北天山安集海河大峡谷3.7 ka以来的快速下切

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摘要 北天山前陆冲断带的河流阶地记录了河流在构造和气候的共同作用下所发生的加积和侵蚀过程。其中, 安集海河大峡谷至少发育了18级基座阶地。应用改进的光释光测年方法, 对阶地上覆黄土及阶地砾石堆积中粉砂透镜体进行了年龄测定。结果表明, 安集海河3.7 ka至今的下切深度为260 m, 最大平均下切速率7 cm/a。3.7 ka以前, 峡谷加积了巨厚的灰黑色砾石层(厚度大于200 m); 3.7 ka以后河流逐级下切砾石层, 发育了13级基座阶地。3.0~2.4 ka的600年间安集海河加速下切, 平均速率达15 cm/a。1.3 ka时, 河流下切至第四纪以前形成的基岩层, 至今形成了5级基岩基座阶地。安集海河大峡谷18级阶地是气候变化、河流水/沙平衡关系等影响的结果。

关键词 天山北麓, 安集海河大峡谷, 年轻阶地, 光释光测年, 加积-侵蚀过程

河流的加积、侧蚀和下切过程及其与构造和气候的关系是近期河流地貌演化研究的热点^[1~11]。通过对河流阶地和冲洪积扇的演化研究, 加深了对河流的加积、下切/侧蚀平衡关系和水沙通量平衡关系的理解^[2,3,5~7]。当河流侧蚀/下切速率之比增大, 流域内发育宽广阶地面。反之, 则发育峡谷^[3]。砾石、砂等碎屑物质在峡谷底部堆积, 河流下切到峡谷底部后侧蚀这些堆积物使之崩塌并充填河道, 减小了河道宽度, 使下切速率加快。这种正反馈机制将下切和侧蚀耦合起来, 促进了阶地发育^[5]。冰期时, 天山山麓地带为暂时性储存碎屑物质的过渡带。这些碎屑物质加大了冲洪积扇地形坡度。在冰期向间冰期过渡、气候逐渐变暖湿期, 河流泥沙通量/水流量变小, 河流的下切速度加快, 在冲洪积扇发育阶地^[6,7]。碎屑物质从山麓区搬运到前陆盆地的过程与流域地貌演化密切相关。要揭示这种地貌演化过程需对碎屑物质在源区的剥蚀时间、冲洪积扇加

积-侵蚀历史, 以及山麓地带和前缘盆地内阶地发育时间进行高分辨率的年龄约束。

准格尔盆地南缘横切北天山前陆冲断带的众多河流在山麓地带和前缘盆地内发育了多级河流阶地(图1(a), (b))。地处山麓地带的安集海河大峡谷, 堆积了厚达200 m的砾石层。河流已经切穿古冲洪积扇面的底部到达基岩, 并发育了18级阶地。这些阶地和古冲洪积扇记录了安集海河在大峡谷段河道的演化^[6]。前人对安集海河大峡谷其中3个阶地的采用宇宙核素成因¹⁰Be暴露测年和光释光测年研究表明, 18级阶地发育于距今5.1 ka前后^[6], 即全新世中晚期。

光释光(OSL)测年技术也被应用到北天山其他河流阶地的测年研究中^[12~22]。但前人研究发现水成样品中石英矿物包含了晒退彻底和不彻底的颗粒^[21]。年轻的石英颗粒光释光信号较暗, 难以用常规单测片再生剂量(SAR)光释光测年方法有效地建立石英的释光信

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图 1 (网络版彩色)研究区位置、地质简图和安集海河大峡谷卫星影像图。(a) 天山及邻区地形地貌图, 方框指示研究区位置。(b) 北天山前陆冲断带地质简图。(c) 安集海河大峡谷卫星影像图。白色虚线指示阶地陡坎, 实线为图2(b)中A-A'剖面的位置

Figure 1 (Color online) The location and geological sketch map of the study area, and the satellite image of the Anjihai River Gorge. (a) Simplified geologic map of the Tianshan range and adjacent areas. Box shows the location of study area. (b) Simplified geologic map of tectonic belts along the northern Tianshan range. (c) Satellite image of the Anjihai River Gorge. The dotted lines are river terrace risers and solid lines indicate the cross section of A-A' in Fig. 2(b)

号-剂量响应曲线, 且常用的年龄计算模型(最小年龄模型、有限混合年龄模型等)对真实埋藏剂量的取值依赖于额外误差值的大小。新改进的光释光测年技术为解决上述问题提供了可能^[22], 本研究将其应用到安集海河大峡谷18级年轻阶地年龄的研究上, 以揭示这些

