Research Article

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Features of terraces and the incision rate along the lower reaches of the Yarlung Zangbo River east of Namche Barwa: Constraints on tectonic uplift

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Abstract: Along the lower reaches of the Yarlung Zangbo River, scattered alluvium sections appear on *T1* and *T2* terraces. The alluvial deposits on the *T1* terrace in Linduo and Ximogou and the *T2* terrace in Guogutang are composed principally of coarse-grained sand particles and rock fragments, with no observable fine-grained components. The *T1* terrace alluvium section is dominated by clay and silt and occurs near the town of Dexing, and optically stimulated luminescence dating of sample from this site revealed an age of 18.2 kyear, which indicates that the incision rate of the Yarlung Zangbo River has been 4.7 mm/year since the formation of this section. On the basis of the component characteristics of terraces in Motuo County, the provenance for the terraces is probably related to the breaking of the palaeo-dammed lakes in the middle reaches of the Yarlung Zangbo River. A 430 m elevation difference still exists between the study area and the local base level downstream of the Yalung Zangbo River (Assam Plain), although this river has a strong incision capability (4.7 mm/year), which suggests that tectonic uplift remains very intense east of the Namche Barwa syntaxis.

Keywords: lower reaches of the Yarlung Zangbo River, terrace, optically stimulated luminescence age, incision rate, tectonic uplift

1 Introduction

The Yarlung Zangbo River drains the southern Tibetan Plateau, and on either side of the river, the interplay between tectonics and climate is exceedingly intense. Thus, this area is an ideal field laboratory for exploring such interactions [1–4]. The terraces along the valley of the Yarlung Zangbo River reflect its intense incision, which lowers the valley bottom level and is related to the regional tectonic movement and climate. Research on this topic has been limited to the upper reaches of the Great Bend knickzone on the river. For example, Zhu (2012) performed a detailed analysis of the characteristics of multiple terraces in the middle reaches of the Yarlung Zangbo River from the city of Shigatse to Milin County and determined the incision rate of this section by dating the multilevel terraces in the town of Gemuding to different time periods [5]. The ravines on both sides of the lower reaches along the Yarlung Zangbo River are well-developed and full of water, with powerful hydrodynamics, causing considerable erosion of terraces along the lower reaches of the river and limiting the preservation of these terraces. Researchers have not thoroughly documented the characteristics of terraces in the lower reaches of the river, and terrace age data are limited.

This study, which is based on detailed field surveys of the lower reaches of the Yarlung Zangbo River, examined the characteristics of river terraces near the following locations: Linduo, Ximogou, Guogutang, and the town of Dexing. Using optically stimulated luminescence (OSL) dating, the age of a terrace located near Dexing was determined. The results are helpful for exploring the genesis and evolution of terraces along the lower reaches of the Yarlung Zangbo River as well as the current tectonic uplift on the east side of the Namche Barwa syntaxis.

2 Methods

2.1 Field observations

The eastern Yarlung Zangbo River drains from Gemuding in Jiacha County and flows eastward through Langxian,

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Figure 1: Distribution of the eastern Yarlung Zangbo River and main branches. NB: Namche Barwa peak. The black box delineates the study area. Red triangle marks the location of the terrace near Gemuding [5]. Digital elevation model (DEM) data were downloaded from <http://www.gscloud.cn/>, and the figure was generated using ArcGIS 10.0 software (<http://www.esrichina.com.cn/softwareproduct/ArcGIS/>).

Milin, and Pai to Namche Barwa peak, which is at the eastern end of the Himalayas. The river then turns 180°, flows southward through Motuo across the China-Indo border, and empties into the Brahmaputra River. The study area is located in the lower reaches of the river (Figure 1).

Field observations indicate that some cross-sections of terraces are exposed sporadically along the two sides of the Yarlung Zangbo River from Linduo downstream from the Great Bend to the village of Yarang, southwest of Motuo. The terrace surfaces have been markedly destroyed or covered by pluvial layers due to intense erosion. This work examined the following four localities to describe the characteristics of the terraces along the river: (1) Linduo, (2) Ximogou, (3) Guogutang, and (4) the town of Dexing (west of the river) (Figure 2).

