1-1-2014

The evolution of a terrace sequence along the Manas River in the northern foreland basin of Tian Shan, China, as inferred from optical dating

Zhijun Gong
*University of Hong Kong*

Sheng-Hua Li
*University of Hong Kong*, shli@hku.hk

Bo Li
*University of Wollongong*, bli@uow.edu.au

Follow this and additional works at: [https://ro.uow.edu.au/smhpapers](https://ro.uow.edu.au/smhpapers)

Part of the Medicine and Health Sciences Commons, and the Social and Behavioral Sciences Commons

**Recommended Citation**

Gong, Zhijun; Li, Sheng-Hua; and Li, Bo, "The evolution of a terrace sequence along the Manas River in the northern foreland basin of Tian Shan, China, as inferred from optical dating" (2014). *Faculty of Science, Medicine and Health - Papers: part A*. 1921. [https://ro.uow.edu.au/smhpapers/1921](https://ro.uow.edu.au/smhpapers/1921)

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
The evolution of a terrace sequence along the Manas River in the northern foreland basin of Tian Shan, China, as inferred from optical dating

Abstract
The Tian Shan range lies in the actively deforming part of the India-Asia collision zone. The uplift rate and deformation pattern of the Tian Shan are important for understanding the dynamics of crustal deformation in the region. The river terraces in northern Tian Shan provide key records of past changes in climate and/or regional tectonics. In this study, a terrace sequence along the Manas River in a tectonically active zone in the northern foreland basin of Tian Shan is investigated. Six river terraces were identified and dated using optically stimulated luminescence (OSL). The results show that the six terraces were abandoned at ~ 0.5 ka, ~ 1.4 ka, ~ 3.1 ka, ~ 4.0 ka, ~ 12.4 ka and ~ 19.9 ka, respectively. Together with high resolution Global Positioning System (GPS) measurements on the terrace treads, the fluvial history of Manas River is reconstructed. From ~ 20 ka to ~ 4.8 ka, the height of the fluvial bed of Manas River decreased at an average rate of 2.2 ± 0.6 mm/yr. From ~ 4.8 ka to the present, the height of the fluvial bed decreased at an average rate of 13.5 ± 0.6 mm/yr, corresponding to intensified incision of Manas River during the late Holocene. This accelerated incision is very likely caused by the tectonic forces rather than climatic influences alone, suggesting that the tectonic uplift activity was significantly intensified since ~ 4.8 ka in the northern piedmont of Tian Shan. Other controlling factors on the incision of Manas River are also discussed.

Keywords
Tian Shan, Incision, OSL dating, Manas River, Terrace, CAS

Disciplines
Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details
Gong, Z., Li, S. & Li, B. (2014). The evolution of a terrace sequence along the Manas River in the northern foreland basin of Tian Shan, China, as inferred from optical dating. Geomorphology, 213 201-212.

This journal article is available at Research Online: https://ro.uow.edu.au/smhpapers/1921
The evolution of a terrace sequence along the Manas River in the northern foreland basin of Tian Shan, China, as inferred from optical dating

Zhijun Gong¹², Sheng-Hua Li¹*, Bo Li¹³
1. Department of Earth Sciences, The University of Hong Kong, Pokfulan Road, Hong Kong, China
2. Present address: Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
3. Present address: Centre for Archaeological Science, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2522, Australia
* Corresponding author. Email: shli@hku.hk

Abstract:

The Tian Shan range lies in the actively deforming part of the India–Asia collision zone. The uplift rate and defomation pattern of the Tian Shan are important for understanding the dynamics of crustal deformation in the region. The river terraces in northern Tian Shan provide key records of past changes in climate and/or regional tectonics. In this study, a terrace sequence along the Manas River in a tectonically active zone in the northern foreland basin of Tian Shan is investigated. Six river terraces were identified and dated using optically stimulated luminescence (OSL). The results show that the six terraces were abandoned at ~ 0.5 ka, ~1.4 ka, ~3.1 ka, ~4.0 ka, ~12.4 ka and ~19.9 ka, respectively. Together with high resolution Global Position System (GPS) measurements on the terrace treads, the fluvial history of Manas River is reconstructed. From ~20 ka to ~4.8 ka, the height of fluvial bed of Manas River decreased at an average rate of 2.2 ± 0.6 mm/yr. From ~4.8 ka to the present, the height of fluvial bed decreased at the average rate of 13.5 ± 0.6 mm/yr, corresponding to intensified incision of Manas River during the late Holocene. This accelerated incision is very likely caused by the tectonic forces rather than climatic influences alone, suggesting that the tectonic uplift activity was significantly intensified since ~4.8 ka in the northern piedmont of Tian Shan. Other controlling factors on the incision of Manas River are also discussed.
1. Introduction

In response to the Cenozoic collision of the Indian and Eurasian continental plates, Tian Shan has been one of the most active intra-continental mountain building belts in central Asia (Fig. 1a) (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Avouac et al., 1993; Fu et al., 2003; Sun and Zhang, 2009). Tian Shan exhibits frequent large earthquakes and rapid rates of deformation, which has drawn the attention of many scientists on the neotectonic activity of Tian Shan (e.g. Avouac et al., 1993; Abdrakhmatov et al., 1996; Deng et al., 1996; Sun et al., 2004; Zhang, 2004; Sun and Zhang, 2009; Lu et al., 2010b). The quantification of late Quaternary tectonic uplift activities in the region is important for understanding mountain-building process and evaluating seismic hazards.