阶地的发育历史。

1 研究区域概况

天山北麓乌鲁木齐坳陷在晚新生代受印欧板块碰撞向北推挤的强烈影响, 引起天山地区地壳发生变形,

形成再生造山带. 这一造山带继续由南向北扩展, 在山前拗陷内形成多排逆断裂-背斜带^[23~27](图1(a)). 准噶尔南缘断裂以北为北天山前陆冲断带, 以南为天山再生造山带(图1(b)). 天山造山带由元古代到新生代以来的地层构成, 海拔3000~4000 m, 终年积雪, 为天山河流的主要发源地^[28]. 北天山前陆冲断带自南向北发育了3~4排近东西向的逆断裂-背斜带, 为低山、丘陵区(图1(b)). 第I排逆断裂-背斜带简称为齐古逆断裂-背斜带, 位于准噶尔南缘断裂以北, 海拔约1300~2100 m. 第II排逆断裂-背斜带在齐古逆断裂-背斜带以北约20~30 km, 简称玛纳斯逆断裂-背斜带, 海拔约1000~1500 m. 第III排逆断裂-背斜带在玛纳斯逆断裂-背斜带西段以北约十余千米处, 简称为独山子逆断裂-背斜带, 海拔为600~1200 m. 此外, 根据地震反射剖面, 在乌苏县城以南正在发展的西湖隆起(图1(b)), 为一隆起幅度更小的最新逆断裂-背斜^[29].

天山北麓年均降水量由高山区的大于500 mm减少到盆地中心的不足100 mm, 属大陆性干旱、半干旱气候^[13]. 降雨主要集中在春夏两季, 盛行风以西风为主导^[30]. 这里发育了包括安集海河在内的一系列的河流和河流阶地(图1(b), (c)). 这些河流自南向北横切三排逆断裂-背斜带, 构造运动等因素的影响迫使河道发生迁移、河流阶地变形和阶地位置发生改变. 北天山高阶地发育较为完整, 低阶地多发育在现今河谷中, 空间展布范围有限^[19].

2 安集海河大峡谷河流阶地分布特征

安集海河发源于天山北麓常年冰川积雪区. 夏季冰川积雪融水为最主要的河流补给方式, 降水补给次之. 从河源区到峡谷所在位置垂直落差约2.5 km, 现代河床纵比降可达3.6%. 安集海河大峡谷位于北天山霍尔果斯背斜西端与南安集海背斜交汇区, 为长约3.5 km、最宽处约2 km、拔河高度约260 m的峡谷(图1(c)). 垂直于河流的流向, 峡谷横剖面为“U”型. 在安集海河与头道沟河交汇处, 安集海河东岸发育至少18级阶地, 但河西岸除最高一级阶地T18外未见其他低阶地分布. 阶地的拔河高度数据通过读取分辨率达12.5 m ALOS数字高程地图、室内谷歌地球卫星影像图的高程数据作为参考, 并比对手持GPS高程数据获得. 安集海河大峡谷东岸T18阶地面前缘拔河高度为264 m. 考虑压实、坡面流水剥蚀等因素的影响, 本研究赋予各阶地拔河高度 ± 5 m的误差(除T2阶地之外). 相邻阶地

前缘之间的高度差赋予 ± 2 m的误差值. 河东岸T18~T13阶地面宽度介于50~300 m不等, T12~T1阶地面宽度小于50 m. T18和T17阶地面较完整, 其余阶地因受坡面流水侵蚀、崩塌等破坏残缺不全(图2(a), (b)). T18阶地沿安集海河上下游连续分布^[16], 其他阶地仅零星出露在安集海河大峡谷区, 未见上下游连续展布现象.

安集海河和头道沟河现代河道内多被灰色、灰黑色砂砾石充填, 分选中等, 砾径一般为4~8 cm, 大者可达16 cm以上(图3). 这些砾石磨圆程度不一, 以棱角至次圆状为主. 灰黄色或深灰色的细粒漫滩相沉积(图3(c), (d))不均匀地覆盖在河床相砾石层之上.

安集海河大峡谷T18阶地之下为厚度大于200 m的冲洪积砾石层, 该砾石层由分选中等的棱角至次圆状砾石组成, 偶夹灰黄或灰色的砂质透镜体. 其底部堆积物以较大的灰黑色砾石为主, 且剖面因砾石突出使表面较粗糙; 砂含量少, 整体粒径偏粗, 地层颜色偏灰黑色, 与现代河道内灰黑色的粗砾石岩性表现特征一致. 其上, 堆积物中砂含量渐多, 整体粒径变细, 地层呈灰色、灰黄色, 与现代河道中观察到的灰黄色细砂砾石层和灰色的砾石层的不均匀互层一致. 在头道沟河西岸T18阶地沉积露头, 可见3~4条可连续追踪的砾石层构成多个阶地的基座(图3(c), (d)).

