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ESR GEOCHRONOLOGY OF THE MINJIANG RIVER TERRACES AT WENCHUAN, EASTERN MARGIN OF TIBETAN PLATEAU, CHINA

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Abstract: The Minjiang River terrace along the Longmen Shan fault zone near Wenchuan, at the eastern margin of the Tibetan Plateau, China, provides archives for tectonic activity and quaternary climate change. However, previous studies were not able to provide ages older than 100 ka due to the limitations of dating material or/and methods applied to date the fluvial sediments. In this study, we used the ESR signal of the Ti-Li center in quartz to obtain the ages of four higher terraces (T3-T6). According to the results, the terraces T3 to T6 were formed at 64±19 ka, 101±15 ka, 153±33 ka, and 423±115 ka, respectively. Combined with previous studies, these results indicate that the formations of all terraces correspond to glacial/interglacial transition periods, such as, T1-T5 being correlated to MIS2/1, MIS4/3, MIS5d/5c, and MIS6/5e respectively, while T6 probably to MIS12/11. According to these data, it is found that the average incision rate was significantly higher over the last 150 ka than that previous 100 ka (250 to 150 ka). As both tectonics and climate have affected the formation of these terraces, in addition to the overall uplifting of Tibetan Plateau, the regional uplift due to isostasy would be an additional tectonic factor in the formation of river terraces in the eastern margin of Tibetan plateau.

Keywords: river terrace, ESR dating, quartz, Minjiang River, Tibetan plateau.

1. INTRODUCTION

The uplifting history of the Tibetan Plateau plays a key role in the continuous debate over large-scale linkages between tectonic and global climate change during the Neogene (Kirby *et al.*, 2002; Molnar, 2005). The eastern Tibet takes largest fluvial relief which not only causes the highest incision rate at the edge of this region, but also leads to the additional uplifting following the intensified erosion assuming isostasy (Pinter and Brandon, 2005).

River terrace sequences furnish some information concerning both tectonic movement and climate change. A single factor or multiple coupled factors lead to the erosion, transport or deposit of fluvial sediments to form a terrace (Li *et al.*, 1996). The tectonic movement and climate change based on the study of river terrace has been becoming a hot topic (Maddy, 1997; Bridgland *et al.*, 2000; Pan *et al.*, 2009).

The river terrace along the margin of the Tibetan Plateau provides hence archives for tectonic activities and climatic changes (Schumm and Parker, 1973), and has been investigated for several decades (Li, 1991; Porter *et al.*, 1992). For example, Pan *et al.* (2009) concluded in

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detail the age of terrace sequences of Yellow River at Lanzhou, in the northeastern Tibetan Plateau. The results declaimed that in past 1.2 Ma there were two stage periods for terrace formation in the upper reach of Yellow River, one ranging from 1.2 to 0.83 Ma, the other from 0.13 to 0.05 Ma, which was correlated to two phases of rapid uplifting, Kunhuang movement and Gonghe movement.

However, the studies at the east margin of the Tibetan Plateau, such as Minjiang River, were faced with the limitations of dating materials or/and methods that have been applied to date these fluvial sediments, such as OSL, TL and ^{14}C (Li *et al.*, 2005, 2006). Cosmogenic dating method (^{10}Be) has been used to dating the river terrace and got some successful results (Brocard *et al.*, 2003), but the sediment for this method should be very stable after deposition. Moreover, independent chronology by other dating methods is required for quaternary profile.

Electron Spin Resonance (ESR) is a potential dating method for fluvial sediments with the dating range from tens of thousands up to millions of years. In recent years, there has been a strong interest to apply ESR dating to quartz (e.g. Yokoyama *et al.*, 1985; Tanaka *et al.*, 1995; Laurent *et al.*, 1998; Beerten *et al.*, 2006; Rink *et al.*, 2007; Liu *et al.*, 2010a; Voinchet *et al.*, 2004, 2010; Tissoux *et al.*, 2007, 2008; Moreno *et al.*, 2012). So it is worthwhile to use this method to develop the independent chronology for the river terrace at the east margin of the Tibetan Plateau.

In this work, we applied the ESR method to dating of four higher level terraces at the upper reach of the Minjiang River. The quartz Ti-Li center ESR signal (Toyoda *et al.*, 2000; Rink *et al.*, 2007) was used to date the river terrace (T3-T6) samples which could be older than 100 ka assuming an initial zeroing of the signal, because bleaching experiments (Toyoda *et al.*, 2000; Tissoux *et al.*, 2007; Gao *et al.*, 2009) have shown that the quartz Ti-Li center ESR signal can be completely bleached after the equivalent of a few days of direct sunlight exposure, that is very quick for quartz ESR centers. The method promises to provide reliable geochronology for quaternary tectonic uplift and climatic change research.