Several rivers originate from glaciers in the northern foreland basin of Tian Shan, transversely cutting the thrusting and folding zones towards the Junggar Basin (Fig. 1a, 1b). Terrace systems were developed along the banks of the rivers, which provide important records for studying the past changes in climate and/or regional tectonics. On one hand, the past climatic fluctuations may have significant effects on the formation of river terraces. On the other hand, active tectonics, as indicated by the existence of the Cenozoic folding, may also affect the river incision in this area. Given their importance for studying the paleo-climatic changes and regional tectonics, the river terraces in northern Tian Shan have been extensively studied (Avouae et al., 1993; Deng et al., 1996; Yang et al., 2011). However, further correlation of the river terraces with past climate changes and/or regional tectonics has been impeded by the lack of a reliable chronological framework for the fluvial sequences.

To interpret the evolution of a fluvial system, a robust chronology is very important. In addition to radiocarbon dating and the cosmogenic exposure dating, optically stimulated luminescence (OSL) dating offers an alternative for dating fluvial
sediments beyond the 50,000 years limit of radiocarbon dating. Such luminescence technique has been widely applied to many aeolian depositional sequences, e.g. sandy deposits from deserts in northeast China and loess deposits from Chinese Loess Plateau (e.g. Li et al., 2002; Sun et al., 2006; Li et al., 2007; Li and Li, 2011). Although fluvial sediments are not the ideal materials for optical dating due to possible heterogeneous bleaching at the time of deposition, it is still possible to date the sediments by assessing the degree of bleaching of sediments using statistical methods (Li, 1994; Galbraith et al., 1999; Olley et al., 1999; Wallinga, 2002; Zhang et al., 2001; 2009).

In this study, the quartz single-aliquot regenerative-dose (SAR) OSL dating technique (Murray and Wintle, 2000) was applied to date the terrace sequence along the Manas River in the northern foreland basin of Tian Shan. At the site studied, six terraces were identified along the eastern bank. By dating the underlying fluvial sand and the overlying aeolian loess on the terraces, a luminescence chronology for the terrace sequence was established. Together with high resolution Global Position System (GPS) measurements on the terraces, the incision history of Manas River was evaluated and its climatic and tectonic implications discussed.

2. Study area

2.1 Geological setting

Lying a northwestern China, the Tian Shan range extends east-west for more than 1700 km with a width of 250-300 km, separating the Tarim Basin to the south from the Junggar Basin to the north (Fu et al., 2003). The active neotectonics of Tian Shan resulted in the intensive deformation of the Mesozoic to Cenozoic strata in the foreland basins (Fu et al., 2003; Zhang, 2004; Sun and Zhang, 2009). During the late Cenozoic, three sub-parallel rows of roughly east-west striking fold and reverse fault zones formed in the northern foreland basin (Fig. 1b). In this study, the three zones were termed as zones I, II and III from mountain front sequentially towards the Junggar Basin (Deng et al., 1996; Burchfiel et al., 1999; Fu et al., 2003). The anticlines in the zones are characterized by a linear shape and approximately west-east
striking axes, indicating a north-south contraction and crustal shortening.

2.2 Manas River terrace characteristics

In the middle part of the fold and reverse fault zone II, the north-trending Manas River transversely incises the Manas Anticline and displays well-developed terrace sequences along the banks (Fig. 2). Six terraces were identified and they were termed T-1, T-2, T-3, T-4, T-5 and T-6 from the lowest terrace to the highest (Fig. 2). The terraces are characterized by a lower fluvial conglomerates intercalated with lenses of sand, and an upper layer of aeolian loess beds (Fig. 3). The loess layer on the terrace T-6 can be over 10 m in thickness, while the lower terraces (from T-4 to T-1) have a relatively thin loess layer on the top (from ~1.5 m to 0.1 m). The loess deposits have typical features of aeolian deposits, such as good sorting, no bedding and lack of coarse sand and gravels. The sharp contact between loess and the underlying gravels can easily be distinguished.

Regional tectonic forces have had significant impacts on the fluvial terraces, as they were tectonically deformed by thrust faults such as the Manas Fault and Hutubi Fault (Fig. 1b) (Deng et al., 1996; Fu et al., 2003). Several fault scarps along the river terraces were also identified within the Manas Anticline (Xu et al., 1992; Deng et al., 1996).

2.3 Climate

The annual precipitation in the study area is less than 300 mm/yr and the precipitation concentrates during the spring and summer months (Poisson and Avouac, 2004; Lu et al., 2010a). Most of rivers in the piedmont of the north Tian Shan originate from glaciers in the high mountain range. The water supply depends strongly on melting water and displays strong seasonal variability. The prevailing winds of the region are westerlies (Poisson and Avouac, 2004), with the area being mainly controlled by near-surface northwest winds (Fang et al., 2002; Sun, 2002; Chen et al., 2008). Under such winds, aeolian loess entrained from Junggar Basin is transported and accumulated along the northern piedmont of Tian Shan (Sun, 2002).
3. Methods

3.1 OSL sampling of terraces along Manas River

In order to provide a reliable chronology for the terrace sequence in the study area, sampling was carried out along the cross-section (A’-A) from the highest terrace (T-6) to the lowest terrace (T-1) (Fig. 3). This cross-section A’-A is approximately perpendicular to the Manas River. OSL samples were taken from the fluvial sand and overlying loess on the terraces and the positions of the OSL samples were shown in the schematic cross-sections in Fig. 3. Samples were collected from the bottom of the overlying loess layers for all the terraces to constrain the minimum ages of the terrace treads. Benefitting from several large trenches created by the engineering work on T-5 and T-6, we collected several fluvial sand samples from sand lenses in these two terraces. These fluvial sand lenses provide constraints on the lower limit of the abandonment ages and the upper limit of the formation ages of the river terraces. For the lower terraces (T-1, T-2, T-3 and T-4), only the overlying loess deposits on the terraces were sampled because no appropriate sand lenses were found.

OSL samples were obtained by hammering stainless steel tubes horizontally into freshly cleaned vertical sections. These tubes were then covered with a lid soon after taking them out from the section, and then sealed in black plastic bags. The detailed sample name, material and positions are shown in Table 1. The potential problems from the incomplete resetting and spatially heterogeneous dose rates on the OSL age determinations are discussed later in this paper.

