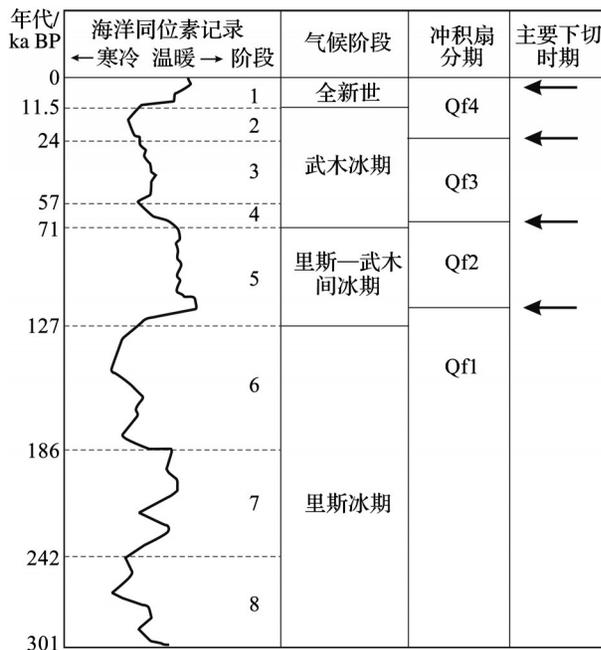


图 6 希腊 Spartan 山麓气候变化与冲积扇分期的关系
(据参考文献[76]修改)

Fig.6 Relationship between climate change and alluvial fan stages in piedmont of the Spartan Mountain, Greece (modified after reference[76])

此外,温度对冲积扇的影响尚不清晰,主要体现在化学风化率随温度剧烈变化^[32]。造山带流域地形起伏引起温度梯度,冲积扇上部风化率随着温度下降而降低。但是在高海拔地区冻融或热胀冷缩过程变得非常重要,风化率随高度增加而增加。长期以来,植被一直被认为是流域产沙的重要因素之一。植被是一个气候变量,能反映气候波动。植被会导致根部附近的有机酸引起化学风化增强,同时可以储存水分,使黏土产量增加^[98]。植物根系也通过增加抗剪强度而增强土壤边坡的稳定性^[32]。

3.4 构造和气候作用对冲积扇形成的争论

在构造活动和气候变化的背景下,因缺乏完善的区域气候和构造历史,很难明确区分其在冲积扇演化中的控制作用^[87,99,100]。正如前两节所述,学术界对构造或气候主导冲积扇形态和发育尚存在很大争议。这也许与研究的时空尺度有关^[16]。一方面,在支持气候因素控制冲积扇发育的研究中,研究对象往往是第四纪冲积扇,特别是万年尺度的全新世冲积扇^[87]。与支持构造作用主导冲积扇形成的研究中描述的古冲积扇规模相比,大多数第四纪冲积扇规模较小,因此存在冲积扇保存信息量的问题。只有更大规模和更长时间尺度上形成的沉积体系,特别是位于沉积盆地边缘,才有可能保存长

期构造活动记录^[16,101]。而且,由于从冲积扇沉积层序中提取古气候信息较为困难,如极端气象事件(如 ENSO)信息在最新的沉积物中表现的很明显,而在较老的沉积物中则很难解读^[96],因此针对更长地质时间尺度的研究更多地集中在构造地质学方面^[102]。

另一方面,冲积扇对气候变化和构造活动的响应属于不同的时间尺度^[8]。第四纪冲积扇对气候变化的响应时间跨度为 $10^2 \sim 10^4$ a,而对构造变化的响应时间跨度超过 10^4 a^[16]。在第四纪全球冰期—间冰期旋回期间,各种气候条件下的冲积扇沉积环境有较大的变化,如三叠纪、白垩纪或第三纪期间的气候变化对地貌阈值的影响较小,因此对沉积物形成的影响可能较小^[16]。此外,在较短的全新世时间尺度内,区域构造活动往往处于稳定期,这为新形成的冲积扇提供了稳定的沉积环境,但不是触发沉积事件的原因^[75]。只有在古代大型冲积扇沉积中才可能记录经历了十万至百万年尺度活动的大型构造事件信息,如造山带隆升和盆地沉降等。

综上所述,构造作用为冲积扇的发育提供了背景条件。根据地质历史时期的古冲积扇层序及形态可以提取构造活动信息,而第四纪冲积扇发育过程中,结合区域构造活动背景,将冲积扇发展演化与气候或极端气象事件相联系,可以有效地反演区域气候变化过程。

