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若尔盖黄河唐克段河岸沉积序列测年 及地表过程变化

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摘要:通过对若尔盖盆地进行野外考察,在盆地中部黄河唐克段右岸发现了包含深湖相的河岸沉积物,进行了细致的地层观测和系统年代学样品采集。在实验室利用光释光和AMS¹⁴C测年技术建立了年代框架,并结合各个层次的地层沉积相宏观特征和理化性质,分析探讨了若尔盖盆地内部从末次冰期古湖消亡以来的环境和地表过程变化规律。研究结果表明:古黄河在37 ka沿着玛曲断陷谷地溯源侵蚀,沟通了若尔盖古湖水系,盆地内部在30.9 ka之前为深湖环境,稳定地沉积了蓝灰色湖相淤泥层。30.9 ka之后,黄河贯穿若尔盖湖盆内部,古湖水外泄消失,原有的古湖水系转变成成为黄河源水系。黄河从湖盆上游远距离搬运携带来的浊黄橙色泥沙大量沉积,覆盖了古湖相沉积层,湖盆内部风沙作用盛行。在末次冰盛期(Last Glacial Maximum, LGM),盆地内部松散沉积物普遍地受到冰缘冻融作用的改造,形成了冻融褶皱现象。到了14.6~12.5 ka,响应B/A(Bølling-Allerød)时期的温暖气候,盆地周边山地冰川消融,冰融水汇入盆地,古湖盆底部各种浅洼地形成了大小不等的浅湖,沉积了滨浅湖相的沙层。在12.5~11.7 ka,对应于全球性新仙女木(Younger Dryas, YD)事件,盆地气候再次变冷,转变为冰缘冻土环境,盆地内部滨浅湖相的沙层受到冻融作用和古地震扰动,形成复式褶皱现象。进入全新世,在11.7~4.8 ka气候逐渐变得温暖湿润,古湖盆底部浅洼地积水成为淤泥质沼泽环境,在全新世中后期4.8~1.8 ka则转变成成为沼泽草甸环境,在1.8 ka之后,盆地内沼泽面积收缩,风沙活动盛行,河岸台地的近源沙尘暴沉积物经过成壤改造形成亚高山草甸黑土类现代土壤。

关键词: 若尔盖盆地; 地层序列; 冻融褶皱; 震积层; 光释光测年

中图分类号: P343.6; P512.4² **文献标志码:** A **文章编号:** 1000-0240(2022)04-1188-15

0 引言

若尔盖盆地位于甘南黄河上游段,地处青藏高原东北缘,是东亚季风、西南季风与西风带交互影响的地带,自然环境脆弱,对气候变化具有敏感性和独特性^[1]。第四纪时期盆地经历了若尔盖大湖-湖泊消亡-黄河贯通等重大地貌水文事件,这些事件是开展青藏高原构造隆升及其环境效应研究的重要的切入点,是认识新生代亚洲地区重大构造和古气候水文事件相互作用的纽带。

若尔盖盆地古湖消亡及黄河贯通的时间和动

力机制争议较大。盆地北部沉降中心深钻孔岩芯RM和RH孔中发现古湖相沉积淤泥层顶界的¹⁴C年龄为21.6 ka BP和37.6 ka BP,并认为黄河袭夺古湖事件发生在38~35 ka^[2-4]。黄河辖曼镇-索克藏寺河岸古河漫滩相沉积层出土的披毛犀、原始牛、马动物化石的测年结果为22.6 ka左右,并认为此时盆地脱离湖泊环境^[5-7],黄河贯通盆地。利用盆地内部的泥炭层沉积重建植被与气候演化过程,发现古湖相淤泥沉积向沼泽泥炭转变发生在10.3 ka与12.1 ka或者12.6 ka,故而认为黄河贯通发生在早

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全新世^[8-9]。这些研究成果多集中在盆地中央湿地沼泽、黑河、白河沿岸,有可能受区域性差异性构造运动和地形、环境与地表过程和沉积相的影响,导致结论各不相同。而对黄河沿岸直接出露,能够真正反映黄河和古湖变迁历史的沉积地层研究较少。本课题组将通过若尔盖盆地内部黄河两岸直接出露的土壤沉积物剖面的研究,为解决这些关键性问题提供可靠的第一手材料和直接证据。

本课题组前期在玛曲-若尔盖沿黄河两岸开展了广泛细致的野外考察和研究,从古洪水水文学、沉积学和年代学角度出发,在若干地点提供对天然剖面的观测研究,确定了晚更新世末期以来的土壤沉积物地层序列及年代框架,并准确鉴别出黄河古洪水泛滥沉积物及其发生年代和成因机制。在黄河玛曲-欧拉秀玛河段发现典型的古洪水沉积物,光释光测年结果显示形成于 14.9~12.8 ka、13.5~12.9 ka 和 11.1~9.8 ka 左右。认为在 B/A (Bølling-Allerød) 暖期气候温暖湿润的气候背景下,盆地周边高山地带冰川融化及降水量的增加使黄河发生了多次大规模的古洪水事件,从而形成洪水泛滥沉积层^[10-13]。这些研究点多位于阿尼玛卿山和西倾山之间的断陷谷地地带,本文的研究主要集中在若尔盖盆地内部黄河唐克段河岸,对黄河下切直接出露的天然沉积剖面进行研究,建立土壤沉积物地层序列和年代框架,深入探讨黄河溯源侵蚀进入若尔盖盆地内部的过程之中区域性地表过程变化特点,为黄河贯通若尔盖盆地提供年代学和地层学证据。

1 研究区概况

青藏高原东部的若尔盖盆地,是受东昆仑大断裂东端新构造运动控制形成的相对沉降区域,西起阿尼玛卿山,东抵岷山,北依西倾山,南靠邛崃山,面积约 $1.96 \times 10^4 \text{ km}^2$,中心部分海拔 3 400~3 450 m,周边山体海拔超过 4 000 m,为典型的四面环山的断陷盆地。盆地基底岩层主要为三叠系地层,以二叠系-三叠系砂岩、板岩、灰岩为主,在一些地段有白垩纪角砾岩和第三系红色黏土层出露^[14-15]。总体地势西高东低,南高北低,内部地形起伏,具有基岩丘陵,也有沉积洼地,分布有第四系河湖相沉积物。黄河从盆地西部的果洛山汇入盆地向东南流去,沿途接纳白河、黑河等水系,在唐克附近黄河转向盆地西北流去,形成巨大“U”形弯曲,称为“黄河第一湾”,最后从玛曲县城南侧紧贴着阿米欧拉山麓流

出盆地,总流程约 110 km。黄河河床类型在不同河段呈现出网状水流、自由曲流、辫状水流及峡谷式深切曲流等,沿岸有河流阶地、山麓台地、冰水-洪积扇台地分布,高度在 8~30 m 之间不等。

若尔盖盆地位于季风区和青藏高原交汇地带,受东亚东南季风和东亚西南季风影响,降水较为丰富,年降水量 648.5 mm,5—9 月降水量占全年 77% 以上;年平均气温 $1.1 \text{ }^\circ\text{C}$,1 月平均温度 $-9.4 \text{ }^\circ\text{C}$,7 月平均温度 $10.8 \text{ }^\circ\text{C}$;夏秋季气温高而短暂,春、冬、冬季气温低且漫长,严寒湿润霜冻期长,四季变化明显;为高原寒温带湿润季风气候^[16-17]。在盆地内部地形低洼地带发育泥炭,总面积达 $4.6 \times 10^3 \text{ km}^2$,泥炭平均深度 2~3 m,最深可达 9~10 m^[9,18]。周边山体普遍发育现代冰川和冻土,中更新世以来发生 2~3 期冰川作用,可见有冰斗、刃脊、角峰等冰川地貌^[19],季节性温度上升,高山冰雪融化会补给黄河及其支流。若尔盖盆地年平均风速为 $2.23 \sim 2.37 \text{ m} \cdot \text{s}^{-1}$,冬春季风速较大,河漫滩相泥沙及古湖泥沙被风力再次搬运堆积形成沙丘,多以斑状、点状分布^[20]。植被类型主要为亚高山草甸和沼泽草甸,土壤为富含有机质的亚高山草甸黑土和沼泽草甸黑土。