安集海河大峡谷18级阶地均为基座阶地. 其中, T18为基岩基座阶地, 基座为前第四纪基岩地层(图2(a), (c)); 阶地T17~T6的基座为T18阶地砾石沉积物, 阶地T5~T1的基座为前第四纪基岩地层(图2(b), 3). T18~T14阶地面上覆约10~45 cm不等的黄土. 由探槽可见(图3(b)), 黄土以下均为分选中等砾石层. 除探槽外未见露头剖面, 难以判断T17~T14是否发育同期加积的阶地沉积物. T13~T6晚第四纪砾石基座面上可见薄层松散砂砾石堆积, 部分阶地发育河流二元结构沉积. T5~T1前第四纪基岩基座面上均发育有砂砾石阶地沉积物堆积(图2(b), 3). T13~T1阶地之上几乎没有或只有极薄的黄土层(厚度小于10 cm)覆盖, 植被稀疏.

大峡谷内堆积物来源于安集海河及其支沟, 且厚逾200 m的砂砾石层沉积物与现代沉积物的表现特征相似, 故判断此处的阶地沉积物是安集海河及其支沟在加积状态下从上游搬运至此堆积而成的冲洪积物.

3 光释光样品的采集和测量

前人对北天山沉积物光释光特征研究发现, 风成

图 2 (网络版彩色)安集海河大峡谷地貌景观与多级河流阶地分布. (a) 安集海河大峡谷景观图和部分阶地的位置, 镜向东南. 红色虚线为基岩和砾石层之间的大致界线. (b) 低阶地基岩基座和上覆的冲洪积物沉积层, 镜向南. 白色虚线指示T18阶地砂砾石堆积中可连续追踪的砾石标志层位置, 表明该期砾石沉积构成T17~T6阶地的基座. (c) 剖面A-A'地质剖面图. 红色虚线指示可连续追踪的砾石层. (d) 安集海河大峡谷阶地堆积-下切过程

Figure 2 (Color online) The landscape of Anjihai River Gorge and the distribution of river terraces. (a) Photo showing the landscapes of the Anjihai River Gorge and the locations of some terrace levels. The red dotted lines indicate the lithological boundary. (b) The bedrock of lower river terraces and fluvial deposits. The white dotted lines are the continuous layers of sands within the T18 terrace, indicating those sand layers are the bases of the T17–T6 terraces. (c) Cross section of A-A' profile. Color photo shows the lithological boundary between bedrock and fluvial deposits. The red dotted lines indicate the continuous layers of sands. (d) The aggradation-incision history of the Anjihai River Gorge. See Fig. 1(c) for the locations of the photos

石英颗粒晒退彻底, 其光释光年龄可以代表沉积物所在地层真实的沉积年龄; 而水成石英颗粒存在晒退不充分的问题^[21], 识别晒退充分的石英颗粒需要测量获取大量的数据进行统计分析, 因此, 本研究采用改进的光释光测年技术, 可快捷高效地获取大量年轻石英颗粒的等效剂量^[22]. 该方法的可靠性已在其他地点得到验证^[30].

T18~T15阶地东西两侧阶地砾石沉积露头剖面十分陡峭, 未见适用于OSL测年的粉砂透镜体, 难以直接采样. 但这4个阶地面均上覆薄层风成黄土, 通过在阶地面上开挖探槽, 在黄土底部取得4个样品, 用于约束阶地地面的最晚废弃年代. 其他阶地黄土层厚度小于10 cm, 不适合OSL测年采样. 但在T11、T5和T2阶地找到了较好的阶地砾石沉积露头剖面. 在T11阶地砾石

沉积底部约4.8 m处、T5和T2阶地砾石沉积底界分别采得粉砂透镜体样品3个, 用于限定对应阶地的加积起始时间.

石英矿物的分选采用传统的光释光测年矿物分选方法^[31,32]. 样品等效剂量值在香港大学释光实验室使用Risø TL/OSL-DA-12 热释光/光释光测量仪测量, 该仪器配备有(⁹⁰Sr/⁹⁰Y)β辐照源, 辐照强度为0.03 Gy/s. 激发光源选择强度为70%的蓝光发光二极管($\lambda=470\pm 30$ nm). 激发后的光释光信号经由厚7.5 mm的Hoya U-340 滤光片进入9235QA 光电倍增管进行记录. 等效剂量值的测量采用改进的光释光测年方法^[22]. 光释光样品的剂量率通过计算铀、钍和钾元素的含量和宇宙射线(单位是 Gy/ka)获取. 铀、钍和钾元素的含量采用电感耦合等离子体质谱法和电感耦合等离子体原子发射