2.2 Chronology

The OSL samples were collected in opaque stainless steel tubes (length, 15–20 cm; diameter, 6 cm). Both ends of each tube were immediately sealed with aluminium foil and taped after sample collection to prevent light leakage and water loss during transport and storage. The samples were extracted from the inner part of the tubes, and

Figure 2: Map showing the locations of the terrace cross-sections in the study area. DEM data were downloaded from <http://www.gscloud.cn/>, and the figure was generated using ArcGIS 10.0 software (<http://www.esrichina.com.cn/softwareproduct/ArcGIS/>).

Figure 3: Terrace section at Linduo and its layering structure. (a) Bed of greyish white rock fragments and coarse sand with few medium-to fine-grained sand particles. (b) Greyish white rock fragment bed with fragment sizes of up to 10 cm and no rounding or rhythmic structure. (c) Gravel bed with no rounding and thicknesses of up to 0.5 m, with lenses at the bottom and top. (d) Gravel bed with no rounding and a maximum thickness of 0.5 m, with greyish clay and fine sand particles as well as plant root systems. The red star shows the location of the OSL sample.

quartz was purified using coarse conventional quartz sample preparation techniques (sieving 180–250 μm grains, treating with 10% HCl and 40% H_2O_2 , etching with 40% HF, and then immersing in 10% HCl). The purity of the quartz extracts was confirmed by the absence of infrared stimulated luminescence (IRSL) signals. The subsamples showed infrared (IR) signals close to the background levels, with an IR-OSL depletion ratio between 0.9 and 1.1. Nevertheless, an IR-OSL depletion test was conducted on every aliquot for small aliquots of coarse quartz [6].

All equivalent dose (De) values of the samples were measured using a Risø TL/OSL Reader model DA-20 equipped with a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ beta radiation source (the dose rate for coarse quartz is 0.1125 Gy/s in the standard configuration), a blue light source ($470 \pm 30 \text{ nm}$; $\sim 50 \text{ mW/cm}^2$), and an infrared light source ($880 \pm 40 \text{ nm}$, $\sim 145 \text{ mW/cm}^2$) and detected through a 7 mm thick U-340 glass filter.

3 Results

3.1 Features of terraces

3.1.1 Linduo terrace

The Linduo (LD) terrace alluvium section outcrops at the end of the Great Bend knickzone, where only T1 terrace alluvium is present. The terrace section is 20 m high and composed of coarse sand particles and rock fragments without fine-grained components (Figure 3). The underlying bedrock is high Himalaya gneiss. The top of the terrace is covered by pluvial layers (layers c and d in Figure 3). On the basis of the elevation curve across the Yarlung Zangbo River (Figure 4a), the top of the terrace alluvium section has an elevation of 908 m above sea level (a.s.l.), and the height of the terrace to the water

Figure 4: Three profiles (a), (b) and (c) across the Yarlung Zangbo River valley showing the terraces at the four localities. The locations of the three cross-sections are shown in Figure 2. Red crosses indicate the locations of the terrace exposures. LD, XMG, DX, and GGT represent the sites of the terrace exposure.

level of the river is 89 m. The level noticeably changes at an elevation of 900 m, which probably represents the original terrace (T1 in Figure 4a).

3.1.2 Ximogou terrace

This terrace section outcrops near Ximogou (XMG) northeast of Motuo County and has a thickness of approximately 4 m. It is principally composed of coarse-grained sand particles and poorly rounded rock fragments, with minimum content of clay. Its upper part consists of an accumulation of pluvial layers dominated by gravel (layers b, c, and d in Figure 5). From the elevation curve, the top of the terrace alluvium section has an elevation of 778 m (a.s.l.), and the height of terrace above the water level of the Yarlung Zangbo River is 42 m (T1 in Figure 4b).

Figure 5: Ximogou terrace section and its layering structure.

(a) Greyish white medium- to coarse-grained sand particles intercalated with poorly rounded rock fragments that have a maximum grain size of approximately 10 cm. (b) Dominated by medium- to coarse-grained sand particles with yellow clay and approximately 20% poorly rounded rock fragments. (c) Gravel bed gravels with no rounding, variable sizes, and a few coarse-grained sand particles and clay. (d) Yellow clay bed with limited gravel. The red star shows the location of the OSL sample.

3.1.3 Guogutang terrace

The Yarlung Zangbo River turns abruptly from the southwest to the northwest near Motuo County and then turns

Figure 6: Guogutang terrace section and its layering structure.