2 剖面特征与样品采集

我们在若尔盖盆地内部黄河第一弯白河汇入口上游黄河两岸进行了详细的调查研究,发现在唐克河段沃曲汇入口与唐克渡口之间,黄河右岸的河岸为松散沉积物构成的陡坎,高度在 8~10 m 之间。其中沃曲东剖面处于黄河故道与阿尔则乔干沼泽草甸之间由松散沉积物构成的低缓平梁状地带,海拔高程 3 440 m。野外调查结合大比例尺卫星影像图观测,可知黄河曾长期在其左岸 3~7 km 范围内反复裁弯取直,产生众多弯曲的废弃河湾与沼泽草甸,后期河道整体向右岸迁移,河岸不断坍塌后退,形成高度 10 m 左右的河岸,暴露出包含古湖相淤泥层的松散沉积物序列(图 1)。经过野外详细观察测量和沉积物鉴别,对沃曲东剖面(WQD)进行了地层划分和土壤沉积物性质的描述(表 1、图 2)。在 WQD 剖面最上部 0~0.8 m 发育现代草甸土壤层(MS);0.8~1.4 m 发育沼泽草甸古土壤层(S_0);1.4~3.9 m 发育泥沼土层(Mud);3.9~9.9 m 为沙层,其中 3.9~5.0 m 为褶皱沙层(Folded-S),5.0~8.0 m 为滨浅湖沙层(Lake-S),8.0~9.9 m 为褶皱河漫滩-风沙层(Folded-S);9.9 m 以下为深湖相淤泥层(Lake-mud)。

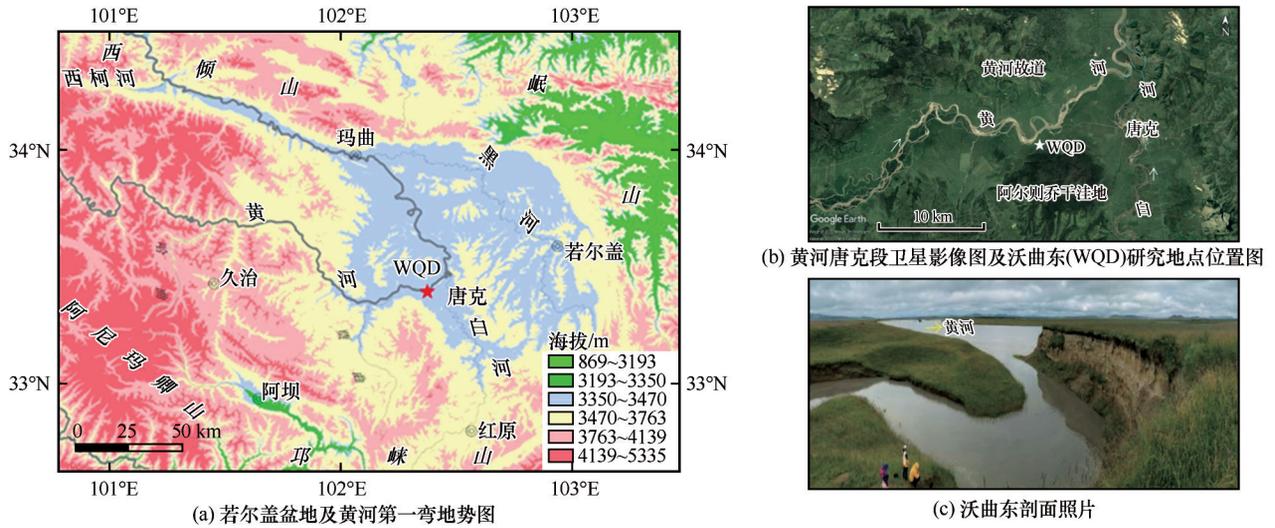


图1 研究区概况

Fig. 1 Overview of the study area: Zoige Basin and the first bend of the Yellow River (a); satellite image of the Tangke reach of the Yellow River and the study Woqudong site (WQD) (b); photo of the WQD profile (c)

表1 若尔盖唐克沃曲东黄河岸剖面(WQD)地层划分与描述

Table 1 Stratigraphic division and pedo-sediment description in the WQD profile on the Yellow River bank along the Tangke reach in the Zoige Basin

| 土壤地层层位 | 深度/m | 土壤与沉积物性质描述 |
|---------------------------|-----------|--|
| 现代草甸土壤层(MS) | 0~0.80 | 亚高山草甸黑土,灰棕色(7.5YR5/2),湿润时为黑棕色(7.5YR2/1),细沙质-粉沙质地,团粒构造,疏松多孔,含有密集的植物根系 |
| 沼泽草甸古土壤层(S ₀) | 0.80~1.40 | 亚高山沼泽草甸黑土,棕灰色(7.5YR5/1),黏土质-粉沙质地,团粒-团块构造,富含有机质,底部含有较多的锈黄色斑,在长期暴露的剖面,可溶盐积累,故而干燥时比较坚硬。其1.05~1.10 m深度 ¹⁴ C校正年龄为(1.78±0.05) cal ka BP |
| 泥沼土层(Mud) | 1.40~3.90 | 浊黄橙色(10YR7/3),粉沙质地,块状构造,无层理,多植物根孔,多有浅层化作用形成的灰白、灰绿、锈黄色斑 |
| 褶皱沙层(Folded-S) | 3.90~5.00 | 浊黄橙色(10YR7/3),分选良好的细沙,疏松,多锈黄色浸染,常见有显著的冻融与古地震扰动形成复杂的复式褶皱现象 |
| 滨浅湖沙层(Lake-S) | 5.00~8.00 | 浊黄橙色(10YR7/3),分选良好的细沙,疏松,具有整齐的薄层水平-波状层理,多锈黄色浸染 |
| 褶皱河漫滩-风沙层(Folded-S) | 8.00~9.90 | 浊黄橙色(10YR7/3),中粗沙,层理不规则,多锈黄色浸染,常见有显著的冻融褶皱现象 |
| 深湖相淤泥层(Lake-mud) | 9.90~? | 蓝灰色(5B6/1),粉沙-黏土质地,均匀致密,无层理,有浓烈的H ₂ S臭味,含有植物残体分解形成的不规则锈黄色斑,属于若尔盖古湖稳定的深水沉积物,未见底。其9.95~10.00 m深度 ¹⁴ C校正年龄为(30.98±0.13) cal ka BP |

根据该剖面土壤地层沉积特征系统地进行了样品采集,在表土层中部(0.35~0.40 m)、古土壤中部(1.05~1.1 m)、泥沼土中部(2.55~2.60 m)、褶皱沙层顶界(3.95~4.00 m)、滨浅湖沙层中上部(5.85~5.90 m)、褶皱河漫滩-风沙层中部(8.85~8.90 m)、深湖相淤泥顶界(9.95~10.00 m)及顶部(10.45~10.50 m)各采集沉积学样品一个,共7个。在沼泽草甸古土壤底界(1.35~1.40 m),褶皱沙层顶界(3.95~4.00 m),褶皱河漫滩-风沙层顶界(8.00~8.05 m)、底部(9.65~9.70 m)、底界(9.80~

9.85 m),各采集光释光(OSL)样品一个,依次命名为 WQD-A-1、WQD-A-2、WQD-A-3、WQD-A-4、WQD-A-5。在古土壤顶界(0.90~0.95 m)、深湖相淤泥顶界(9.95~10.00 m)采集两个 AMS¹⁴C 样品。