3.2 OSL dating for terraces along Manas River

OSL samples were pre-treated under subdued red light in the Luminescence Dating Laboratory, the University of Hong Kong. Two centimetres of material at each end of the tube was scrapped away and used for dose rate measurements. Raw samples in the centre of the tubes were at first treated with 10% hydrochloric acid (HCl) and 10% hydrogen peroxide (H₂O₂) to remove carbonates and organic material, respectively. Coarse grains (63-90 µm, 90-125 µm and 150-180 µm) were selected by
mechanical dry sieving. Potassium-feldspar (K-feldspar) grains and quartz grains were separated using sodium polytungstate heavy liquid (2.58 g/cm³ for K-feldspar, 2.75 g/cm³ for quartz). The K-feldspar grains were etched with 10% HF for 30 minutes to remove the outer alpha-dosed layer; while the quartz grains were etched with 40% HF for 80 minutes to remove the outer alpha-dosed layer as well as any remaining feldspar. HCl (10%) was then used again to dissolve any residual fluorides after etching before final rinsing and drying. The etched grains were mounted as a monolayer on aluminum discs of 9.8 mm diameter using silicone oil as an adhesive. Grains covered the central ~4 mm diameter portion of each disc, corresponding to several hundreds of grains per aliquot. The purity of quartz grains was tested by measuring the infrared stimulated luminescence (IRSL) and 110 °C thermal luminescence (TL) peak (Li et al., 2002). At least twenty aliquots were measured for each sample.

OSL signals were measured using automated Risø TL/OSL readers equipped with excitation units of blue light (BL) (Δλ=470 ± 30 nm) and infrared light (IR) (Δλ=870 ± 40 nm). The BL and IR stimulations deliver ~50 mW/cm² and ~135 mW/cm² on the sample, respectively (Bøtter-Jensen et al., 2003); 90% of their full powers were used for stimulation in this study. The quartz OSL signals were detected through 7.5 mm Hoya U-340 filters, with a peak transmission at ~340 nm. The IRSL signals from K-feldspar were detected through a filter pack containing Schott BG-39 and Corning 7-59 filters, which allows for a transmission peak in blue (320-480 nm). Irradiation was carried out using ⁹⁰Sr/⁹⁰Y beta sources built into the readers.

Quartz equivalent dose (Dₑ) was determined by the SAR OSL dating protocol (Murray and Wintle, 2000). In the protocol, the pre-heating temperature was determined from pre-heat plateau tests using two samples; one the loess sample (T-5-loess-bottom), the other the sand sample (T-5-sand-3) (Fig. 4a, 4b). A Dₑ plateau was observed between 200 and 240 °C for the loess sample, and no obvious dependence of Dₑ on the pre-heat temperature from 200 to 280 °C was observed for the sand sample. Based on the pre-heat plateau results, we selected pre-heat conditions at 220 °C for 10 s and cut-heat to 180 °C for the regenerative dose and test
dose OSL measurements, respectively, for all the samples. In order to further confirm the above results, a dose recovery test was also performed on the sample (T-5-loess-bottom) (Murray and Wintle, 2003). Twenty aliquots were at first bleached with blue light at 125 °C, which was followed by a laboratory irradiation of 40 Gy. Such a dose was then measured as an “unknown” dose using the above pre-heat condition. It was found that the SAR protocol can recover a laboratory given dose (recovery ratio: 1.04±0.03). Additionally, a zero dose was used for monitoring recuperation effects and a repeat dose same to the first regeneration dose was used for checking the reproducibility of the sensitivity correction (i.e. recycling ratio). Aliquots with recuperation higher than 5% or recycling ratio falling out the range of 1.0 ± 0.1 were discarded for age calculation.

K-feldspar grains can also be used for dating of sediments. K-feldspar has the advantages of bright luminescence and homogeneous $D_e$ results over quartz. Recently, the multi-elevated-temperature post IR IRSL (MET-pIRIR) protocol was proposed to overcome the problem of anomalous fading (Li and Li 2011). In such protocol, it measures the IRSL signals from K-feldspar by progressively increasing the IR stimulation temperature from 50 °C to 250 °C in steps of 50 °C. These IRSL signals at different stimulation temperatures were termed as the MET-pIRIR signals. Good performance of the protocol has been reported for its use of dating aeolian sedimentary samples from deserts in northern China and loess samples from Chinese Loess Plateau (Li and Li 2011; Fu et al., 2012; Li and Li, 2012). In this study, the MET-pIRIR protocol was applied to the sample T-5-loess-bottom for cross-checking. In the MET-pIRIR protocol, pre-heating at 280 °C for 10 seconds was used for both the regenerative dose and test dose IRSL measurements. Ten aliquots were measured for K-feldspar grains of sample T-5-loess-bottom.

The environmental dose rate was measured using a variety of techniques. The thick-source alpha counting technique (Aitken, 1985) was used to measure contributions from uranium (U) and thorium (Th) decay chains. A Littlemore 7286 TSAC system with 42-mm-diameter ZnS screens was used. X-ray florescence (XRF) was used to measure the potassium (K) content. Water content was calculated as the
ratio of water weight to the dried sample weight. As the water content changes with time, a 20% error was assigned for the measured water content to take account of the long-term variation in water content (refer to Table 2). The cosmic ray contribution to the dose rate was calculated from the burial depth, latitude, longitude and altitude of the samples (Prescott and Hutton, 1994). The internal dose rate for K-feldspar was calculated using a potassium concentration of 13 ± 1% and a Rb concentration of 400 ± 100 μg/g, using published absorbed beta dose fractions for spherical grains (Huntley and Baril, 1997; Zhao and Li, 2005; Li et al., 2008).