图 3 (网络版彩色)部分河流阶地剖面的沉积特征和光释光样品的位。 (a) T2阶地沉积剖面。夹于砾石层之间的、厚约15 cm的透镜体约束该阶地最老的堆积年龄。虚线为砂质透镜体和砾石层的大致界线。 (b) T17阶地沉积剖面。上部风积黄土层厚约45 cm, 该阶地地面的废弃时间应早于该黄土的底界年龄。虚线为黄土层和砾石层的大致界线, 箭头指示阶地砾石。 (c) 安集海河大峡谷头道沟河现代河道与西岸阶地堆积体露头。插图(d)位于图(c)东侧, 指示T18阶地厚逾200 m的砂砾石层。红色箭头指示可连续追踪的砾石层位置, 该砾石层构成了其余阶地的基座

Figure 3 (Color online) Representative stratigraphy for two river terraces and OSL sampling positions. (a) Stratigraphic characteristics of the T2. Sand lenses with a thickness of ~15 cm represent the upper limit of aggradation age of this river terrace. The dotted lines are the boundaries of lens and fluvial sands. (b) Same as (a) but for T17. The bottom of loess layer with ~45 cm in thickness determines the minimum incision age of this river terrace. The dotted lines are the boundaries of loess and fluvial sands. The arrows indicate positions of fluvial sands. (c) The exposed surface of river terraces at the west channel of the Toudaogou River. The location of inserted figure (d) is at the east side of figure (c), indicating the fluvial sands with ~200 m thickness within the 18 terrace. Red arrows show the position of continuous fluvial sand layer. The sand layer is the basement of other river terraces

光谱法分析获得. 将盛有一定量样品的烧杯放入马弗炉, 在125°C下烘干8 h后, 计算干重和湿重获得含水量. 图4列举了T2和T17阶地光释光样品等效剂量值分布图. 在T17采集的黄土底界样品(图4(a))等效剂量值分布较集中, 说明石英颗粒在沉积之前得到了充分曝光.

采用中央年龄模型(central age model, CAM)计算黄土样品的等效剂量值^[33]. 通过中央年龄模型计算T17黄土样品的额外误差值为0.27, 并将该值作为所有黄土样品的额外误差值. 此外, 通过对T11砂质透镜体做剂量恢复实验, 得到该样品的等效剂量值的额外误差值为0.17, 并将此值作为所有砂质透镜体样品的额外误差值. 如图4(b)所示, 根据有限混合年龄模型(finite mixture age model, FMM)^[34]分析结果, T2砂质透镜体等效剂量值的分布至少包含5个组分. 这说明砂质透镜体的部分石英颗粒在最后一次沉积事件之前见光不彻底, 保留了最后一次沉积事件之前的光释光信号, 故本研究采用改进的光释光测年技术^[22], 通过测量大量的测

片(每个样品约300~500个), 从中挑选见光最为充分的石英颗粒计算年龄. 光释光测年结果可见表1和2.

4 结果

由表2可知, T18~T15黄土底部的年龄分别为 3.7 ± 0.2 、 3.0 ± 0.1 、 2.3 ± 0.1 和 3.1 ± 0.3 ka. 这些年龄均代表相应阶地最晚废弃年龄, 约束阶地的最大下切速率. 需要指出的是, T17和T15、T16和T11的年龄在 1σ 误差范围一致, 且T15和T16的年龄在 2σ 范围内一致(表2). 出现这一现象的原因可能是受到释光测年技术本身精度的制约, 也不排除T16阶地老于2.3 ka的黄土在沉积之后受到坡面流水侵蚀等作用被扰动改造的可能. 但至少T18黄土底界年龄可以约束安集海河大峡谷3.7 ka以来最大平均下切速率. T11、T5和T2阶地堆积的加积起始年龄分别为2.4、1.3和0.6 ka, 可用于约束相应阶地的最小下切速率, 也表明阶地T12、T6和T3最晚在2.4、1.3和0.6 ka废弃形成阶地面.

图4 安集海河大峡谷T17(a)和T2(b)光释光样品等效剂量值分布辐射图

Figure 4 Pseudo-radial plots of De distribution for the T17 (a) and T2 (b) OSL samples in the Anjihai River terrace levels, respectively

表1 安集海河大峡谷阶地光释光样品年剂量分析结果

Table 1 Summary of OSL samples and annual dose rate within the Anjihai River terrace levels