3 研究方法

3.1 光释光测年

光释光样品的年龄测试在陕西师范大学释光断代实验室完成,测试粒径为 63~90 μm,样片直径 2 mm,测试仪器为 Riso-TL/OSL DA20,其光电倍增

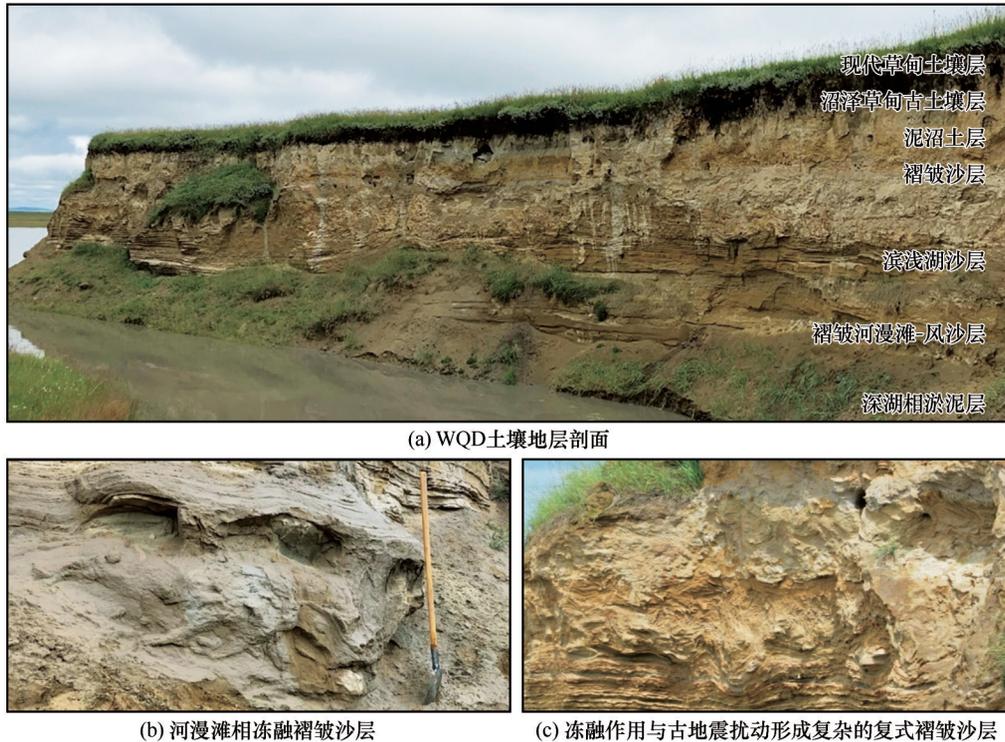


图 2 若尔盖唐克黄河岸沃曲东剖面(WQD)地层划分和土壤沉积物性质

Fig. 2 Stratigraphic division and soil sediment properties of WQD on the Yellow River Bank along the Tangke reach of Zoige Basin: soil stratum profile (a); the freeze-thawed folds in the flood plain sand (b); the earthquake disturbed freeze-thawed folds in the shallow lake deposit (c)

管为 EMI9235QB15, 激发光源包括红外光源 $[(880 \pm 80) \text{ nm}, 40 \text{ mW} \cdot \text{cm}^{-2}]$ 、蓝光光源 $[(470 \pm 30) \text{ nm}, 50 \text{ mW} \cdot \text{cm}^{-2}]$, 滤光片为 Hoya U-340, β 辐射源 $^{90}\text{Sr}/^{90}\text{Y}$ 源, 剂量率为 $0.122683 \text{ Gy} \cdot \text{s}^{-1}$ 。

光释光样品的环境剂量率主要由放射性元素 U、Th、K 含量、含水量以及宇宙射线的贡献决定。U、Th 含量在西安地质调查中心采用全谱直读等离子光谱仪 (ICP-OES) 测得、K 含量采用电感耦合等离子体质谱仪 (ICP-MS) 测得。样品含水量在实测基础上, 根据沉积相特征, 采用区域性土壤沉积物含水量校正, 误差为 $\pm 3\%$ 。宇宙射线的贡献由采样点的经度、纬度、海拔高度、和样品埋藏深度等决定^[21]。通过相关公式计算得出样品的环境剂量率^[22]。

3.1.1 等效剂量(D_e)测定

光释光测年技术已广泛应用于第四纪沉积物的测年工作中, 其基本原理为最后一次埋藏年代=等效剂量/环境剂量率^[23]。

光释光样品等效剂量(D_e)采用单片再生剂量法 (SAR) 测定^[24]。等效剂量(D_e)测试需要选择合适的测试条件, 根据样品沉积相特征, 选择代表性 WQD-

A-1、2、5 号样品进行预热坪区实验。在 $180 \sim 300 \text{ }^\circ\text{C}$ 区间内, 以 $20 \text{ }^\circ\text{C}$ 为间隔, Cutheat 比预热温度 (Pre-heat) 低 $40 \text{ }^\circ\text{C}$, 每个温度点测试 6 个样片。预热坪实验表明 (如图 3), WQD-A-1、2、5 分别在 $180 \sim 300 \text{ }^\circ\text{C}$ 、 $180 \sim 280 \text{ }^\circ\text{C}$ 、 $180 \sim 300 \text{ }^\circ\text{C}$ 温度区间内, 等效剂量 (D_e) 不随温度升高改变, 出现一个“坪区”, 样品的温度“坪区”宽。

为了检验以上温度区间的可靠性, 需要进行剂量恢复实验。先将 WQD-A-1、2、5 样品自然释光信号彻底晒褪, 然后分别辐照接近样品等效剂量 (D_e) 的人工剂量 (11.90 Gy 、 26.73 Gy 、 38.15 Gy)。WQD-A-1、2、5 样品在预热温度 $260 \text{ }^\circ\text{C}$ 、 $220 \text{ }^\circ\text{C}$ 、 $260 \text{ }^\circ\text{C}$ 下得到的恢复剂量为 12.04 Gy 、 26.48 Gy 、 38.16 Gy 与人工剂量最接近, 人工剂量与恢复剂量的比值 (恢复系数) 分别为 0.98 、 1.01 、 1.00 , 介于 $0.9 \sim 1.1$ 之间 (图 3)。最终 WQD-A-1、3、4、5 以预热温度 $260 \text{ }^\circ\text{C}$ 和割热温度 $220 \text{ }^\circ\text{C}$ 作为实验测试条件, WQD-A-2 以预热温度 $220 \text{ }^\circ\text{C}$ 和割热温度 $180 \text{ }^\circ\text{C}$ 作为等效剂量 (D_e) 测试条件。循环比在测试条件下介于 $0.9 \sim 1.1$ 之间 (图 3), 说明感量变化也得到较好校正^[24]。