(a) Grey medium- to coarse sand bed that is intercalated with rock fragments, has a sedimentary rhythm, and presents poorly rounded and weakly cemented rock fragments with a maximum fragment size of 1.5 cm. (b) Medium- to fine-grained sand bed containing an approximately 3 cm thick gravel bed with moderately rounded rock fragments that show rhythmic layering and minimal grey clay. (c) Rock fragment bed with coarse-grained sand particles and poorly rounded rock fragments of up to 5 cm in diameter and the observed layering structure. (d) Medium- to coarse-grained sand bed with a few rock fragments; the angle with respect to the sand bed was 30° to 45°. (e) Medium- to fine-grained sand bed showing uniformly distributed detritus at the bottom and discontinuous detritus in the upper portion and poorly rounded grains intercalated by yellow clay. (f) Greyish white coarse-grained rock fragment bed with moderately to poorly rounded grains with a size of 4 cm and somewhat rhythmic layering and a 2 cm thick yellow clay bed that is sporadically distributed and weakly cemented. (g) Medium- to coarse-grained sand bed with interbedded gravel that is irregularly distributed and lacking obvious layering, with poorly rounded and weakly cemented rock fragments. The top is yellow clay, and fine-grained sand beds are irregularly distributed. (h) Boulder bed that is poorly rounded, subangular, and unsorted with yellow clay and greyish black medium-grained sand particles. (i) Yellow clay bed with a few gravels with medium rounding that are unevenly distributed and composed of granite. (j) Black cultivation soil. The red star shows the location of the OSL sample.

sharply towards the southwest, forming the Guoguantang bend (Figure 2). The Guoguantang terrace (GGT) section outcrops southwest of the Guoguantang bend over a relatively large area and has a thickness of approximately 7 m. Overall, this section consists of greyish white-grey coarse-grained sand particles and gravels with poor to medium rounding which are intercalated with yellow clay bands (Figure 6). The top of the terrace section is covered by pluvial layers that consist of clay-bearing gravel beds (layers h–i in Figure 6). On the basis of the elevation of the Guoguantang bend, this section should be a T2 terrace. The top of the terrace alluvium has an elevation of 867 m (a.s.l.) and is 197 m above the water level of the Yarlung Zangbo River (T2 in Figure 4c).

3.1.4 Dexing terrace

This terrace (DX) section is exposed near the town of Dexing northeast of the Guoguantang bend with a thickness of 6 m. It is composed of steel grey silt and brownish red clay (Figure 7), with an upper portion of gravel-dominant pluvial layers (c and d layers in Figure 7). The elevation profile suggests that this is a T1 terrace where the landform has changed considerably. The top of the terrace alluvium section has an elevation of 806 m (a.s.l.) and is 92 m above the water level of the Yarlung Zangbo River (T1 in Figure 4c).

Figure 7: Terrace section from the town of Dexing and its layering structure. (a) Steel grey fine-grained sand and silt bed that has massive yellow clay and is weakly cemented without obvious layering. (b) Brownish red clay bed that is highly consolidated without obvious layering. (c) Gravel bed that contains yellow clay and is loosely packed. (d) Black organic soil with gravel and plant root systems. The red star shows the location of the OSL sample.

Figure 8: Kernel density estimate (KDE) plot of the small-aliquot De value for sample dx (n : accepted aliquots; N : total aliquots measured).

3.2 Chronology of the terraces and the incision rate of the lower reaches of the Yarlung Zangbo River

Four samples (ld, xm, ggt, and dx) were processed. Samples ld, xm, and ggt mainly contain rock fragments and coarse or medium sand, and sample dx is composed of fine-grained sand. According to the composition of the samples, only sample dx has an adequate amount of pure quartz; therefore, the OSL signal was measured for only this sample (Figure 8).

The evaluation indicated an age of 18.2 ± 3.1 kyear as the minimum age model. In combination with the height of the sample (dx) above the water level of the Yarlung Zangbo River, the river has had an incision rate of 4.7 mm/year in this area since 18.2 kyear ago.

4 Discussion

Climate change or tectonic uplift is the main controlling factor for river terrace development [7–9]. Climate change determines river hydrodynamic conditions by adjusting the volume of runoff and the content of sand. Tectonic uplift provides the background conditions for the continuous, substantial downward incision of rivers. Climate-tectonic coupling controls the variation in river base levels of erosion and thus affects the river incision rate and terrace development.