阶地	岩性	埋深 (m)	铀 (μg/g)	钍 (μg/g)	钾 (%)	含水量 (%)	宇宙射线 (Gy/ka)	年剂量 (Gy/ka)	等效剂量 (Gy)
T18	黄土	0.20	3.5	11.5	2.0	10±2	0.3	3.6±0.1	13.0±0.3
T17	黄土	0.35	2.9	14.7	2.1	10±2	0.3	3.7±0.1	11.2±0.3
T16	黄土	0.10	2.8	9.5	2.0	10±2	0.3	3.2±0.1	7.2±0.3
T15	黄土	0.15	2.2	14.2	2.0	10±2	0.3	3.4±0.1	10.5±1.1
T11	砂质透镜体	4.80	2.2	10.0	1.7	5±2	0.1	2.8±0.1	6.8±0.2
T5	砂质透镜体	2.40	2.3	11.6	2.2	5±2	0.2	3.5±0.1	4.6±0.1
T2	砂质透镜体	1.85	2.6	10.2	2.1	5±2	0.2	3.4±0.1	1.9±0.1

表2 光释光样品的埋藏年龄和河流下切速率表

Table 2 OSL ages for quartz sediments from the Anjihai River terraces and river incision rates

阶地	纬度(°N)	经度(°E)	拔河高度(m)	与下一级阶地高差(m)	年龄(ka)	平均下切速率(cm/a)	下切速率(cm/a)
T18	44.0828	85.0899	264±5	20±2	3.7±0.2	7.2±0.1	3.1±0.3
T17	44.0865	85.0918	244±5	12±2	3.0±0.1	8.1±0.2	
T16	44.0903	85.0968	232±5	13±2	2.3±0.1	- ^{b)}	15.2±0.3 ^{a)}
T15	44.0914	85.0977	219±5	24±2	3.1±0.3	- ^{b)}	
T11	44.0936	85.0974	153±5	90±2	2.4±0.1	6.4±0.3	8.5±0.2
T5	44.0975	85.0979	63±5	33±2	1.3±0.0	4.7±0.4	4.3±0.3
T2	44.1009	85.0984	28±2	28±2	0.6±0.0	4.9±0.4	4.9±0.4

a) 代表T17~T11的平均下切速率; b) 短线表示因年龄倒置无数据

安集海河大峡谷最高阶地T18阶地面连续分布在安集海河上下游(图1(b), (c)), 与前人在同一流域报道的F₆¹洪积扇面、下游安集海背斜T1阶地在地形上为同一阶地^[6,16,20]. 前人采用光释光测年技术在该阶地上获得的砂质透镜体年龄约为3.6~4.0 ka, 上覆黄土的起始堆积年龄约为3.5~3.6 ka^[16,20]. 采用¹⁰Be测年技术获得该阶地地面的暴露年龄为5.1±1.7 ka^[6]. 由本研究测年结果可知, 安集海河大峡谷最高阶地T18阶地面上覆风成黄土起始堆积于3.7±0.2 ka. 这些年龄在1σ误差范围内一致. 综上所述, 安集海河大峡谷最高阶地T18最晚废弃年龄约为3.7 ka.

在距本研究研究地点约13 km处, 前人对头道沟河上游中晚全新世黄土-古土壤剖面研究发现, 在距今约2.5~4.0 ka黄土的堆积在该区域是连续的^[32]. 此外, 采用光释光测年技术获得的北天山玛纳斯河、安集海河下游阶地和安集海大峡谷T18阶地面上覆黄土底界年龄和阶地砾石堆积顶部砂质透镜体年龄结果, 在1σ误差范围内一致^[16,18,20], 说明黄土限制的阶地最晚废弃年龄和前人用阶地沉积物限制的堆积上限年龄是一致的. 这两个河段内阶地面废弃后, 随即堆积了风成黄土, 因而可以利用黄土的起始堆积年龄来约束下伏阶地地面的最晚废弃时间. 采用透镜体细砂限定低阶地的堆积上限年龄. 水成样品因晒退不彻底会导致沉积年龄被高估, 故此需要讨论水成细砂的晒退特征和对年龄的影响. 这些碎屑物质从母岩剥离之后, 随水流搬运到达安集海河大峡谷沉积. 在沉积之前, 可能在上游经历过多次的搬运-堆积循环, 在每一次循环过程中, 这些测年矿物颗粒会不同程度地接受阳光的曝晒, 最后堆积在安集海河大峡谷阶地上. 根据见光程度的不同, 可将这些

颗粒划分为不完全晒退和晒退彻底两种类型, 前者会导致沉积物真实堆积年龄被高估, 后者则反映真实的埋藏年龄. 这种现象反映在等效剂量频率分布图上. 等效剂量至少有两个“峰值”(或更多)分布, 对应至少两个(或更多, 图4(b))等效剂量值的组分^[22]. 安集海河大峡谷阶地的水成透镜体细砂样品没有经历长距离的搬运, 部分石英颗粒也会受到光释光信号不完全晒退的影响. 本研究采用改进的光释光测年技术, 把由晒退彻底的石英颗粒组成的等效剂量的分布从总的分布中单独剥离出来, 从而将晒退不彻底的颗粒去掉, 即获得由晒退彻底的颗粒组成的、能代表真实堆积年龄的埋藏剂量.