2. GEOLOGY AND SAMPLING

The Longmen Shan marks the transition between the low-elevation Sichuan Basin (~500 m) and the Tibetan Plateau (~4000 m) and is characterized by a steep topographic transition (**Fig. 1**) (Burchfiel *et al.*, 1995; Chen and Wilson, 1996; Chen *et al.*, 2000). It has a complex structure resulting from a complex multiphase history of three main faults, Wenchuan-Maowen Fault, Beichuan-Yingxiu Fault, Jiangyou-Guanxian Fault (Burchfiel *et al.*, 1995; Chen *et al.*, 1995; Burchfiel *et al.*, 2008). Deformation of the Longmen Shan during Cenozoic time is associated with the Himalayan orogenic cycle and Tibetan Plateau uplift. Despite the rarity of active tectonics markers in this area (Godard *et al.*, 2009), previous studies indicated that the topography in the Longmen Shan apparently developed with minimal shortening of the upper crust during the Tertiary (Dirks *et al.*, 1994; Burchfiel *et al.*, 1995; Royden *et al.*, 1997; Kirby *et al.*, 2002; Zhang *et al.*, 2011). Studies on active faults indicate that the average slip rates (both dip-slip and strike-slip) in tens of millennium time scale are around 1 mm/a, consistent with decadal GPS observations (King *et al.*, 1997; Chen *et al.*, 2000; Zhang *et al.*, 2004; Ma *et al.*, 2005). Those observations lead to important questions on the nature of tectonic and denudation processes along this margin and their potential interactions. It also is pointed out the Longmen Shan region as a critical target to test the geodynamical models proposed to describe the evolution of the region (Godard *et al.*, 2009).

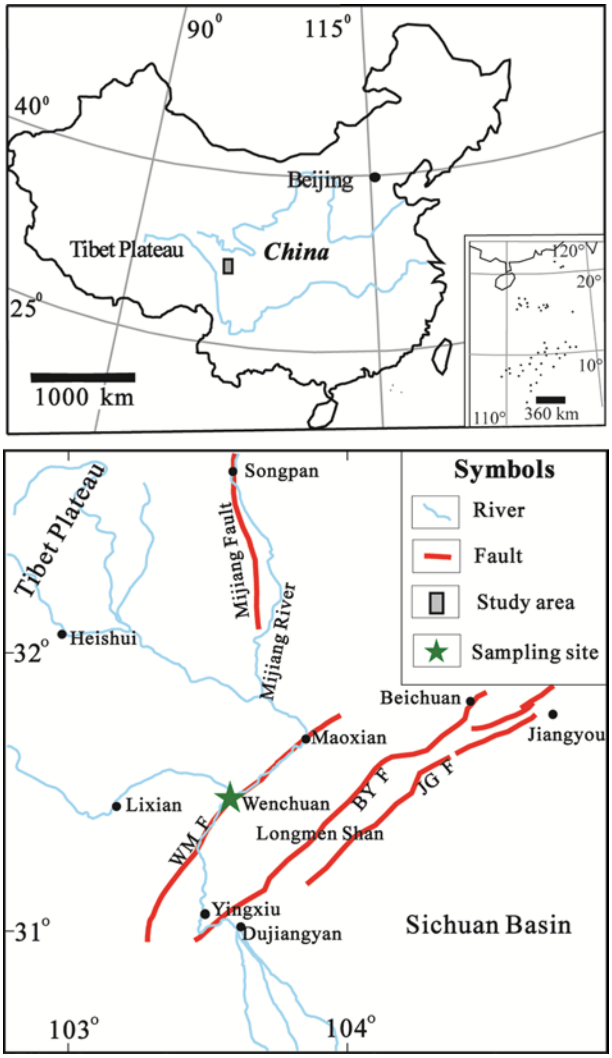

Fig. 1. *Location of ESR sampling, Longmen Shan and Mingjiang River, at the east margin of the Tibet Plateau. WM F: Wenchuan-Maowen Fault; BY F: Beichuan-Yingxiu Fault; JG F: Jiangyou-Guanxian Fault.*