3.3 Measurement of terrace elevations

Terrace elevations were measured along the cross-section A’-A using a kinematic GPS consisting of two receivers (Real Time Kinematic) (Fig. 3). One of the two receivers was used as a base station with its antenna fixed on a tripod. The other one was mobile, with its antenna attached to a hand-carried pole. Both receivers recorded position data from at least four satellites. In this study, the base GPS receiver was set at the tread of T-5. The elevation data of the six terrace treads were collected by the mobile GPS receiver. High resolution elevation data were obtained after the correction using the base GPS receiver. Re-measurements of starting points indicate that horizontal and vertical uncertainties are on the order of ~1 cm. It should be noted that the elevation for each terrace was measured at the bottom of its overlying loess layer and immediately above the gravel-loess contact.

4. Results

4.1 Dose rate determinations

Table 2 shows the annual dose rate results, which were derived from the contributions of radioactive nuclides in the samples and surroundings, and cosmic rays. It is found that the loess samples were generally subjected to relatively higher radiation field than the fluvial sand. As gamma radiation has a higher penetrating distance (~30 cm) than beta radiation (a few millimeters), the loess samples may have received inhomogeneous gamma radiation from the surroundings of the loess and the
underlying fluvial deposits. In order to evaluate the effect of inhomogeneous gamma radiation to the results for loess samples, a loess sample (T-6-loess-bottom) is taken as an example. The average gamma dose rate contribution from the radioactive nuclides of T-6-sand-1, T-6-sand-2, T-6-sand 3 and T-6-sand 4 is about 1.15 Gy/ka, which is lower than that of T-6-loess-bottom (1.44±0.05 Gy/ka). If the average value of the above two data (1.15 Gy/ka and 1.44 Gy/ka) was used to estimate the corresponding gamma dose rate contribution for T-6-loess-bottom, the annual dose rate will be 3.8% lower than the calculated dose rate in Table 2, which is comparable to the uncertainty of dose rate estimates. Similar cases were obtained for other samples. We, therefore, ignore the uncertainty of annual dose rate from inhomogeneous gamma radiation for our samples.

4.2 OSL chronology of the terrace treads

The $D_e$ distribution from each sample was analyzed using radial plot, which has been widely used to show the distributions of single-grain or single-aliquot $D_e$ estimations (Galbraith et al., 1999; Olley et al., 1999; Jacobs et al., 2003, 2006; Zhang et al., 2009). Fig. 5a displays examples of radial plots for six loess samples from the five terraces (T-6, T-5, T-4, T-3 and T-2). In the plots, the central lines of the shaded regions with $2\sigma$ width of the $D_e$ distribution represent the mean $D_e$ values of the measured aliquots. Based on the radial plots, there is no evidence of variable bleaching for these loess samples, i.e. the $D_e$ values are symmetrically distributed around the central values. The calculated over-dispersion values (Fig. 5(a)) range from 20% to 50% value, which is consistent or higher than the commonly reported value (~20%) for well-bleached sedimentary quartz samples (Arnold and Roberts, 2009; Arnold et al., 2012). Since the loess deposits are aeolian in origin, we infer that the dominant control on the distribution of $D_e$ values is the spatially heterogeneous dose rates rather than incomplete bleaching.

Fig. 5b displays the radial plots for six sand samples from sand lenses of the T-6 and T-5. Compared to the results of loess samples in Fig. 5a, a large $D_e$ scatter among aliquots was observed for the fluvial sand samples. Most of our sand samples yield at
least three groups of $D_e$ estimation (Fig. 5b). Higher over-dispersion values (range from $\sim$31.6% to $\sim$54.2%) were also obtained for the sand samples. There are two possible reasons for the larger scatter in the $D_e$ distribution of the fluvial samples: 1) heterogeneous bleaching of the fluvial sand grains at the time of deposition (e.g. Olley et al., 1999; Zhang et al., 2003; Zhang et al., 2009); or 2) micro-dosimetry due to the inhomogeneous depositional settings for the sand lenses. To deal with these various possibilities, several informal approaches and parametric statistical models have been used to estimate the $D_e$ of interest. Some of these were developed originally for fission track analysis (Galbraith and Green, 1990; Galbraith and Laslett, 1993). The age models are presented in detail in Galbraith et al (1999), Bailey and Arnold (2006) and Galbraith and Roberts (2012). The case insufficient bleaching would require a minimum age model to calculate the ages. However, the minimum age model yields much younger ages of the fluvial sand than the ages of the overlying loess samples for both T-5 and T-6, which is impossible because loess samples should be younger than the sand due to their stratigraphic order. The central age (or mean age) model for the sand samples, however, yield similar ages with the overlying loess samples (Table 3), suggesting that it is micro-dosimetry that resulted in the large scatter in the $D_e$ values for the sand samples rather than the incomplete bleaching problem.

Table 3 summarizes the OSL ages of all the samples based on mean age model and the central age model, respectively. It is found that the two age models produce consistent ages within the error for all the samples. For simplification, the mean age model was chosen for final determination of the OSL ages. To further test the reliability of the quartz OSL ages, K-feldspar grains from sample T-5-loess-bottom were also dated with the MET-pIRIR protocol (Li and Li, 2011). The details of $D_e$, dose rate and IRSL ages for K-feldspar from the sample are shown in Table 4. Homogeneous $D_e$ values were obtained from the K-feldspar aliquots. Fig. 6 shows the age plateau from 150 °C to 250 °C in the MET-pIRIR age plot. The age plateau has an agreement with the quartz OSL age. The results of the age plateau in MET-pIRIR age plot support the determination that the sample were well bleached before deposition, since K-feldspar IRSL signals were bleached more slowly than quartz OSL signals.
The consistency of the quartz age with the K-feldspar ages from sample T-5-loess-bottom provides a cross check on the reliability of these dates. We conclude that our OSL ages are reliable based on the following aspects: 1) our samples yield good results in the SAR performance tests, in terms of pre-heat plateau, dose recovery test, recycling ratio and recuperation (see section 3.2); 2) the OSL ages are in a good order, either stratigraphically within the same terraces or in the correct sequence between different terraces; 3) parallel samples were measured and yield consistent ages (Table 3); and 4) K-feldspar and quartz grains from the loess sample produce consistent OSL ages.