结合各采样阶地前缘的拔河高度和阶地间的高度差值(表2), 并基于黄土和阶地沉积的释光年代序列, 我们重建了安集海河大峡谷18级阶地加积-下切的历史过程(图2(d)): 古冲洪积扇形成于约3.7 ka以前. 3.7~3.0 ka, 安集海河自T18阶地面位置下切至T17阶地面处, 至少下切了20±2 m. 距今3.0~2.4 ka, 河流下切至T11阶地, 至少下切了91±2 m, 在约600年间形成了7级阶地, 该时间段内平均下切速率为15 cm/a.

2.4~1.3 ka, 下切至T6之后, 安集海河开始侵蚀前第四纪基岩. 1.3 ka以来经历了至少5次下切, 形成5级基岩基座阶地. T11~T5、T5~T2和T2~T0阶地前缘的高度差分别为90±2、33±2和30±2 m. 结合本研究和前人测年数据^[6], 安集海河大峡谷阶地18级阶地平均下切速率应介于4~7 cm/a(图5(a)). 由于安集海河在3.7~1.3 ka下切大峡谷段晚第四纪阶地松散沉积物, 与低阶地基岩相比, 下切相对容易(图2(b), 5(a)). 该地点的平均下切速率显著高于北天山其他河流已知平均下切速率^[6,18]. 但需要说明的是, 该速率仅为安集海河大

图 5 (网络版彩色)北天山主要河流全新世下切速率图和安集海河河流纵剖面。(a) 安集海河、奎屯河和玛纳斯河全新世以来的下切速率对比^[6,18]。(b) 安集海河现代河床纵剖面。插图为安集海河水系平面图

Figure 5 (Color online) Compile the Holocene river incision rates of the major rivers, in the northern Tianshan. The longitudinal profile of the Anjihai River. (a) Comparison of the Holocene river incision rates in the Anjihai River, Kuitun River and Manas River^[6,18]. (b) The longitudinal profile of the modern river bed of the Anjihai River. The inserted figure is the Anjihai River system

峡谷T18 废弃以来短期的平均下切速率^[35,36]。

5 机制探讨

前人研究认为, 北天山河流阶地主要是气候变化和构造运动的产物^[13,15,18,37]。图6总结了本研究 and 近年来北天山河流阶地加积和废弃年龄的数据。结果显示北天山主要河流阶地加积年龄和废弃年龄的峰值集中在晚更新世-全新世气候过渡期(图6(a), (c))。阶地废弃高峰期出现在全新世中期气候适宜期向晚期冷期的过渡阶段, 而并非全新世气候最适宜期(图6(d)), 且在气候过渡期阶地的废弃频率要明显高于阶地的加积频率(图6(b), (d))。在单一冷期/暖期气候阶段, 阶地的数量比气候过渡期少(图6(d))。这说明在气候过渡期, 气候系统的波动变化可能对河流系统的扰动影响大。这种扰动体现在打破河流系统原先的稳定状态, 而演化至新的稳定状态, 以便适应气候系统变化。这一发现与前人在祁连山主要河流阶地的研究结果一致^[38,39]。如全新世中期至晚期, 北天山黄土-古土壤剖面记录了古土壤向黄土发育的过程^[32], 奎屯河下游艾比湖古湖岸线降低^[36], 这些都是古气候由湿润向干旱过渡的证据。这与中国黄土高原黄土-古土壤剖面记录的全新世中期湿润期向晚期干旱期过渡一致^[40,41]。安集海河在此期间也自T18下切至T11。

北天山冰川积雪区在冰期时由于冰川下蚀和展宽

形成的“U”型冰川谷积累了大量的松散堆积物。这些碎屑物质充填河谷打破河流中水沙平衡, 使河流中泥沙含量增大, 即泥沙通量/水流量之比变大^[6,7]。在气候变暖、山地降水增加和冰雪融水的作用下, 河流中水量增加, 将这些碎屑物质进一步搬运至山麓地带堆积, 形成冲洪积扇, 也加大了冲洪积扇面的地形坡度, 如安集海河大峡谷T18阶地面(2.7%)^[16]。在气候过渡期或湿润期, 流域内发生强降雨并爆发洪水, 安集海河大峡谷段受安集海河和支沟汇水的影响, 在大峡谷出山口以上水量增大, 河流水量超过了搬运碎屑物所需要的水量阈值, 即泥沙通量/水流量之比变小, 河流下切冲洪积扇发育阶地(T18为安集海河下切冲洪积扇而成)^[42~45]。此外, 坡面流水强烈侵蚀阶地面(安集海河大峡谷T17以下阶地面上发育有多条冲沟), 松散的砾石层被快速下切侵蚀并可能发生部分崩塌(图2(a))。这些因素会导致河流发生快速下切。多次这样的过程会在较短时间内发育多级小型阶地(如T17~T11)^[19]。所以, 安集海河大峡谷阶地的快速下切速率出现在T17~T11之间, 而T18~T17的下切速率相对较慢。T11以后随着气候变干, 泥沙通量/水流量之比相对增大, 河流下切可能因坡面侵蚀或从上游搬运的碎屑物质堆积而成的较年轻的砾石层, 下切速率减慢^[6,7]。安集海河和头道沟河在T5切穿砾石层到达基岩, 下切难度进一步增加。这些因素使安集海河自T5以来下切速率进一步减慢。