The Minjiang River runs along the eastern margin of the Tibetan Plateau, mostly perpendicularly across the Longmen Shan fault zone. Along the upper reach of the Minjiang River, characterized by sharp V-type valleys, at least six level terraces were developed. A part of these were previously dated by TL or ^{14}C method (Li *et al.*, 2005; Ma *et al.*, 2005). Li *et al.* (2005) identified five level terraces, from T1 to T5, and gave the ages of T1 to T3 by TL and ^{14}C method. In the present study, we identified six level terraces based on previous studies in this area including the characteristics of fluvial sediment and geomorphology, and dated the higher terraces (T3 to T6) using ESR signals in quartz. Thus, we took seven ESR samples from T3 to T6 in the Wenchuan profile (**Fig. 2**). The sampling method is similar as that for OSL dating. We used a stainless tube to keep the sediment sample, and sealed and protected from light.

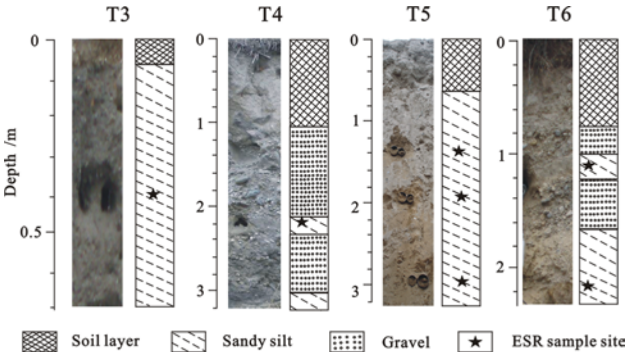

Fig. 2. *Stratigraphy of different terrace layer in the Wenchuan profile, on the upper reach of the Minjiang River at the east margin of the Tibetan plateau and ESR sampling location.*

3. QUARTZ EXTRACTION AND ESR MEASUREMENT

The sample was dried at low temperature. The 105-200 µm fraction was separated by sieving and pure quartz was obtained through chemical separation techniques (Liu *et al.*, 2010a; Liu and Grün, 2011). After drying, the samples were soaked in 15% H_2O_2 for 1 h followed by heavy liquid separation using sodium polytungstate. The samples were then etched by 40% HF for 100 min followed by 10% HCl for 100 min. Magnetic minerals were removed using a magnetic separator after drying. At the end, the grains <90 µm were removed by sieving. Each sample was divided into 200 mg subsamples. These aliquots have received additional gamma doses ranging from 0 to 6500 Gy using the ^{60}Co source of Peking University, Beijing.

The quartz Ti-Li center ESR signal intensity was measured for samples by a BRUKER ER041XG X-band spectrometer at low temperature in a finger dewar cooled to 77 K with liquid nitrogen. The microwave power was 5 mW, modulation amplitude was 0.16 mT, conversion factor was 20.48 ms, time constant was 40.96 ms and spectrum resolution was 2048 bit (resulting in a total sweep time of 41.94 s). The Ti-Li center intensity was measured from the top of the peak at g=1.979 to the bottom at g=1.913 (Rink *et al.*, 2007; Liu *et al.*, 2010a), from P1 to P2 in **Fig. 3**. The angular dependence of the ESR signal due to the sample heterogeneity was taken into account. Each aliquot was measured with six rotations, in which scan six times after every 60° azimuths rotation in the cavity, to obtain the average quartz Ti-Li center ESR intensity.

The dose rate (D) was calculated from the concentrations of U, Th and K of each sample (Aitken, 1998). U