Fig. 7 shows the six terrace treads together with the OSL ages. The terrace treads were formed from ~20 ka to ~0.5 ka. For the T-6 terrace, the formation age of the terrace tread is constrained between ~20 ka and ~22 ka according to the loess and fluvial sand samples. Similarly, the formation age of the T-5 tread was constrained between ~12.4 ka and ~13.1 ka. Since there are no appropriate sand lenses sampled from the lower terraces (T-1-T-4), only the minimum ages were obtained using the overlying loess samples. The minimum ages of the terrace treads of T-4, T-3, T-2 and T-1 were constrained to be ~4.0 ka, ~3.1 ka, ~1.4 ka and ~0.5 ka, respectively. We, however, infer that the ages of the loess samples are close to the ages of terrace treads, based on the following reasons. Firstly, the loess deposits are expected to be continuous and mantle the terraces soon after the terraces were abandoned. This is supported by the fact that the loess samples from T-6 (T-6-loess-bottom) and T-5 (T-5-loess-bottom) yield OSL ages very close to the OSL ages of the underlying sand lenses. Secondly, the bottom loess samples from the lower terraces produce younger OSL ages. Thus, we propose that the OSL ages of the bottom loess samples on the terraces can be used as a close estimation for the formation ages of the terrace treads.

4.3 Terrace elevation and reconstruction of the fluvial history of Manas River

The elevation data for the six terrace treads are summarized in Table 5. It is found that the elevation of the terraces range from 656.90 ± 0.03 m for the tread of T-6 to 556.82 ± 0.04 m at the modern river bed along the cross-section A’-A (Fig. 3). Here,
the terrace treads serve as the mark for the old river bed surfaces. As OSL dating indicates that the tread of T-6 was formed at ~20 ka, it suggests that the height of the bed of Manas River has decreased ~100 m over the last ~20 ka.

Combining the elevation data with the corresponding OSL ages for the terrace treads, we can reconstruct the fluvial history of Manas River during the last ~20 ka (Fig. 8a). Two periods with distinctively different incision rates can be identified. One period is from ~20 ka to ~4.8 ka, during which the bed of the Manas River decreased in height at an average rate of $2.2 \pm 0.6$ mm/yr. After ~4.8 ka, the height of river bed decreased at a much faster rate of $13.5 \pm 0.6$ mm/yr. It is noted that the descending rate of the river bed does not necessarily equal to the incision rate of the rivers, because the lowering of the river bed is actually a net result of erosion, accumulation and balance between them. Besides, the actual river bed was not lowering continuously all the time. The river bed should decrease in height during the phase of incision, while the river bed increased in height during the formation of terrace as a result of sedimentation. In the following, a schematic graph (Fig. 8b) was illustrated to help understand the abandonment and formation processes of the terraces. In our study, the OSL age of the sand sample (T-6-sand-1), which is at about 5 m in height below the upper layer of aeolian loess beds on T-6, can be used to constrain the minimum formation age of T-6, if the insufficient bleaching problem is not taken into account. Thus, the formation of T-6 lasted at least from ~25.3 ka to ~20 ka, while the river bed increased from ~651.9 m to ~656.9 m (Fig. 8b). At ~20 ka, the terrace (T-6) was abandoned as a result of incision and this incision phase lasted until the beginning of the formation of T-5. Similarly, the OSL age of the sand sample (T-5-sand-3) at about 0.7 m below the upper layer of aeolian loess beds on T-5 can be used to constrain the minimum formation age of T-5. Thus, the river bed decreased from ~20 ka to before ~14.6 ka after the abandonment of T-6. From ~14.6 ka to ~12.4 ka, river bed increased from ~639.5 m to ~640.2 m to form T-5. Such cycles of incision and sedimentation were repeated, which created the T-4, T-3, T-2 and T-1 terraces. It is to be noted those formation ages of T-4, T-3, T-2 and T-1 in Fig. 8b was only schematic because no appropriate sand lenses were found for them. The natural processes of
abandonment and formation processes of the terraces might be more complex. The increased lowering rate of the river bed calculated from the data of terrace treads (Fig. 8a), however, can still be a useful proxy to quantify the strength of incision of Manas River over the last ~20 ka. They results clearly indicate that the incision of Manas River was significantly intensified during the last ~4.8 ka.

5. Controlling factors on the incision of Manas River

Factors that could affect incision rates include climatic conditions (e.g. discharge), bedrock type, and/or uplift rate (Kirby et al., 2003). Bedrock type determines the resistance to river incision (Stock and Montgomery, 1999; Duvall et al., 2004) and, hence, may consequently influence the incision rate. In the site studied, the bases of the different terraces are similar (Tertiary strata) so we ignore the influence of bedrock type. Discrimination of the different factors on river incision has proved difficult in practice (Kirby et al., 2003). In the following, only the influences of climate and tectonic uplift on the magnitude of the river incision were discussed.

In the northern piedmont of Tian Shan, the water supply from melting water might vary with time as a result of climate change. We infer that the dominant control on the evolution of T-5 and T-6 is climatic change during glacial-interglacial cycles, based on two reasons. Firstly, the chronological data of the two oldest terraces (T-6 and T-5) shows synchronicity with Last Glacial Maximum and the termination of last glacial stage, respectively. Secondly, from field investigation, it is found that T-5 and T-6 were distributed on a regional scale. Such topography should be a result of non-localized effects arising from climatic forcing.