4 未来研究趋势

冲积扇作为地貌和沉积学研究的重要对象,日益得到学界的关注。国际上关于冲积扇研究的专门会议最早可追溯到 1995 年在美国死亡谷(Death Valley)召开的首届国际冲积扇会议,探讨了冲积扇的沉积特点与成因控制因素。第二届会议于 2003 年在西班牙索巴斯召开,针对此次会议,2005 年伦敦地质协会出版了《冲积扇:地貌学、沉积学和沉积动力学》会议论文集,内容聚焦 3 个主题:冲积扇形成过程、第四纪冲积扇动力学和冲积扇沉积序列。最近一次会议是 2015 年在新西兰克赖斯特彻奇召开的第五届冲积扇会议,研究热点为冲积扇的沉积机制与沉积过程、冲积扇的分类及其内部构型、构造对冲积扇沉积的控制作用、冲积扇定年技术等。2018 年,伦敦地质协会出版了《冲积扇地质和地貌:地球和行星视角》论文集,内容涉及辫状河控制的冲积扇与碎屑流形成的冲积扇的对比、第四纪冲积扇成因分析、冲积扇形态特征、冲积扇控制因素讨

论等。这些研究成果斐然,涌现出大量新方法和新技术,但当前仍存在许多问题需进一步完善。

4.1 新技术和新方法的应用

新技术和新方法越来越多地用于监测和调查冲积扇的形成过程,这有助于未来冲积扇的精细化研究。

相关的高精度观测技术是了解冲积扇形态特征的有力手段。在野外调查中,三维摄影测量技术有助于获取暴露在难以接近的悬崖上的沉积体几何形状、宽度、厚度和内部结构。Ghinassi等^[69]在意大利 Valdarno 盆地从多角度获取了垂直高差 50~70 m 冲积扇悬崖剖面的 1 210 万像素的重叠照片,利用 Agisoft photocan 建立了冲积扇三维摄影测量模型。合成孔径雷达 (Interferometric Synthetic Aperture Radar, InSAR) 是一种主动遥感技术,使用精确形状的无线电波照射地表,并使用回波延迟和多普勒频移信息将回波能量映射到地形景观的不同部分^[103,104]。SAR 图像可以显示表面粗糙度、粒度、分层和成分等特征^[105]。Radebaugh 等^[103]获取了 Cassini 号宇宙飞船合成孔径雷达获得的图像,揭示了土卫六(土星卫星)上扇形地貌的形态、粗糙度和纹理模式等地形地貌特征。这为了解其他遥远的地外星球以及寻找地外生命或人类新家园提供了参考。

计算机技术的发展也为传统冲积扇研究提供了有利条件。数值模拟可以有效地预测泥石流泛滥区的范围、流速和沉积物的深度,从而模拟诸如泥石流等自然灾害,结合实地调查有助于防灾减灾对策设计^[106]。目前已经发展了几种预防泥石流灾害的数值模型^[107,108]。Deganutti 等^[106]利用从阿尔卑斯山的一个活动冲积扇中提取的地形和水文边界条件,验证了泥石流数值模型可再现洪水区域的范围、泥石流溢出距离和沉积厚度,证实了数值模型在模拟冲积扇泥石流运动过程中的可靠性。

基于物理模拟实验的构造地貌研究方法,如沙盘和水槽模拟,可以近距离、短时间观察冲积扇形成过程。Reitz 等^[109]和 Van Dijk 等^[110]在室内沙盘完整地记录了在不同的水流、泥沙含量和高差等边界阈值条件下随时间变化的冲积扇形成过程,对自然界冲积扇的形成趋势预测具有借鉴意义。

更精确和更全面的年代测定法能在把冲积扇研究纳入更广泛的盆地地貌和沉积学模型。在较长的时间尺度上对冲积扇精确测年一直是个难题。传统方法是通过对冲积扇面进行测绘和对比得到

相对年龄,如通过沙漠路面或土壤的发育^[111~113]。由于年代学框架约束不佳,导致冲积扇体系沉积和侵蚀历史存在较大的不确定性^[75]。近年来,地质年代学技术的不断发展有力地推动了冲积扇研究。宇生核素测年法、U/Th 定年法和光释光 (Optically Stimulated Luminescence, OSL) 定年法等年代学技术已广泛应用于冲积扇沉积物,为冲积扇研究开辟了新的机遇^[15,16]。

4.2 研究趋势

当前对冲积扇的研究主要集中在冲积扇对控制因素做出的反应及其在沉积层序中的表现两方面,仍有许多问题需要我们关注。

首先,地貌学和沉积学研究之间的联系需要更多的跨学科综合研究,以确保对现代冲积扇的观察和形成机理有更深入的了解,特别是对大型河控型冲积扇。对冲积扇的现代地貌调查获得的信息如何转换成更长时间尺度下的沉积学信息是亟待解决的问题。