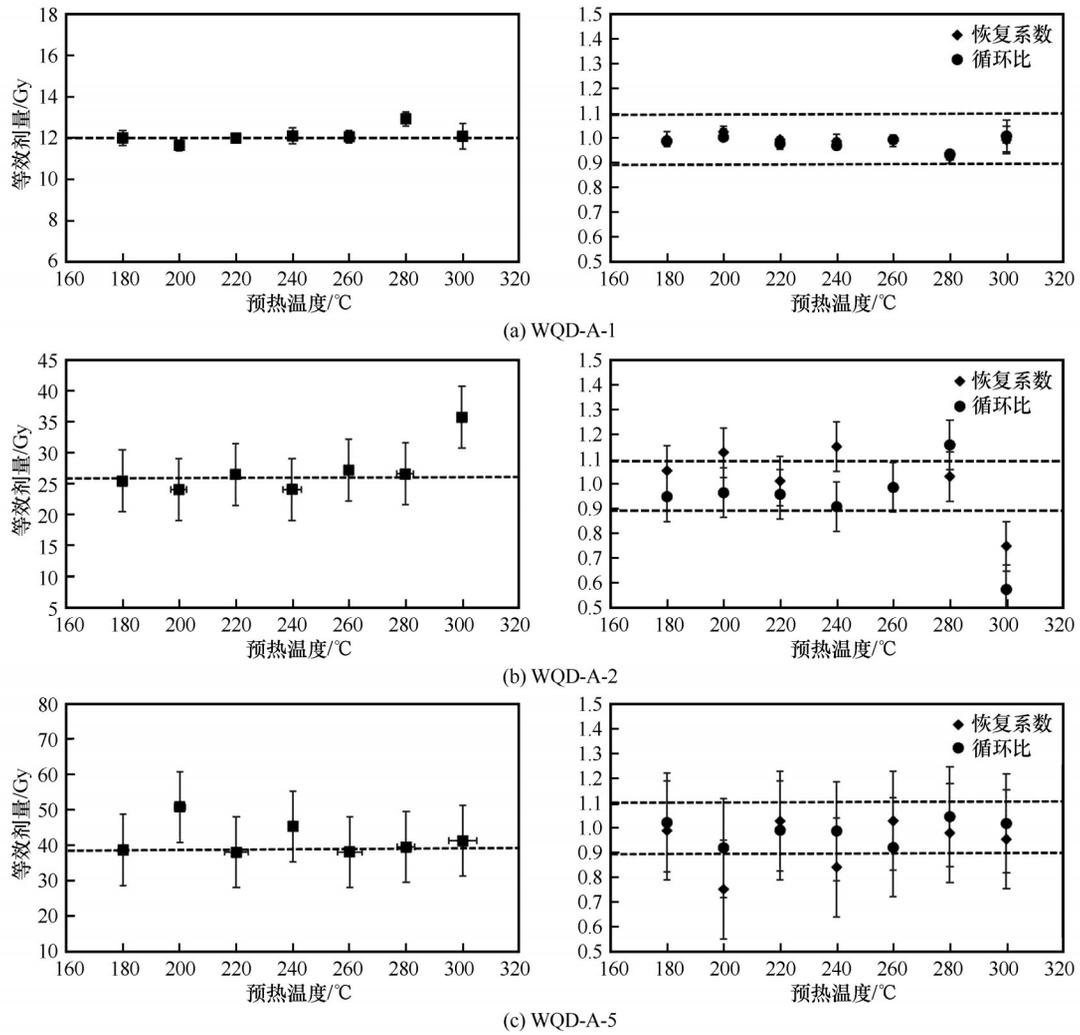


图3 若尔盖唐克黄河岸沃曲东(WQD)剖面样品预热坪实验和剂量恢复实验及循环比

Fig. 3 Preheating plateau experiments and dose recovery experiments and recycling ratio of samples WQD profile on the Yellow River bank along the Tangke reach of the Zoige Basin

3.1.2 光释光信号特征和晒褪程度分析

WQD-A-1、2、3、4、5样品的光释光晒褪曲线均在2 s左右快速晒褪至本底值,样品光释光信号以快速组分为主,采用前背景法确定释光信号的积分区

间,每个通道0.16 s,利用前1~5通道的光释光信号值减去随后的6~10通道的光释光信号值^[25-26]。光释光生长曲线拟合良好,释光信号未达到饱和,通过内插法获取每个样片的等效剂量(D_e)。

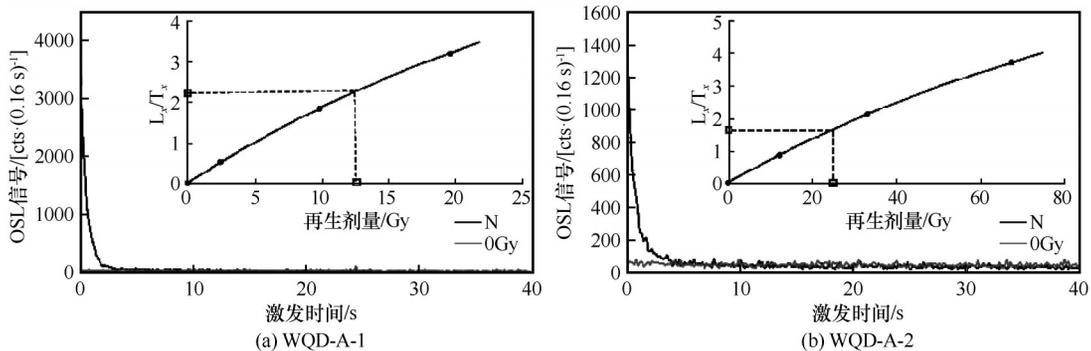


图4 若尔盖唐克黄河岸沃曲东(WQD)剖面部分光释光样品晒褪和生长曲线

Fig. 4 Decay and growth curves of the samples from the WQD profile on the Yellow River bank along the Tangke reach of the Zoige Basin

样品释光信号在最后一次被埋藏前被完全晒褪或者达到可忽略的水平是获得可靠、准确的年代结果的必要前提^[27]。对 WQD-A-1、2、3、4、5 光释光样品等效剂量(D_e)进行统计分析,如图 5 所示。光释光样品的等效剂量(D_e)分布集中,说明样品在最后一次埋藏前释光信号充分晒褪^[28]。样品的等效剂量(D_e)集中,WQD-A-1、2、3、4、5 分别有 66.7%、90%、75%、84.6%、75% 的测片集中在

2σ 置信区间内。前人的研究显示,晒褪彻底的样品,其等效剂量(D_e)与感量变化校正后的光释光信号值的相关性弱^[29]。WQD-A-1、2、3、4、5 样品的等效剂量(D_e)与感量变化校正后的光释光信号值的相关性只有 4.08%、7.90%、4.02%、0.44%、14.45%,两者之间的相关性较低,即样品在最后一次埋藏前信号晒褪彻底,保证了数据结果的准确可靠。

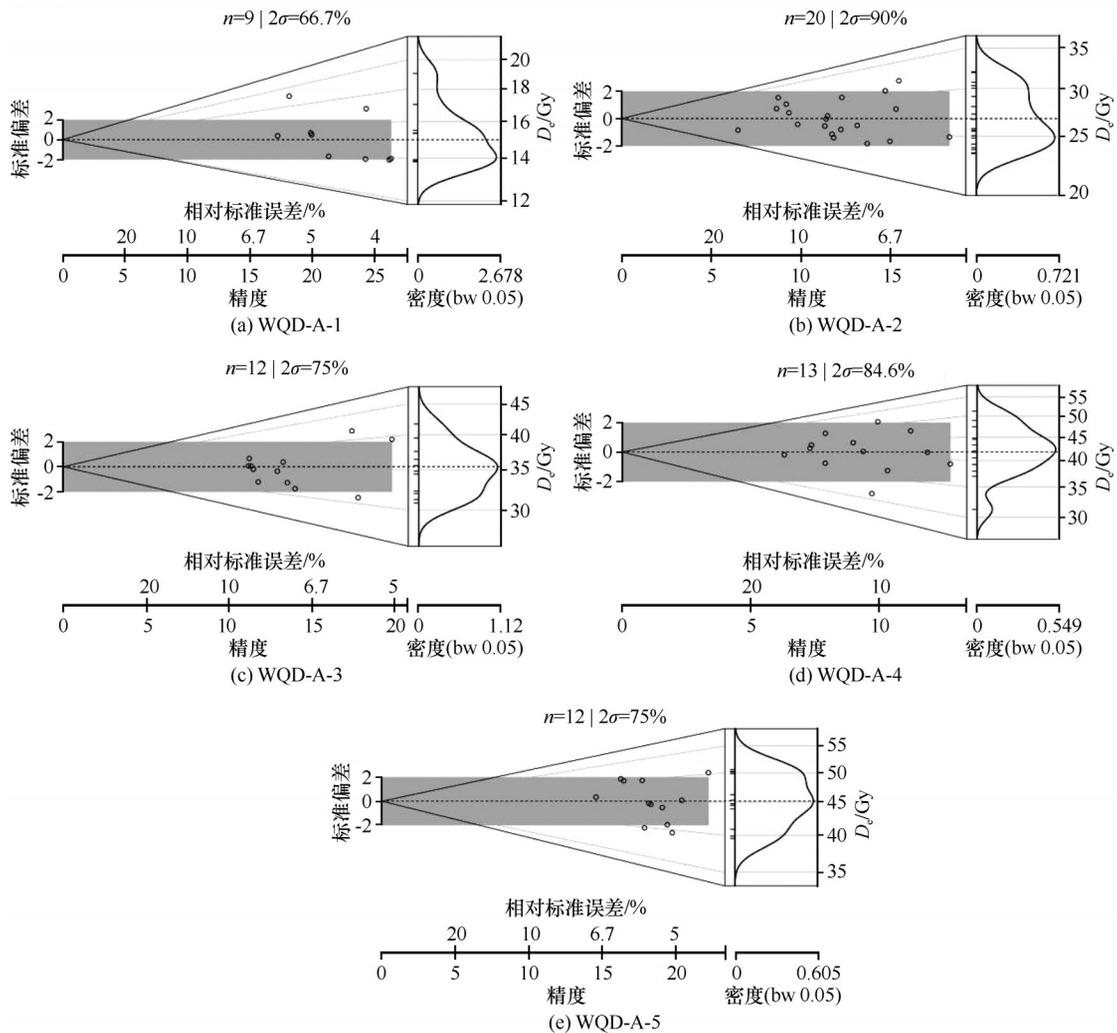


图5 若尔盖唐克黄河岸沃曲东(WQD)剖面光释光样品等效剂量(D_e)分布图

Fig. 5 Equivalent dose (D_e) distribution of OSL samples from the WQD profile on the Yellow River bank along the Tangke reach of the Zoige Basin