A dramatic acceleration in the incision rate of the Manas River happened around 4.8 ka (Fig. 8). Such a fast incision rate cannot be explained by the climatic forces alone. We explain the dominant control of the accelerated incision rate as mainly a result of regional tectonic uplift. There are several lines of evidence to support this. Firstly, unlike T-5 and T-6, which are distributed over extensive areas along the river valley, the lower terraces T-1, T-2, T-3 and T-4 are mostly distributed within the Manas Anticline. This suggests that the formation of the T-1 to T-4 terraces is likely to
result from a localized effect (e.g. tectonic forces). Secondly, study of the lake level changes in the Manas lake, the catchment at downstream of Manas River at the Junggar Basin (Fig. 9), suggested that the precipitation in this region did not vary significantly in the last 5 ka (Fan et al., 2012). It was found that there was no high lake level record since ~5 ka, suggesting a relatively dry climate (Fan et al., 2012). Study on the Gurbantunggut Desert from Junggar Basin indicates that the climate was dry since ~5 ka (Li and Fan, 2011). Thus, climate forcing (e.g. increase in river discharge) is unlikely to be the cause for the accelerated incision of Manas River during the late Holocene.

Based on the results shown above, we conclude that the accelerated incision of Manas River during the last ~4.8 ka is unlikely to be a result of climatic changes, and, hence, it can be associated with the intensified tectonic uplift activity in the northern piedmont of Tian Shan. Such uplift might have caused increased streamflow and intensified downcutting in response to a more steepened gradient. The intensified tectonic activities in the Tian Shan region have been reported in previous studies. Abdrakhmatov et al. (1996) observed that the present crustal shortening rate (~ 20 mm/yr) of Tian Shan deduced by the GPS data in the last two years was significantly faster than the rate inferred from the estimate of slip rate (~ 6 mm/yr) in the early Holocene (Avouac et al., 1993), indicating that Tian Shan experienced a much more intensified deformation in the late Holocene compared to early Holocene. The intensified deformation will result in an accelerated uplift rate in the region, which subsequently led to increase in the incision rate of the Manas River.

A significant implication of our results is that the northern piedmont of Tian Shan might have higher risk from seismic hazards during the late Holocene, as a result of stronger tectonic activity in the region. Thus, further investigation of fault activity during the late Holocene will be necessary in further research, in order to help evaluate the seismic hazards in the region.

5. Conclusion

Six terraces along the Manas River in the northern foreland basin of Tian Shan
were identified and they were studied to recover the fluvial history of Manas River during the last ~20 ka. The OSL dating results show that the six terrace treads were formed at ~ 0.5 ka, ~1.4 ka, ~3.1 ka, ~4.0 ka, ~12.4 ka and ~19.9 ka, respectively. Together with high resolution GPS measurements on the terrace treads, the fluvial history of Manas River was reconstructed. It is found that two periods of river incision can be identified. One period is from ~20 ka to ~4.8 ka, during which the height of river bed decreased at an average rate of 2.2 ± 0.6 mm/yr. The other period is from ~4.8 ka to present, during which the river bed decreased in height at a faster rate of 13.5 ± 0.6 mm/yr, corresponding to the intensified incision of Manas River. The fast river incision in the last ~4.8 ka is mainly controlled by the regional intensified tectonic uplift activities in the area rather than climate changes alone.

6. Acknowledgements

The authors would like to thank Anchuan Fan, Zhengqing Zhang and Junliang Ji for their help in fieldwork. The authors thank Dr. Sun Jimin for reviewing on the manuscript. The authors thank the reviewers and the editor for providing valuable comments and suggestions on the manuscript. This study was financially supported by the grants to Sheng-Hua Li from the Research Grant Council of the Hong Kong Special Administrative Region, China (Project no. 7028/08P and 7033/12P).
References


dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia, part 1, Experimental design and statistical models. Archaeometry 41, 339-364.


Sun, J.M., Li, S.-H., Han, P., Chen, Y., 2006. Holocene environmental changes in the central Inner Mongolia, based on single-aliquot-quartz optical dating and


Zhang, P.Z., 2004. Late Cenozoic tectonic deformation in the Tianshan Mountain and

Table 1: Sample names, materials and depths of OSL samples for the terraces along Manas River.