其次,冲积扇的物理模拟实验表明,自生因素的反馈作用对冲积扇演化具有重要作用。这需要发展更多新的技术用于区分古层序演化历史中自生动力和外部因素的影响^[14,102]。如何确定古冲积扇过程(即沉积相组合)和形态(即地层结构)的变化?其在多大程度上反映了内在反馈(自生因素)或环境变化(外部因素)的共同影响?仍是具有较大挑战的科学问题。

第三,未来研究的一个潜在方向是从目前活跃的、易于考察的冲积扇中获取来自不同构造和气候环境的信息,并将这些证据与第四纪地层资料相结合,基于高分辨率的年代和古环境信息进行综合分析。

最后,由于自然界环境是不断变化的,这将影响冲积扇的形成,并可能增加冲积扇系统洪水和泥石流对一些城市产生的灾害风险。当前世界上许多城市位于冲积扇环境中,如美国的洛杉矶、丹佛和菲尼克斯,以及印度和意大利等国的部分地区^[51,114,115]。进一步了解并对未来冲积扇地质灾害风险进行预估对于这些城市的防灾减灾具有重要意义。

5 结 语

本文通过大量的文献调研,对冲积扇这一构造运动和气候变化的敏感记录器的形态特征、控制因素及其未来发展的趋势进行了概述。主要认识

如下:

(1)根据重力流和牵引流沉积过程的区别,冲积扇可划分为碎屑流型和河控型冲积扇两大类,前者是在重力流作用下形成的碎屑流泥沉积,与较短时间内发生的偶发性洪水和突发流有关,而后者是在牵引水流搬运作用下向扇缘方向以放射状散开且逐渐变浅的辫状支流沉积,二者沉积学和地貌学特征不同。

(2)流域下伏基岩易蚀性可影响下游冲积扇规模,这取决于流域的产沙和沉积因素:一方面,基岩易蚀可能产生较多泥沙,使下游冲积扇面积变大;另一方面,源区岩石可蚀性可影响流域山谷坡度和水文特征,使泥沙更多沉积在上游流域内,下游形成的冲积扇较小。同时,基岩性质决定了沉积物粒径大小以及冲积扇沉积结构。

(3)构造活动是冲积扇发育的前提,为冲积扇提供了山前沉积空间。山前断层作用会改变古冲积扇位置和形态,也会引起厚层沉积序列的变形或扭曲,记录区域构造活动。第四纪冲积扇层序与冰期—间冰期气候变化对应较好,但要注意极端气象事件引发的洪水事件对冲积扇沉积的影响。

(4)冲积扇研究领域尚存在许多科学问题,如冲积扇形成的边界条件和内在机理、古冲积扇过程和形态的变化、冲积扇层序记录更长时间尺度的构造和气候信息等。一系列新技术和新方法(高精度观测技术、物理模拟实验、精确的定年技术等)的应用有助于未来对冲积扇开展精细化研究。

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Morphology and Dynamics of Alluvial Fan and Its Research Prospects^{*}

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Abstract: Alluvial fans can preserve historical records of sediment transport to middle and lower river systems or piedmont basins, which are considered to be sensitive recorders of climate change and tectonic activity. In this paper, the morphological characteristics, control factors and future development trend of alluvial fan are summarized and described. The main understanding is as follows: ① According to the gravity flow and traction flow process, fan can be divided into debris flow alluvial fan and fluvial fan. The former is formed under the action of debris gravity flow deposits, which is related to the occasional flood and burst flow in a short time. The latter is braided tributaries depositions which are gradually shallower and spread radially in the direction of fan toe under the traction water transport. ② The erodibility of underlying bedrock can affect the scale of downstream alluvial fan, which depends on the sediment production and store factors in the catchment. The easily eroded bedrock may produce more sediment, making the alluvial fan area larger. In the contrast, the erodibility of rocks in the source area can also affect the slope and hydrological characteristics of the valley so that more sediment is deposited in the upstream basin and the alluvial fan formed in the downstream is smaller. ③ Tectonic activity is the pre-condition for the development of alluvial fans, which provides a space for alluvial fans depositions. Faulting in the piedmont can change the position and morphology of the ancient alluvial fan, and also cause deformation or distortion of the thick sedimentary sequence to record the regional tectonic activity. The quaternary alluvial fan sequence corresponds well to the climate change during the glacial-interglacial period. However, the influence of the flood events caused by extreme meteorological events on alluvial fan deposition should be focused on. ④ The application of a series of new techniques and methods will help to carry out deep research on alluvial fan in the future, such as high-resolution observation technique, physical simulation experiment, and precise dating.

Key words: Alluvial fan; Fluvial fan; Bedrock lithology; Tectonic activity; Climate change.

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