3.2 AMS¹⁴C 测年

沼泽草甸古土壤顶界(0.90~0.95 m)、深湖相淤泥顶界(9.95~10.00 m)样品的 AMS¹⁴C 样年龄由南京大学地理与海洋学院 AMS 实验室完成,经由树轮校正曲线校正后^[30],得到日历年龄。

3.3 粒度测试

粒度测试仪器为英国马尔文仪器公司产的

Mastersizer-2000 激光粒度仪,测试粒径范围 0.02~2 000 μm 。先用镊子挑出样品中的树根等杂质;然后根据样品沉积特征称取 0.4~0.9 g;再加入足量的 10% 的盐酸和双氧水彻底去除碳酸盐和有机质;洗至中性;再加入 5 mL 0.05 mol·L⁻¹ 的六偏磷酸钠,用超声波震荡使其充分分散后上机测试。遮光度保持 8%~12% 左右,重复测试三次取其平均值。

4 实验结果

4.1 年代结果与地层年代框架

利用平均年龄模型 (average age model, AAM)、中值年龄模型 (central age model, CAM)、最小值年龄模型 (minimum age model, MAM)^[31]

三种方法,分别得到样品的三种年龄模型等效剂量(D_e)。结果如表2所示,三种模型计算出的等效剂量(D_e)接近,说明样品晒褪彻底。样品的最终等效剂量(D_e)采用均值年龄模型(WAM)的结果,利用DRACv1.2年龄软件^[32]得出样品的光释光年龄。

表2 若尔盖唐克黄河岸沃曲东(WQD)剖面光释光测年数据表

Table 2 OSL age in the WQD profile on the Yellow River bank along the Tangke reach of the Zoige Basin

| 样品编号 | 深度/m | 粒径/ μm | 含水 量/% | U/ $(\mu\text{g}\cdot\text{g}^{-1})$ | Th/ $(\mu\text{g}\cdot\text{g}^{-1})$ | K/% | 环境剂量率/ ($\text{Gy}\cdot\text{ka}^{-1}$) | MAM等效 剂量/Gy | CAM等效 剂量/Gy | AAM等效 剂量/Gy | OSL年龄 (WAM)/ka |
|---------|-----------|-------------------|-----------|--------------------------------------|---------------------------------------|-----------|--|----------------|----------------|----------------|-------------------|
| WQD-A-1 | 1.35~1.40 | 63~90 | 22±3 | 2.06±0.3 | 12.60±0.7 | 2.15±0.04 | 3.11±0.08 | 13.38±1.29 | 15.02±0.89 | 14.96±0.23 | 4.81±0.15 |
| WQD-A-2 | 3.95~4.00 | 63~90 | 23±3 | 1.68±0.3 | 8.67±0.6 | 1.69±0.04 | 2.27±0.07 | 26.77±0.49 | 26.81±0.64 | 26.63±1.28 | 11.75±0.43 |
| WQD-A-3 | 8.00~8.05 | 63~90 | 23±3 | 1.78±0.3 | 9.21±0.6 | 1.81±0.04 | 2.41±0.07 | 35.07±2.03 | 35.11±1.06 | 35.38±0.72 | 14.66±0.54 |
| WQD-A-4 | 9.65~9.70 | 63~90 | 24±3 | 1.54±0.3 | 7.69±0.6 | 2.11±0.04 | 2.49±0.07 | 41.81±2.66 | 41.78±1.54 | 42.70±1.22 | 16.76±0.68 |
| WQD-A-5 | 9.80~9.85 | 63~90 | 24±3 | 1.52±0.3 | 7.63±0.6 | 2.10±0.04 | 2.49±0.07 | 45.15±2.95 | 45.14±1.68 | 45.36±0.71 | 18.22±0.99 |

根据光释光和AMS¹⁴C测年结果以及各地层特征绘制地层柱状图和年龄-深度曲线图(图6)。沉积序列由下向上年龄逐渐减小,无倒置现象,符合沉积学规律。古土壤顶界和蓝灰色古湖泥顶界的AMS¹⁴C年龄分别为(1.78±0.05) cal ka BP、(30.98±0.13) cal ka BP。光释光测年结果显示古土壤底界的年龄为(4.81±0.15) ka,褶皱沙层顶界的年龄为(11.75±0.43) ka,褶皱河漫滩-风沙层顶

界、底部、底界的年龄分别为(14.66±0.54) ka、(16.76±0.68) ka、(18.22±0.99) ka。依据褶皱沙层顶界和褶皱河漫滩-风沙层顶界年龄计算,3.95~8.00 m沙层的平均沉积速率为1.39 m·ka⁻¹,则滨浅湖相沙层顶界对应年龄为12.50 ka。通过建立WQD剖面年龄-深度关系曲线,获得沉积物序列年代框架如下(图7):在30.9 ka之前为蓝灰色淤泥沉积,18.2~14.6 ka形成冻融褶皱河漫滩-风沙层,

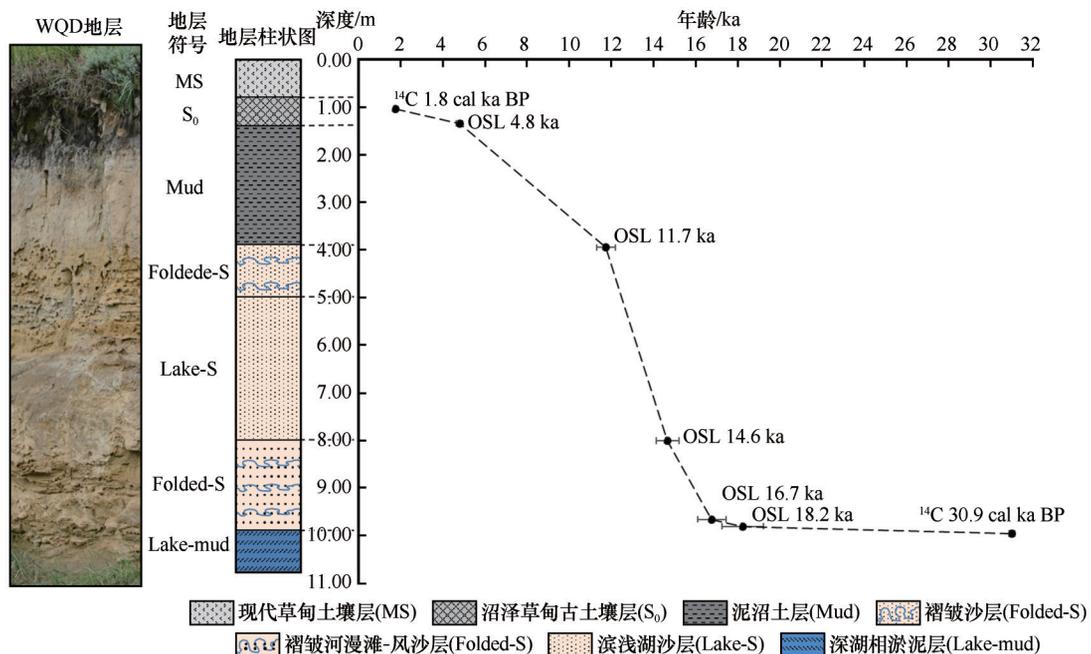


图6 若尔盖唐克黄河岸沃曲东(WQD)剖面地层柱状图与年龄-深度关系图

Fig. 6 Stratigraphy and the age-depth relationship in the WQD profile on the Yellow River bank along the Tangke reach of the Zoige Basin