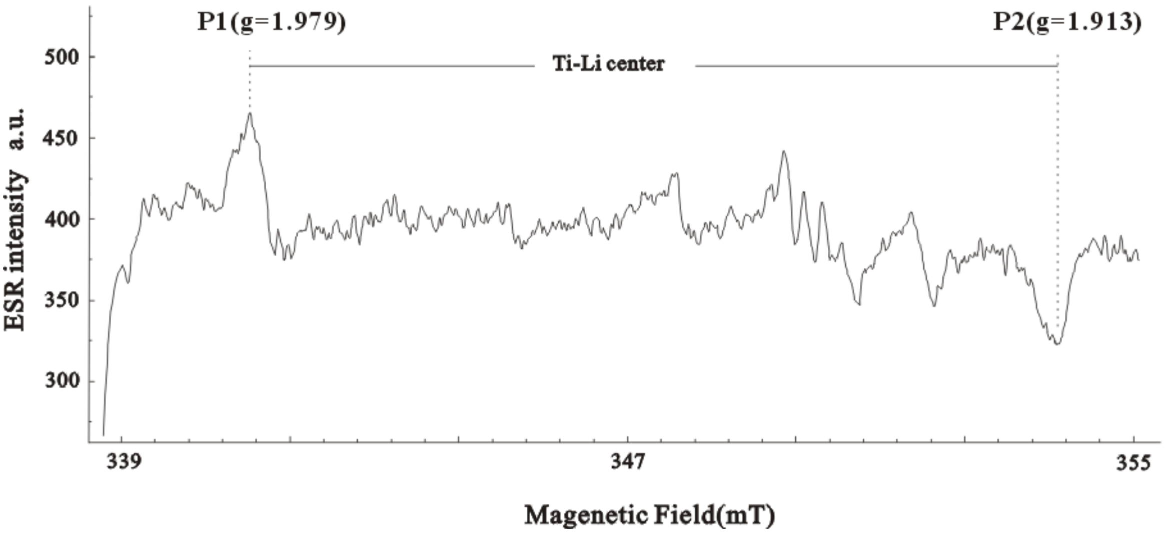

Fig. 3. *ESR spectrum showing the method used to determine the intensity of the quartz Ti-Li center. This is the natural quartz Ti-Li center ESR spectrum of the sample MJ-4.*

and Th contents were obtained using a thick source Daybreak 530 Model alpha counter (Aitken, 1985, 1998). The potassium oxide content was determined by atomic absorption. The water content and grain sizes were considered during age calculation. Cosmic dose rates were calculated at the burial depth and altitude and latitude of the sample (Prescott and Hutton, 1994).

For all samples, the equivalent doses (D_E) values and their individual errors were determined from the dose response data fitted with a single saturating exponential (SSE) function using the protocol described by Yokoyama *et al*. (1985). All D_E values were obtained assuming complete bleaching.

4. RESULT AND DISCUSSION

Voinchet *et al*. (2007) investigated the natural bleaching of quartz ESR signals in modern sediment on the Creuse River (France). The study showed, for the samples collected at about 170 km downstream from its source, that the bleaching of the Ti-Li center of quartz is practically complete and even a total bleaching is observed at 1km downstream from the source. In the present study, the Wenchuan profile located at the upper reach of the Minjiang River (China) from its spring to about 200 km downstream. We took one modern sediment sample of the Minjiang River on the Wenchuan profile. Its quartz ESR spectrum showed that the Ti-Li center was totally bleached (**Fig. 4**). Hence, the assumption that the quartz Ti-Li center ESR signal is bleached to zero before the last sediment was validated.

Fig. 5 shows the dose responses of quartz ESR signal of Ti-Li center observed in the MJ-2 and MJ-3 samples. ESR data and ages of fluvial terraces obtained from the Wenchuan profile at the upper reach of the Minjiang River are shown in **Table 1**. The ESR ages of T3 and T4