<table>
<thead>
<tr>
<th>Name</th>
<th>Sediment unit</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-6</td>
<td>T-6-loess-bottom</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>T-6-sand-1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>T-6-sand-2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>T-6-sand-3</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>T-6-sand-4</td>
<td>8.5</td>
</tr>
<tr>
<td>T-5</td>
<td>T-5-loess-bottom</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>T-5-sand-1</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>T-5-sand-2</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>T-5-sand-3</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>T-5-sand-4</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>T-5-sand-5</td>
<td>1.3</td>
</tr>
<tr>
<td>T-4</td>
<td>T-4-loess-bottom-1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>T-4-loess-bottom-2</td>
<td>0.2</td>
</tr>
<tr>
<td>T-3</td>
<td>T-3-loess-bottom</td>
<td>1.5</td>
</tr>
<tr>
<td>T-2</td>
<td>T-2-loess-bottom</td>
<td>0.1</td>
</tr>
<tr>
<td>T-1</td>
<td>T-1-loess-bottom</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Note: (1) T-5-sand-1 and the T-5-sand-2 are the two parallel samples from one sand lens in T-5;
(2) T-6-sand-3 and the T-6-sand-4 are the two parallel samples from one sand lens in T-6;
Table 2: Dose rate results for the quartz samples of the terraces from the Manas River.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Alpha counting ratea</th>
<th>K content (%)</th>
<th>Water content b</th>
<th>Cosmic ray c</th>
<th>External dose rated (Gy/ka)</th>
<th>Dose rate (Gy/ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-6-Loess-bottom</td>
<td>11.7±0.2</td>
<td>2.07±0.21</td>
<td>2.4</td>
<td>0.12</td>
<td>1.44±0.05</td>
<td>2.29±0.15</td>
</tr>
<tr>
<td>T-6-sand-1</td>
<td>6.87±0.17</td>
<td>2.01±0.20</td>
<td>2.0</td>
<td>0.09</td>
<td>1.04±0.05</td>
<td>1.87±0.14</td>
</tr>
<tr>
<td>T-6-sand-2</td>
<td>6.94±0.17</td>
<td>2.25±0.23</td>
<td>2.0</td>
<td>0.16</td>
<td>1.10±0.06</td>
<td>2.05±0.16</td>
</tr>
<tr>
<td>T-6-sand-3</td>
<td>7.60±0.17</td>
<td>2.26±0.23</td>
<td>2.0</td>
<td>0.08</td>
<td>1.15±0.06</td>
<td>2.10±0.16</td>
</tr>
<tr>
<td>T-6-sand-4</td>
<td>9.34±0.19</td>
<td>2.32±0.23</td>
<td>2.0</td>
<td>0.08</td>
<td>1.31±0.06</td>
<td>2.25±0.17</td>
</tr>
<tr>
<td>T-5-Loess-bottom</td>
<td>11.4±0.2</td>
<td>2.10±0.21</td>
<td>2.7</td>
<td>0.22</td>
<td>1.42±0.05</td>
<td>2.27±0.15</td>
</tr>
<tr>
<td>T-5-sand-1</td>
<td>8.53±0.18</td>
<td>2.20±0.22</td>
<td>2.0</td>
<td>0.20</td>
<td>1.21±0.05</td>
<td>2.11±0.16</td>
</tr>
<tr>
<td>T-5-sand-2</td>
<td>7.21±0.18</td>
<td>2.10±0.21</td>
<td>2.0</td>
<td>0.20</td>
<td>1.08±0.05</td>
<td>1.96±0.15</td>
</tr>
<tr>
<td>T-5-sand-3</td>
<td>6.68±0.14</td>
<td>2.17±0.21</td>
<td>2.0</td>
<td>0.21</td>
<td>1.06±0.05</td>
<td>1.97±0.15</td>
</tr>
<tr>
<td>T-5-sand-4</td>
<td>6.54±0.17</td>
<td>2.01±0.20</td>
<td>2.0</td>
<td>0.19</td>
<td>1.01±0.05</td>
<td>1.85±0.14</td>
</tr>
<tr>
<td>T-5-sand-5</td>
<td>6.14±0.14</td>
<td>2.03±0.20</td>
<td>2.0</td>
<td>0.20</td>
<td>0.98±0.05</td>
<td>1.84±0.15</td>
</tr>
<tr>
<td>T-4-Loess-bottom-1</td>
<td>11.2±0.2</td>
<td>2.09±0.21</td>
<td>5.6</td>
<td>0.23</td>
<td>1.34±0.05</td>
<td>2.18±0.15</td>
</tr>
<tr>
<td>T-4-Loess-bottom-2</td>
<td>10.2±0.2</td>
<td>2.00±0.20</td>
<td>2.7</td>
<td>0.23</td>
<td>1.29±0.05</td>
<td>2.11±0.15</td>
</tr>
<tr>
<td>T-3-Loess-bottom</td>
<td>10.7±0.2</td>
<td>2.00±0.20</td>
<td>3.1</td>
<td>0.19</td>
<td>1.40±0.06</td>
<td>2.38±0.17</td>
</tr>
<tr>
<td>T-2-Loess-bottom</td>
<td>10.1±0.2</td>
<td>2.00±0.20</td>
<td>3.0</td>
<td>0.23</td>
<td>1.24±0.05</td>
<td>2.01±0.14</td>
</tr>
<tr>
<td>T-1-Loess-bottom</td>
<td>11.7±0.2</td>
<td>2.20±0.22</td>
<td>2.7</td>
<td>0.22</td>
<td>1.46±0.05</td>
<td>2.35±0.16</td>
</tr>
</tbody>
</table>

a The alpha counting rate is for a 42-mm-diameter ZnS screen and is given in units of counts per kilo second.

b The error for the water content is estimated at ± 20%.

C The error for the cosmic rays dose rate is estimated at ± 0.02 Gy/ka.

d The dose rate contribution were estimated from the radioactive nuclides of the sample.
Table 3: OSL ages for quartz samples from terraces along the Manas River.

<table>
<thead>
<tr>
<th></th>
<th>Mean Age model (ka)</th>
<th>Central Age model (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-6-loess-bottom</td>
<td>19.9±1.5</td>
<td>19.4±1.0</td>
</tr>
<tr>
<td>T-6-sand-1</td>
<td>25.3±2.4</td>
<td>23.0±2.1</td>
</tr>
<tr>
<td>T-6-sand-2</td>
<td>21.9±2.5</td>
<td>19.1±2.3</td>
</tr>
<tr>
<td>T-6-sand-3</td>
<td>22.1±2.0</td>
<td>21.1±1.9</td>
</tr>
<tr>
<td>T-6-sand-4</td>
<td>22.2±2.2</td>
<td>20.6±2.0</td>
</tr>
<tr>
<td>T-5-loess-bottom</td>
<td>12.4±0.8</td>
<td>12.3±0.8</td>
</tr>
<tr>
<td>T-5-sand-1</td>
<td>13.2±1.7</td>
<td>12.1±1.2</td>
</tr>
<tr>
<td>T-5-sand-2</td>
<td>15.2±1.4</td>
<td>14.3±1.3</td>
</tr>
<tr>
<td>T-5-sand-3</td>
<td>14.6±1.2</td>
<td>13.7±1.3</td>
</tr>
<tr>
<td>T-5-sand-4</td>
<td>13.1±1.4</td>
<td>11.9±1.4</td>
</tr>
<tr>
<td>T-5-sand-5</td>
<td>16.1±1.5</td>
<td>14.8±1.9</td>
</tr>
<tr>
<td>T-4-loess-bottom-1</td>
<td>4.0±0.4</td>
<td>3.7±0.4</td>
</tr>
<tr>
<td>T-4-loess-bottom-2</td>
<td>4.1±0.4</td>
<td>3.9±0.3</td>
</tr>
<tr>
<td>T-3-loess-bottom</td>
<td>3.1±0.3</td>
<td>2.9±0.3</td>
</tr>
<tr>
<td>T-2-loess-bottom</td>
<td>1.4±0.3</td>
<td>1.1±0.2</td>
</tr>
<tr>
<td>T-1-loess-bottom</td>
<td>0.5±0.1</td>
<td>0.6±0.1</td>
</tr>
</tbody>
</table>
Table 4 Equivalent dose, dose rate and IRSL ages for K-feldspar from sample T-5-loess-bottom, measured using the MET-pIRIR protocol.