14.6~12.5 ka 形成滨浅湖沙层, 12.5~11.7 ka 形成冻融作用与古地震扰动形成的复式褶皱沙层。11.7~4.8 ka 发育泥沼土层, 4.8~1.8 ka 形成沼泽泥炭古土壤层, 1.8 ka 之后发育现代草甸土壤层。

4.2 沉积物粒度特征

沉积物粒度可以反映其沉积环境、搬运动力及物质来源等重要信息^[33-35]。根据粒度测试结果绘制粒度自然频率分布曲线和谢帕德三角分类图(图7), 结果显示。蓝灰色古湖泥层粒度频率曲线在细粉沙 6 μm 和粗粉沙 55 μm 附近各有一个峰

值, 属于黏土质粉沙。褶皱河漫滩风沙层峰值为 230 μm , 有明显细尾, 属于沙。滨浅湖沙层粒度频率曲线为多峰分布, 主峰 100 μm , 次峰在 230 μm 附近与褶皱沙主峰接近, 属于粉沙质沙。褶皱沙层粒度频率曲线主峰介于 100~200 μm 之间, 并有小粗尾。泥沼土层和沼泽草甸古土壤层粒度曲线都为双峰分布, 主峰介于 40~50 μm 之间, 次峰介于 7~16 μm , 属于沙质粉沙。现代草甸土壤层粒度曲线峰值在 70 μm 附近, 有明显细尾, 为粉沙质沙。

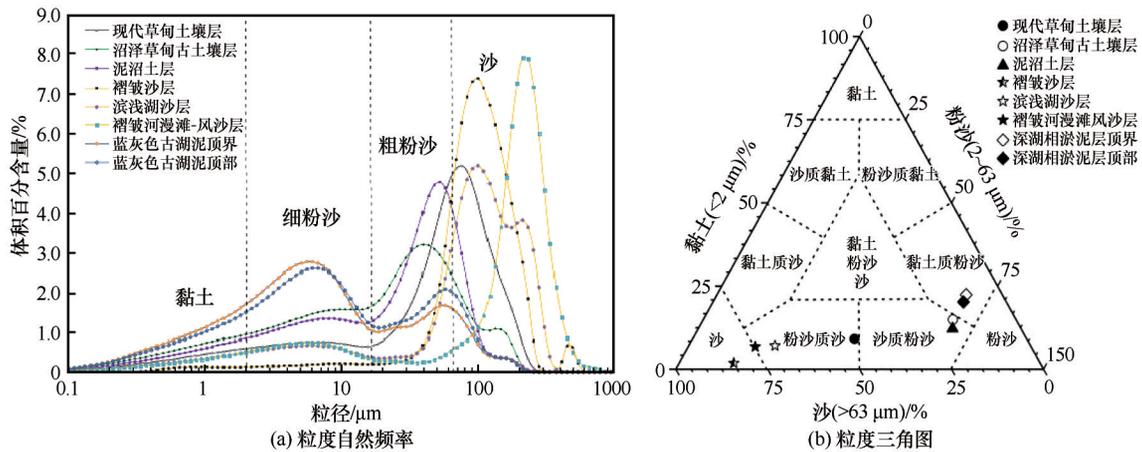


图7 若尔盖唐克黄河岸沃曲东(WQD)剖面沉积物粒度自然频率曲线图和粒度三角图

Fig. 7 Sediment grain-size distribution in the WQD profile on the Yellow River bank along the Tangke reach of the Zoige Basin

5 讨论

本课题组在玛曲县城西南部黄河流出盆地瓶颈段欧强村黄河左岸第二级阶地剖面, 发现古滨浅湖相沉积物顶界埋深为 9.5 m, 蓝灰色古湖泥顶界埋深 10.0 m, 其 OSL 年龄分别为 35 ka 和 37 ka^[36]。在盆地内部索克藏寺以北黄河右岸甲央玛发现蓝灰色古湖泥埋深 9.6 m。其顶部 OSL 年龄为 35 ka。本次在若尔盖盆地内部唐克段沃曲东剖面(WQD)发现蓝灰色湖相淤泥层埋深 9.9 m, 其顶界 ¹⁴C 校正年龄为 30.9 ka。按照前人的研究成果, 若尔盖盆地在被黄河贯通之前曾长期维持着古湖泊环境, 沉积了青灰色古湖相淤泥质沉积物, 盆地北部黑河牧场 RH 孔古湖相地层顶部年龄为 37.6 ka^[4]。由此可知, 古黄河沿着玛曲-欧拉断陷谷地溯源侵蚀, 在 37 ka 时期切断了欧拉-玛曲县城之间的低矮分水岭, 沟通了若尔盖盆地古湖, 导致湖水泄流。这样, 若尔盖古湖水系就转变为现在的黄河源水系。而盆地内部洼地在 30.9 ka 之前是仍然是古湖泊环境,

说明黄河从溯源侵蚀沟通若尔盖湖盆水系, 到彻底贯通湖盆内部, 导致唐克区域洼地古湖水完全消失, 经历了 6 000 多年时间。在时间上对应深海气候记录 MIS3 中晚期(图 8), 夏季太阳辐射异常增强, 可能由于暖湿夏季风深入, 亚洲中部地区有效湿度增强^[37-38]。该时期青藏高原地区暖湿程度明显超过现代, 众多高原湖泊属于扩张期, 古湖水位大幅度上升, 被称为青藏高原“大湖期”^[39-42]。如青海湖最高湖岸形成于 38 ka 左右, 在 33.8~23.6 ka 多次经历湖泊扩张; 察尔汗盐湖经历多次扩张过程^[43-44]。所以若尔盖盆地内部唐克段黄河岸剖面底部的蓝灰色古湖泥, 正是形成在这种气候温暖湿润, 古湖扩张时期。其沉积物质地细腻, 分选性良好, 伴有臭鸡蛋气味, 其中丰富的有机质长期处于水下封闭还原环境, 分解过程生成大量 H₂S 气体, 也表明这是在深湖环境中稳定沉积形成。