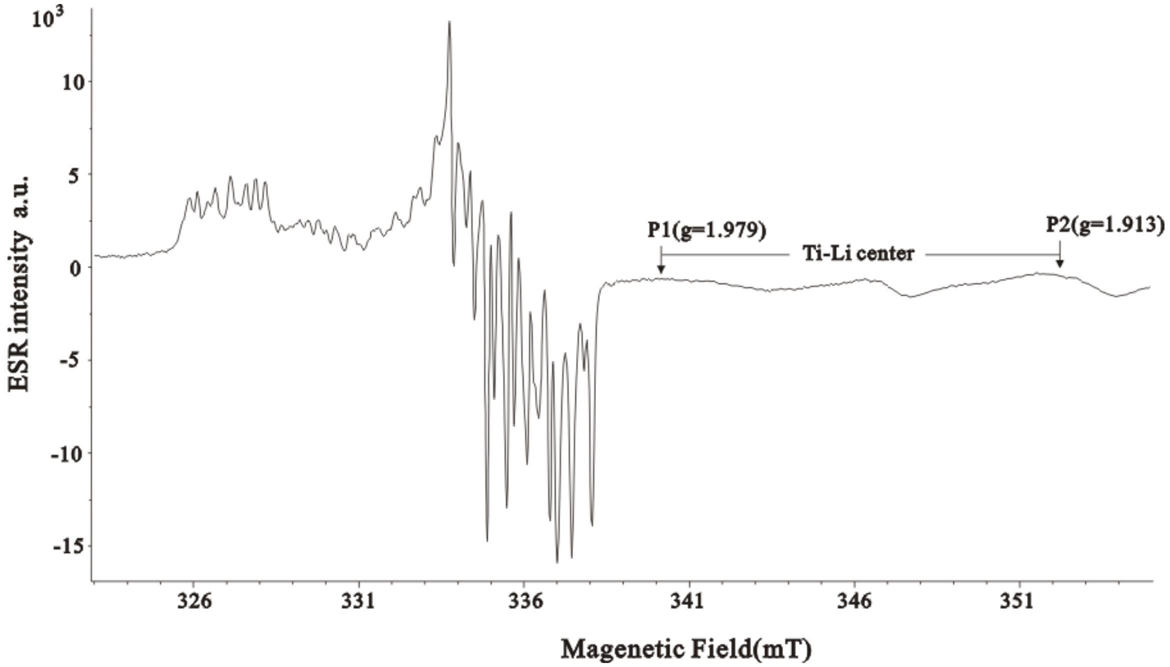

Fig. 4. *ESR spectrum of the modern sediment sample of Minjiang River on the Wenchuan profile. The g value of T1 is 1.979. The g value of T2 is 1.913.*

Table 1. *ESR dating results using quartz Ti-Li center signal from fluvial terrace samples of the Wenchuan profile on the upper reach of the Minjiang River, at the east margin of the Tibetan plateau. The elevation (column 2) is relative to river.*

Sample No.	Elevation (m)	Depth (m)	U (ppm)	Th (ppm)	K_2O (%)	Water (%)	Cosmic dose rate (Gy/ka)	D (Gy/ka)	D_E (Gy)	ESR age (ka)	Terrace level
MJ-1	172	1.2	4.9±0.3	14.8±0.7	2.70±0.14	5±5	0.208±0.011	4.824±0.302	2161±470	450±102	T6
MJ-2	172	2.2	4.3±0.2	13.2±0.7	2.80±0.14	5±5	0.182±0.010	4.631±0.291	1828±576	396±127	
MJ-3	153	1.4	4.6±0.3	14.0±0.7	2.40±0.12	8±5	0.203±0.011	4.329±0.389	624±106	145±29	T5
MJ-4	153	1.9	4.3±0.2	13.0±0.7	2.70±0.14	10±5	0.190±0.010	4.334±0.466	612±150	143±38	
MJ-5	153	3.0	5.1±0.3	15.5±0.8	2.50±0.13	10±5	0.164±0.009	4.509±0.489	762±130	171±34	
MJ-6	101	2.2	5.2±0.3	16.1±0.8	3.40±0.17	4±4	0.182±0.010	5.646±0.310	568±79	101±15	T4
MJ-7	75	0.4	4.6±0.3	14.2±0.7	3.30±0.17	5±5	0.232±0.012	5.258±0.330	336±80	64±19	T3

are 64±19 ka and 101±15 ka respectively. T3 age is consistent with the TL dating result (50.8±3.9 ka) by Li *et al.* (2005) at the Wenchuan profile and (51-58 ka) by Ma *et al*. (2005) at the upper reach of the Minjiang River. Three T5 samples address the ages of 145±29 ka, 143±38 ka, 171±34 ka, with the average of 153±33 ka. Our ESR results show that the ages of T4 and T5 at Wenchuan profile are older than the TL dating results (57.2±4.3 ka and 76.6±5.7 ka) on the Zipingpu (at Dujiangyan, in **Fig. 1**) by Li *et al*. (2005), and these results are consistent with the results that the incision rate is higher at the area of Longmen Shan than Sichuan Basin. The ages of two T6 samples are 450±102 ka and 396±127 ka, with the average of 423±115 ka (**Fig. 6**).

According to our ESR results (**Fig. 7**), two periods of incision are indicated: period one, from T6 to T5, took an average incision rate of 0.07 mm/a and stage two, between T5 and T1, was 1.02 mm/a, which are consistent with the results from the north-east and north margins of the Tibetan Plateau (Li, 1991; Li *et al*., 1996; Porter *et al*., 1992; Pan *et al*., 2009; Liu *et al*., 2010b). The average incision rates of Yellow River near Zaoshugou (north of Lanzhou city, north-east of Tibet Plateau) are 0.033 and 0.346 mm/ka at the period of 0.13-0.8 Ma and 0.13 Ma-present respectively (Pan *et al*., 2009). Therefore, the formation age of terrace at the Wenchuan profile is similar with north and north-east margin of the Tibet margin, and this indicated the spatial and temporal synchronization response to the overall uplifting of the Tibetan Plateau at the margin.

Tectonic movement of the Tibet plateau provides the base to formation of the terrace (Porter *et al*., 1992).