图6 北天山中更新世以来主要河流阶地加积和废弃年龄的频率分布图^[6,7,18]。(a) 加积年龄的频率分布图。(b) 如图(a), 为北天山全新世主要河流阶地加积年龄的频率分布图。(c) 废弃年龄的频率分布图。(d) 如图(c), 为北天山全新世主要河流阶地废弃年龄的频率分布图

Figure 6 The probability density function of aggradation and abandonment ages of major river terraces in the northern Tianshan during the middle Quaternary^[6,7,18]. (a) The probability density function of aggradation ages. (b) Same as (a) but for the probability density function of aggradation ages of major river terraces in the northern Tian Shan during the Holocene. (c) The probability density function of abandonment ages. (d) Same as (c) but for the probability density function of abandonment ages of major river terraces in the northern Tian Shan during the Holocene

该峡谷18级阶地发育在两条河流交汇位置, 而非安集海河西岸, 说明这些阶地的形成可能是安集海河和头道沟河两条河流共同作用的结果。南安集海河背斜和霍尔果斯背斜交汇位置为安集海河和头道沟河的出山口。出山口以上的上游为宽广的山麓地带, 使该河段的河道平面形似上宽下窄的喇叭口状。3.7 ka前, 流水受到出山口处较高前第四纪基岩崖壁的阻挡(图1(c)), 两条河流携带的碎屑物质发生叠加堆积, 发育宽广的冲洪积扇。河流侵蚀拓宽出山口, 碎屑物质向下游搬运, 形成贯通上下游的冲洪积扇^[3]。3.7 ka前后, 在两河交汇处水量更大, 下切冲洪积扇和出山口的速度比其他位置快。在下切的过程中, 河流可能进一步侧向掏蚀安集海河西侧河道底部^[5], 使峡谷西侧河道发生崩塌堆积, 进一步推挤河道向东侧迁移, 所以年轻阶地并没有在西侧发育。

构造运动亦可导致北天山阶地变形、河道迁移, 下切速率加快, 但存在显著的空间差异。以奎屯河为例, 已

有研究认为独山子背斜构造抬升运动对该处阶地下切速率的贡献仅占10%^[42], 而玛纳斯河下游4.8 ka以来强烈的下切却主要是由玛纳斯背斜隆升而导致^[18]。安集海河大峡谷穿过南安集海背斜, 前人研究发现安集海河大峡谷西岸、横跨南安集海背斜两翼, 从现代河床到高阶地的地形坡度随阶数增加而增大, 这可能记录了该背斜持续隆升的过程^[16]。但3.7 ka以来安集海河是如何响应南安集海背斜隆升过程的还需定量研究。此外, 安集海河从源头到大峡谷位置地势较高、地形起伏大, 现代河床的纵比降大(3.5%), 落差大、跌水位置较多(图5(b)), 河流的侵蚀能力强。而大峡谷以北流入准噶尔盆地, 地势降低, 且河道地形起伏小, 现代河床纵比降仅约1%, 河流携带的碎屑物质发生堆积, 形成规模巨大的冲洪积扇。前人在东祁连山和澜沧江也报道了因气候变化或构造运动导致河流快速下切的现象^[10,38,39]。比如, 自76 ka以来, 东祁连山7条主要河流上游的下切速率约是下游的2倍。河流的下切速率自上游至下游变慢

的空间分布特征与东祁连山地形抬升高度自上游至下游降低的空间分布特征一致,反映了构造运动对河流下切速率的影响^[38]。祁连山北麓有些河流在晚更新世至全新世以来平均下切速率介于5~10 mm/a,远大于构造抬升的长期平均速率。这可能是冰消期冰川融水和降雨等汇入河流使河流水量增加并发生快速下切的结果^[39]。另外,对澜沧江流域5级阶地开展了晚更新世河流下切时空变化特征研究,发现芒康-玉龙段自晚更新世(>120 ka)以来,阶地的下切速率从下游至上游逐渐降低,这和西南季风降雨量在澜沧江峡谷沿上游逐渐减少相对应。其中,阶地的加积对应冷湿的冰期,阶地的下切出现在冷湿的冰期和更温暖、更湿润的间冰期。在100~10 ka时间尺度内,水文系统对区域气候变化做出响应的过程在阶地的加积-侵蚀循环过程中发挥了更大的作用^[10]。综上所述,约3.7 ka以来,在古气候变化的作用下,安集海河河流系统在大峡谷段通过内部的自我