在黄河唐克段 WQD 剖面底部蓝灰色深湖相淤泥层被褶皱的浊黄橙色河漫滩-风沙层覆盖。这个

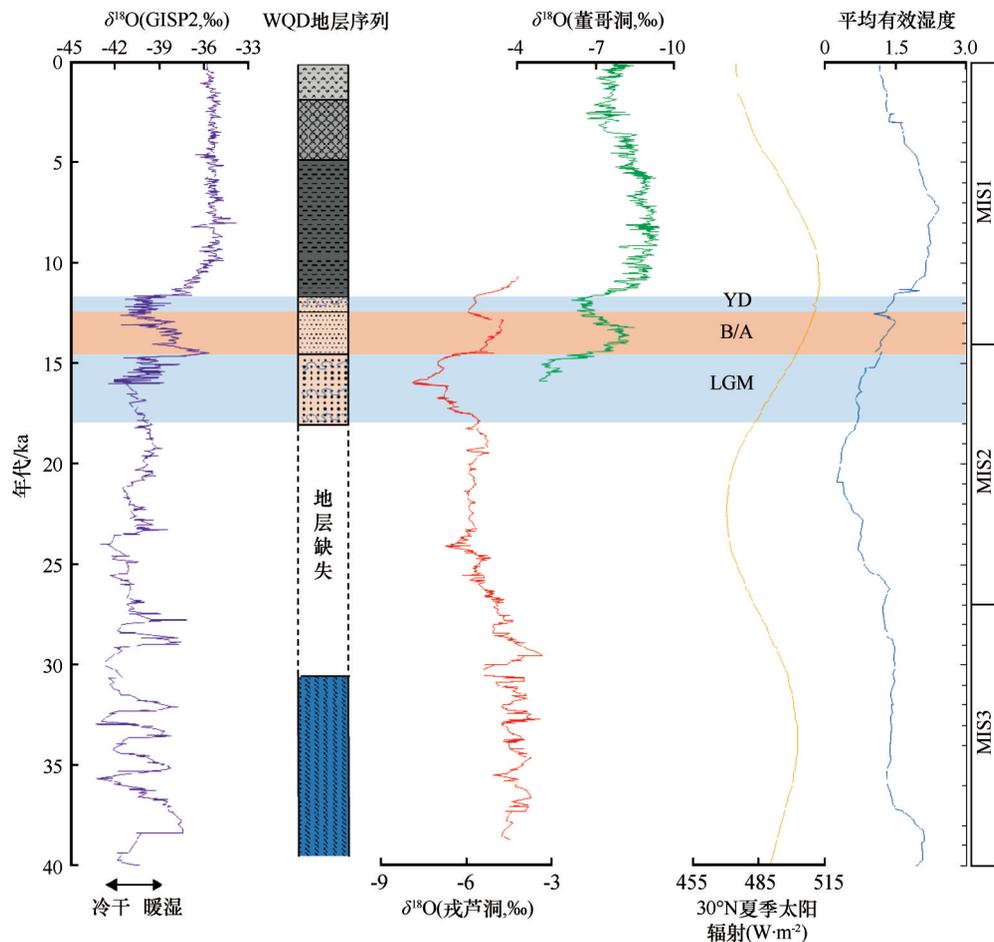


图8 若尔盖唐克沃曲东(WQD)剖面(图例见图6)及其与格陵兰 GISP2 冰芯 $\delta^{18}\text{O}$ 曲线^[45]、南京葫芦洞石笋 $\delta^{18}\text{O}$ 曲线^[46]、贵州董哥洞石笋 $\delta^{18}\text{O}$ 曲线^[47]北纬 30°N 夏季太阳辐射强度曲线^[37]和亚洲中部平均有效湿度^[38]对比图

Fig. 8 The WQD profile (The legend of the WQD stratigraphy is the same as that in Fig. 6) and its correlation with Greenland GISP2 ice core $\delta^{18}\text{O}$ ^[45]; stalagmite $\delta^{18}\text{O}$ in Hulu Cave, Nanjing^[46]; stalagmite $\delta^{18}\text{O}$ in Dongge Cave, Guizhou^[47]; 30°N summer solar radiation intensity^[37]; and Average effective humidity in central Asia^[38]

覆盖层底界的 OSL 测年结果为 18.2 ka, 与古湖泥的年龄差异距大, 表明两者之间存在地层缺失, 为不整合接触关系。这可能黄河在贯通盆地过程当中, 普遍的溯源侵蚀下切作用造成的。前人在索克藏寺以北杂威黄河岸剖面下部河漫滩沙层中发现披毛犀化石, 其 ^{14}C 年龄为 22.6 ka, 黑河下游黄河岸剖面出土的原始牛化石, 其 ^{14}C 年龄为 26.6 ka^[7]。这说明在此期间黄河在盆地之内溯源侵蚀, 古湖水外泄消失, 黄河古河道逐渐形成。在这个时期盆地内部曾经发生黄河洪水泛滥的事件^[13] 这个过程可能造成了唐克段 WQD 剖面在 30.9~18.2 ka 之间沉积物缺失, 形成了两个地层单元之间的不整合。

这种褶皱的河漫滩-风沙层覆盖层, 形成年龄为 18.2~14.6 ka, 是黄河上溯穿过若尔盖盆地之后, 从黄河源远距离搬运来的的浊黄橙色泥沙在古湖盆地面堆积的产物, 具有河漫滩沉积物的特点, 同

时又受到强烈的风沙活动改造成为河漫滩-风沙层。这时正处于深海沉积气候记录 MIS-2 阶段(图 8), 也就是末次冰盛期(LGM), 该时期 30°N 太阳辐射减弱、有效湿度下降, 格陵兰 GISP2 冰芯记录、葫芦洞石笋 $\delta^{18}\text{O}$ 记录均显示气候寒冷干旱^[37-38, 45-46]。根据前人研究, 末次冰盛期(LGM)青藏高原降温显著, 平均温度比现代低 7°C , 东北部冰川舌下伸到海拔 3 800 m, 东北部多年冻土下限降至海拔 2 200~2 400 m, 东部的横断山系与昆仑山区冰川规模比现代冰川规模大 45~145 倍^[48-51]。当时若尔盖盆地玛曲降温幅度超过 10°C , 气候寒冷, 冰楔假型、冻融褶皱等冰缘地貌广泛发育^[50]。冻融褶皱是多年冻土区土体反复冻融及蠕变, 其中含水层与隔水层产生冻胀差异, 使土体产生塑性变形, 冻融褶皱现象是多年冻土区的标志^[52-53]。另据前人研究, 该时期气候冷干, 风力强大, 区域风沙活动强烈^[54]。在 WQD

剖面褶皱的河漫滩-风沙层之中,有显著的冻融褶皱现象[图2(b)],说明末次冰盛期若尔盖盆地处于冰缘环境中,气候极其寒冷,黄河从源区搬运来的浊黄橙色沙在两岸河漫滩普遍堆积,被风力改造的同时,也受到冻融作用的影响与改造。

在WQD剖面具有薄层水平-波状层理的滨浅湖相细沙层,堆积形成在14.6~12.5 ka。此时处于Bølling-Allerød(B/A)温暖期^[42,55],北半球气候明显暖湿,温度快速上升(图8)。该时期北半球气候明显暖湿,温度快速上升。董哥洞和葫芦洞石笋、格陵兰GISP2冰芯记录显示气候明显温暖湿润,温度快速上升,降水量逐渐增加^[45-47,56](图8)。据前人研究,B/A温暖期青藏高原众多封闭湖泊因为降水量增多及冰川融水补给增加而进入扩张期,茶卡湖、色林错、龙木错、白硷湖、贝里克库勒湖、青海湖出现40 ka以来的次高湖面,尕斯库勒湖由沙漠环境向湖泊环境转变^[57-59]。若尔盖盆地气候回暖,温度在短时间快速上升,周围山地冰川对温度变化敏感,冰川融化,形成大量冰融水汇入盆地,降水和冰融水在低洼地积聚形成大小浅湖。结合卫星影像图的分析,可知此时黄河唐克段河道尚在左岸远处蜿蜒曲折地流动,黄河右岸阿尔则乔干洼地积水扩张成为浅湖,而WQD剖面所在地就处于其滨浅湖环境,沉积了具有密集的薄层水平-波状层理的细沙层。根据盆地南部的瓦切乡瓦松和日干桥泥炭沼泽剖面的研究,这个时期的浅湖环境大致在12.6 ka前后结束,湖相沉积层中发现介形类化石,当时盆地内气候环境温暖适宜^[8,59]。这个时期盆地周边高山冰川融水及降水量的增加,致使黄河发生大洪水,本课题组在唐克索克藏寺北侧甲央玛黄河岸剖面 and 玛曲断陷谷地达尔琼-太吾若河段曾经发现了这个时期的典型的古洪水沉积层^[11,13]。

在唐克段WQD剖面在12.5~11.7 ka堆积形成具有冻融与古地震扰动的复杂的复式褶皱沙层。这个时期正处于全球性新仙女木事件(YD)^[60-61],根据洞穴石笋、极地冰芯氧同位素等记录(图8),亚洲季风-西风带YD发生在12.9~11.7 ka,是因为北冰洋浮冰和大量冰融水注入北大西洋导致全球气温突发性显著降低,造成冰期气候回返^[62-63]。此时青藏高原东部降温幅度达到12℃以上,冰川舌下伸到海拔4 000 m,多年冻土下界高程比现代降低800 m^[64]。若尔盖盆地内的红原二矿泥炭剖面、黑河牧场DC剖面记录的 $\delta^{13}\text{C}$ 浓度突然下降、H指数近