The lower reaches of the Yarlung Zangbo River are located in the southern foothills of the Himalayas. A strong summer monsoon and humid climate characterized the early Holocene, and a weakened summer monsoon climate prevailed during the late Holocene in the

area [10,11]. In the section from the lower reaches of the Yarlung Zangbo River to the Pailong section of the upstream Great Bend knickzone, rainfall is abundant, with annual amounts reaching 2,000 mm in recent years due to the Indian Ocean tropical monsoon [12], and multiple tributaries of the upper streams, such as the Niyang River and the Parlung Zangbo River, feed into the region of the Great Bend (Figure 1). Abundant water flow passes through a 2,500 m fall (Figure 9a), thereby creating a strong hydrodynamic force resulting in the considerable incision capability of the lower reaches of the Yarlung Zangbo River in the Motuo County area. Along the middle and the lower reaches of the Yarlung Zangbo River, high Himalaya gneiss is present, with similar erosion resistance properties. Since 18.2 kyear, the incision rate has been 4.7 mm/year, which is greater than the incision rate of 2 mm/year since 10 kyear in the middle reaches of the river near the town of Gemuding [5].

Terraces in the study area are composed of mostly coarse-grained sand particles and rock fragments, lack fine-grained components, and exhibit poor gravel round-

ing without sorting. These features suggest that the upper reaches of the river near the Great Bend knickzone have a sufficient provenance to have accumulated rapidly in the lower reaches. Because glaciers blocked the Yarlung Zangbo River, two phases of dammed lakes were formed at the mouth of the Niyang River during the last glacial period (75–40 kyear) and the 1.8–1.2 kyear neoglacial period [13,14]. Additionally, two phases of palaeo-dammed lakes with deposition ages of 7–9 and 20–30 ka formed upstream of the Great Bend during the early Holocene glaciation event and the last glacial maximum, respectively [15]. The latest phase had a height of only 20 m above the water level of the Yarlung Zangbo River [15]. Liu *et al.* (2018) proposed that sand bed magnetic minerals found in lacustrine sediments are not destroyed by weathering and represent near-source sediments that were buried quickly, which indicates the breaking event of palaeo-dammed lakes [16]. The breaking of the palaeo-dammed lakes might have provided sufficient sedimentary sources for the lower reaches over a very short time period. Therefore, according to the component characteristics of the

Figure 9: Longitudinal profiles of the knickpoints on the Yarlung Zangbo River (a, b, and c represent Sections 1, 2, and 3 in Figure 1, respectively).

Yarlung Zangbo River terraces exposed in the study area, the sedimentation process is probably related to the breaking of the palaeo-dammed lakes in the middle reaches of the river.

The river incision rate is commonly used to infer the multistage uplift of mountains and the uplift of the ground surface. Although the river incision rate does not always precisely reflect the ground uplift, it can reveal the general trend of changes in surface elevation [17–20]. Schumm (1993) indicated that the influence of sea level change on the incision capacity of a river is restricted to within an approximately 300 km river segment above the mouth of the river [21]. The study area in this work is more than 1,000 km from the ocean. Therefore, the incision capacity of the study area is not affected by sea level change, and the Assam Plain is the base level of erosion controlling the incision capability of the Yarlung Zangbo River. This river has two knickpoints between the study area and the entrance to the Assam Plain which have falls of 350 and 80 m (Figure 9b and c). The Yarlung Zangbo River in the study area has an incision rate of 4.7 mm/year, implying a considerable incision capability. However, the elevation difference between the study area and the local base level of erosion remains at 430 m according to the falls of the two knickpoints, suggesting that intense tectonic uplift is currently ongoing east of the Namche Barwa peak. This explanation is consistent with the conclusions from Zhang et al. (2020) based on the analysis of basin hypsometry and discussions on the dominant variables controlling landscape evolution [22]. They argued that the present tectonically induced rock uplifting is concentrated in the southeastern area of the Namche Barwa peak [22].

5 Conclusions

Terraces along the lower reaches of the Yarlung Zangbo River east of the Namche Barwa are mostly composed of coarse-grained sand particles and rock fragments, and the sedimentation process is likely related to the breaking of the palaeo-dammed lakes in the middle reaches of the river. The Yarlung Zangbo River in the study area has a high incision rate of 4.7 mm/year, suggesting that intense tectonic uplift is ongoing to the east of the Namche Barwa peak.

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