调节出现了快速下切的现象。

6 结论

北天山安集海河流经安集海大峡谷处下切厚逾200 m的砾石层和前第四纪基岩地层形成至少18级阶地。依据地层接触关系,将18级阶地划分为12级晚第四纪砾石基座阶地和6级前第四纪基岩基座阶地。这些阶地很好地记录了安集海河在大峡谷段的堆积和侵蚀过程。3.7 ka以前,安集海河在基岩以上堆积了厚逾200 m的砾石层。3.7 ka以来安集海河大峡谷以最大平均速率7 cm/a快速下切,最大下切速率可达15 cm/a。安集海河大峡谷18级阶地是河流系统通过自我调节对气候变化作出响应的产物。此外,安集海河大峡谷古冲洪积扇面记录的砾石堆积过程和对应的堆积速率、新构造运动对安集海河大峡谷阶地形成的影响等是进一步研究的重点。

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Summary for “北天山安集海河大峡谷3.7 ka以来的快速下切”

Rapid incision events since 3.7 ka in the Anjihaihe Gorge along the northern Tianshan range, China

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Young river terrace levels distributed along active tectonic regions and major river channels record the histories of the most recent tectonic activities and geomorphological evolution. There are 18 terraces in the upper reach of the Anjihaihe River, along active zones of the northern Tianshan in China. The surface of these young terrace insets is covered by Aeolian loess and fluvial deposits. Consequently, optically stimulated luminescence (OSL) dating was used to reveal the burial ages of those sediments, and to calculate the tectonic deformation and fluvial incision rate. However, the ages of young quartz sediments are difficult to determine due to the weak and dim OSL signal characteristics, and therefore geological and geomorphological information was not forthcoming. Recently, however, a “simplified procedures” methodology was developed to overcome these dating problems.

Loess deposits can constrain the minimum abandonment age and fluvial sands were used to provide the age limits of formation, which correspond to the maximum and minimum incision rates. The elevation of each terrace above the modern river bed was obtained using a Digital Elevation Map with 12-m resolution, Google Earth images, and portable Global Positioning System measurements. Together with the results of the OSL dating and the elevation measurements, we conclude that the Anjihaihe River has incised the gorge to a depth of ~ 260 m since 3.7 ± 0.2 ka, with a maximum average incision rate of 7.2 ± 0.1 cm/a. The incision record can be divided into four major stages: ~ 3.7 – 3.0 , ~ 3.0 – 2.4 , ~ 2.4 – 1.3 ka, and from 1.3 ka to the present; the respective average incisive rates are 3.1 ± 0.3 , 15 ± 0.3 , 8.5 ± 0.2 , and 4.6 ± 0.4 cm/a. The results indicate that the incision occurred in a series of steps which coincided with environmental changes in the region. As a result, this set of 18 strath terrace levels has recorded the aggradational-degradational surface processes of the Anjihaihe River gorge since ~ 3.7 ka. Before ~ 3.7 ka, a thickness of ~ 260 m of fluvial sands was aggraded above the pre-Quaternary bedrock. Subsequently, the river incised these sand layers until T11, and then, before the formation of T11, younger fluvial sands were deposited on the top of older deposits after 2.4 ka. The AJH River then continued to vertically erode these younger sands until 1.3 ka, when the incision reached the pre-Quaternary bedrock. From 1.3 ka to the present, at least five strath terraces were formed in the gorge.

These surface processes and rapid incisive rates are ascribed to the specific lithological and geomorphological characteristics of the area, under the influence of climate change. First, the bedrock of the terrace levels is composed of pre-Quaternary sandstones, and more homogeneous, less consolidated siltstones and sandy mudstones. In addition, the upper terraces are covered by mixed cobbles and sands with a thickness of ~ 100 m above the bedrock, and the lower terraces by a thin layer of fluvial sands above the pre-Quaternary bedrock. Second, the variations in the flux of river water and sediments during episodes of climate change influenced the slope of the terrace surface, resulting in changes in aggradational-degradational processes and in the energy of the incision. Climate change was also a driving force, because the abrupt changes in incision rate correspond well to anomalous climatic events. Overall, the specific geomorphological characteristics and location of the Anjihaihe River have resulted in its recording an unusually rapid incision rate within the Anjihaihe Gorge.

the northern Tianshan, Anjihaihe Gorge, Young river terrace, OSL dating, aggradational-degradational processes

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