于零、介形类突然消亡等,皆指示新仙女木事件导致气候急剧变冷^[65-66]。同时,根据在玛曲县城附近针对东昆仑大断裂活动进行的深入研究,发现在12.2 ka曾经发生大地震,导致被风成黄土覆盖的古冰水扇-洪积扇地面破裂,并且被后来的沉积物和土壤层深埋在地下深处^[67]。在WQD剖面发现的这层复杂的复式褶皱细沙层[图2(c)],其形态特征完全可以与死海西岸剖面的震积岩层相比拟^[68],故而认为其是受到YD时期冻融作用扰动,再加上古地震波冲击扰动所形成的特殊现象。

在黄河唐克段WQD剖面中上部的泥沼土层的OSL测年结果为11.7~4.8 ka,表明在全新世早中期该区域地表转变为淤泥质沼泽环境。早中全新世太阳辐射增强,亚洲夏季风增强及其携带的降水丰富,高分辨率孢粉记录重建的全新世气候环境显示暖湿条件优于现代环境^[69]。青海湖在此时出现高湖面、湖水盐度下降^[70],古里雅冰芯^[71]、董哥洞等 $\delta^{18}\text{O}$ 曲线^[47]均显示温暖气候(图8)。若尔盖盆地底部地形表现为丘陵洼地,在气候湿润时期地表洼地积水,就会形成淤泥质沼泽或者泥炭质沼泽。在WQD剖面泥沼土层厚达2.5 m,为浊黄橙色粉沙,块状构造,无层理,多植物根孔,并有潜育化作用形成的灰白、灰绿、锈黄色斑。若尔盖盆地南部瓦切沼泽日干桥剖面记录显示其沼泽从12.0 ka开始发育形成^[72],与唐克地区淤泥质沼泽基本对应。在这个时期红原地区洼地沼泽泥炭积累速率最快^[72-73]。看来这应当是阿尔则乔干洼地积水沼泽扩张,影响到了WQD所在地区。

到了全新世中后期,OSL年龄4.8~1.8 ka,在WQD地区的淤泥质沼泽结束长期发育,转变为泥炭质沼泽,因此堆积形成了沼泽草甸黑土类古土壤。董哥洞石笋 $\delta^{18}\text{O}$ 气候记录显示从6.0 ka左右开始(图8)夏季风逐渐衰退,气候暖湿程度减弱^[47]。若尔盖红原泥炭地纤维素 $\delta^{13}\text{C}$ 升高、 $\delta^{18}\text{O}$ 数值降低,泥炭积累速率减小^[74-76]。这表明盆地内部在全新世中晚期温度下降明显,洼地沼泽植物残体不能完全分解,而快速积累泥炭黑土类古土壤。

在WQD剖面最顶部覆盖现代亚高山草甸黑土类土壤,是在1.8 ka之后发育形成。这类土壤在若尔盖黄河两岸高台地、冰水扇-洪积扇台地和基岩山丘坡麓台地地面分布广泛,皆为3.0 ka之后全新世晚期沙尘暴堆积物经过成壤改造而成^[13]。这类土壤在湿润时呈黑棕色,质地为细沙质粉沙或者粉

沙质细沙,疏松多孔,团粒构造,植物根系密集,成熟度很高。全新世晚期,若尔盖盆地风力强劲,风沙及沙尘暴过程很活跃^[77-79]。黄河河漫滩沙之沉积物受到风力改造成为风沙层,黄河两岸各种台地高地则主要接受沙尘暴沉积物,被成壤改造形成亚高山草甸黑土类现代土壤。

6 结论

本文研究了若尔盖盆地内部黄河右岸唐克段土壤沉积物地层,从下至上地层依次发育:深湖相蓝灰色淤泥层(Lake-mud)→褶皱河漫滩-风沙层(Folded-S)→滨浅湖沙层(Lake-S)→褶皱沙层(Folded-S)→泥沼土层(Mud)→沼泽草甸古土壤层(S₀)→现代草甸土壤层(MS)。该剖面反映在30.9 ka之前若尔盖盆地内部仍然维持着深湖环境,在30.9 ka之后黄河则彻底贯通若尔盖盆地,古湖水彻底的外泄消失,黄河在古湖盆底部切割形成了新的河槽,并且从盆地上游搬运来大量灰黄色泥沙,在宽广的古湖底散布堆积。

在末次冰盛期、B/A温暖期和新仙女木事件中,沉积了厚层的松散的浊黄橙色沙层。这种物质最初是由黄河从盆地上游流域搬运而来,在盆地之内宽广的河漫滩或者洼地分散浅湖水体中沉积,并且受到末次冰盛期和YD事件中冰缘冻土作用的改造,形成了冻融褶皱构造。全新世早中期(11.7~4.8 ka),气候逐渐变得温暖湿润,唐克地区古湖底洼地形成淤泥质沼泽环境。到了全新世中晚期(4.8~1.8 ka),气候暖湿程度明显减弱,转变为泥炭沼泽草甸环境。进入全新世晚期以来(1.8 ka至今),盆地内部洼地变得干燥,泥炭沼泽显著缩小或者消失,高原风力强劲,黄河河漫滩沙受到风力改造成为沙丘或者斑状沙地,黄河河岸台地沙尘暴堆积物被改造形成亚高山草甸黑土类现代土壤。

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Chronology of the sedimentary sequence and the changes in surface processes along the Tangke reach of the Yellow River in the Zoige Basin

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Abstract: The research in this paper mainly focuses on the banks of the Tangke section of the Yellow River in the Zoige Basin, and studies the natural sedimentary profiles directly exposed by the lower cut of the Yellow River. The purpose is to establish the stratigraphic sequence and age frame of soil sediments, and to deeply explore the upstream erosion of the Yellow River into the interior of the Zoige Basin. The characteristics of regional surface process changes during the process provide chronological and stratigraphic evidence for the Yellow River running through the Zoige Basin. Through field investigation of the Zoige Basin, a sequence of riparian soil sediments containing deep lacustrine sediments was found on the right bank of the Tangke section of the Yellow River in the middle of the basin, and in-depth observations and systematic sampling were carried out. In the laboratory, the chronological framework was established by using the optical luminescence and AMS¹⁴C dating tech-

niques. Combined with the macroscopic characteristics and physicochemical properties of soil sedimentary facies at various levels, the environment and surface processes were thoroughly analyzed and discussed in the Zoige Basin since the demise of the last glacial paleolake. The research results show that the ancient Yellow River eroded headward along the Maqu rift valley at 37 ka, which connected the Zoige ancient lake water system, while the interior of the basin was a deep lake environment before 30.9 ka, and a blue-gray lacustrine silt layer was deposited stably. After 30.9 ka, the Yellow River penetrated through the interior of the Zoige Lake Basin, the ancient lake water leaked out and disappeared, and the original ancient lake water system was completely transformed into the Yellow River source water system. A large amount of turbid yellow-orange sediment carried by the Yellow River from the upper reaches of the lake basin was deposited in large quantities, covering the paleolacustrine sediment, and aeolian sand action prevailed in the lake basin. During the Last Glacial Maximum (LGM), the loose sediments in the basin were generally transformed by the freezing and thawing of the periglacial environment, forming freeze-thaw folds. From 14.6 to 12.5 ka, in response to the warm climate in the Bølling-Allerød (B/A) period, the mountain glaciers around the basin melted and melted water flowed into the basin. Various shallow depressions at the bottom of the ancient lake basin formed shallow lakes of different sizes. Sand layers of littoral-shallow lacustrine facies were deposited. From 12.5 to 11.7 ka, corresponding to the global Younger Dryas (YD) event, the climate became cold again and transformed into a permafrost environment in the basin. Paleo-earthquake disturbances have formed complex double-fold folds. In the Holocene, the climate gradually became warm and humid from 11.7 to 4.8 ka, and the shallow depression at the bottom of the ancient lake basin became a silty swamp environment, and a muddy soil layer was developed. In the middle and late Holocene 4.8~1.8 ka, it transformed into a swamp meadow environment and developed swamp meadow black soil paleosols. After 1.8 ka, the marshes in the basin shrank, aeolian sand activities prevailed, the floodplain sand was transformed into sand dunes by wind, and the near-source sandstorm sediments in the riparian highlands were transformed into subalpine meadow black soil modern soils by pedogenesis.

Key words: Zoige Basin; stratigraphic sequence; freeze-thaw folds; seismogenic deposits; OSL dating

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