<table>
<thead>
<tr>
<th>IR stimulation temperatures</th>
<th>50 °C</th>
<th>100 °C</th>
<th>150 °C</th>
<th>200 °C</th>
<th>250 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&lt;sub&gt;E&lt;/sub&gt;, Gy</td>
<td>43.3 ± 0.3</td>
<td>46.4 ± 0.8</td>
<td>50.7 ± 0.6</td>
<td>53.7 ± 0.9</td>
<td>54.0 ± 1.3</td>
</tr>
<tr>
<td>Dose rate, Gy/ka</td>
<td>4.39 ± 0.17</td>
<td>4.39 ± 0.17</td>
<td>4.39 ± 0.17</td>
<td>4.39 ± 0.17</td>
<td>4.39 ± 0.17</td>
</tr>
<tr>
<td>Age, ka</td>
<td>9.9 ± 0.4</td>
<td>10.6 ± 0.4</td>
<td>11.5 ± 0.5</td>
<td>12.2 ± 0.5</td>
<td>12.3 ± 0.6</td>
</tr>
</tbody>
</table>
Table 5: Elevation of the terrace treads and the modern river bed along cross-section A’-A (Manas River). The data were collected by the kinematic GPS using two receivers (Real Time Kinematic). One of the two receivers was set at the tread of T-5, as the base.

<table>
<thead>
<tr>
<th>Terraces</th>
<th>GPS Base (T-5)</th>
<th>T-0 (Riverbed)</th>
<th>T-1</th>
<th>T-2</th>
<th>T-3</th>
<th>T-4</th>
<th>T-5</th>
<th>T-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation (m)</td>
<td>640.20</td>
<td>556.82</td>
<td>567.51</td>
<td>579.11</td>
<td>601.15</td>
<td>614.59</td>
<td>640.26</td>
<td>656.90</td>
</tr>
<tr>
<td>error (m)</td>
<td>0</td>
<td>0.04</td>
<td>3.49a</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*a* The larger uncertainty of the elevation data of T-1 is due to the weaker signals received by the GPS receivers when the data was collected.
Figure caption

Figure 1(a): Geologic map showing the location of Tian Shan. The intra-continental regions were deformed within the Eurasia continent, in response to the convergence of India and Eurasia continents.

Figure 1(b): Geologic structural map of the three roughly east-west stretching fold and fault zones in the northern foreland basin of Tian Shan (modified from (Fu et al., 2003)). The Manas River transversely incises across the Manas Anticline towards the Junggar Basin.

Figure 2: Schematic geomorphology of fluvial terraces along the east bank of the Manas River in the study area.

Figure 3: Schematic terrace profiles along the east bank of the Manas River within the Manas Anticline area; OSL samples were collected along the cross-section A’-A from T-6 to the modern river bed.

Figure 4(a): Single-aliquot regeneration (SAR) equivalent dose versus pre-heat temperature for T-5-loess-bottom. The mean values with the standard errors are obtained from results of six aliquots. The horizontal line denotes the pre-heat plateau was reached from 200 °C to 240 °C.

Figure 4(b): Single-aliquot regeneration (SAR) equivalent dose versus pre-heat temperature for T-5-sand-3.

Figure 5 (a): Radial plot results for $D_e$ distributions of six loess samples.

Figure 5 (b): Radial plot results for $D_e$ distributions of six fluvial sand samples.
Figure 6: MET-pIRIR dating results of K-feldspar from T-5-loess-bottom.

Figure 7: Quartz OSL dating results for the six terraces along the Manas River.

Figure 8 (a): Reconstruction the height of fluvial bed of Manas River in the study area. Elevations at different terrace treads were plotted against their corresponding OSL ages.

Figure 8 (b): a schematic graph showing the abandonment and formation processes of the terraces along the Manas River.

Figure 9: Map showing the locations of the study site, Manas Lake and Gurbantunggut Desert (after Fan et al. (2012)).
Figure 1(a)
Figure 1(b)
Figure 2
Figure 4(a)

Figure 4(b)
Figure 5 (a)
Figure 5(b)

T-6-sand-1
D_: 76.0±6.0 Gy
Over-dispersion = 42.3±1.0 %

T-6-sand-2
D_: 72.5±7.3 Gy
Over-dispersion = 54.2±1.6 %

T-6-sand-3
D_: 73.7±5.7 Gy
Over-dispersion = 31.6±1.3 %

T-5-sand-2
D_: 49.1±3.7 Gy
Over-dispersion = 32.9±1.3 %

T-5-sand-3
D_: 47.0±3.0 Gy
Over-dispersion = 37.8±1.1 %

T-5-sand-4
D_: 40.1±3.9 Gy
Over-dispersion = 47.3±1.6 %
Figure 6

T-5-loess-bottom

- Obtained ages from MET pIRIR signals of K-feldspar
- Corresponding quartz age
- Age plateau

Age, ka

IR stimulation temperature, °C

0 50 100 150 200 250

8 10 12 14 16 18
Figure 7
Figure 9