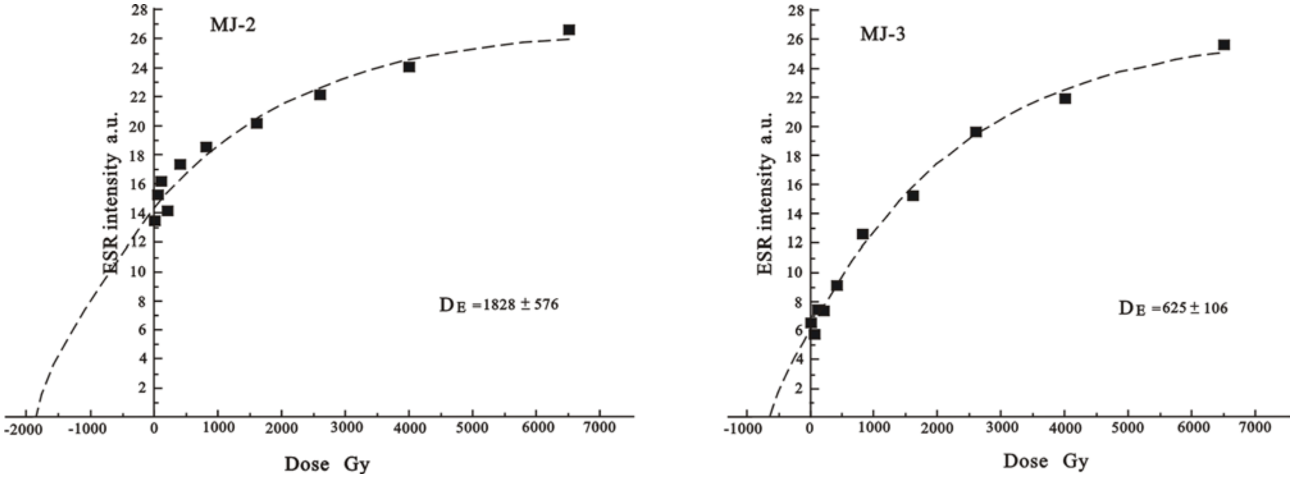

Fig. 5. *The dose responses of quartz ESR signal of Ti-Li center observed in the MJ-2 and MJ-3 samples.*

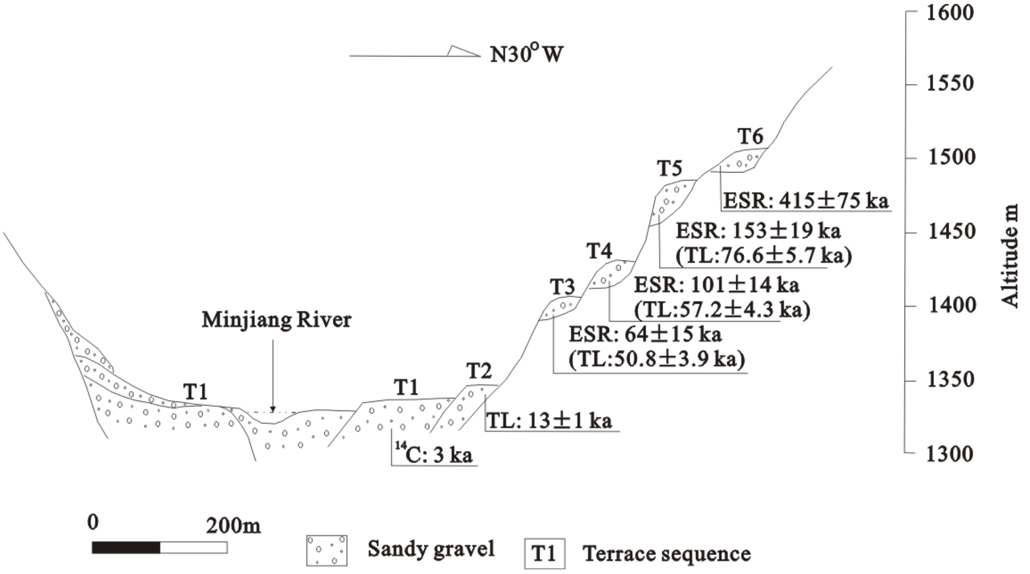

Fig. 6. *The ages of fluvial terrace obtained from the Wenchuan profile on the upper reach of Minjiang River, at the east margin of the Tibetan plateau. The TL and ^{14}C ages refer to Li* et al. *(2005).*

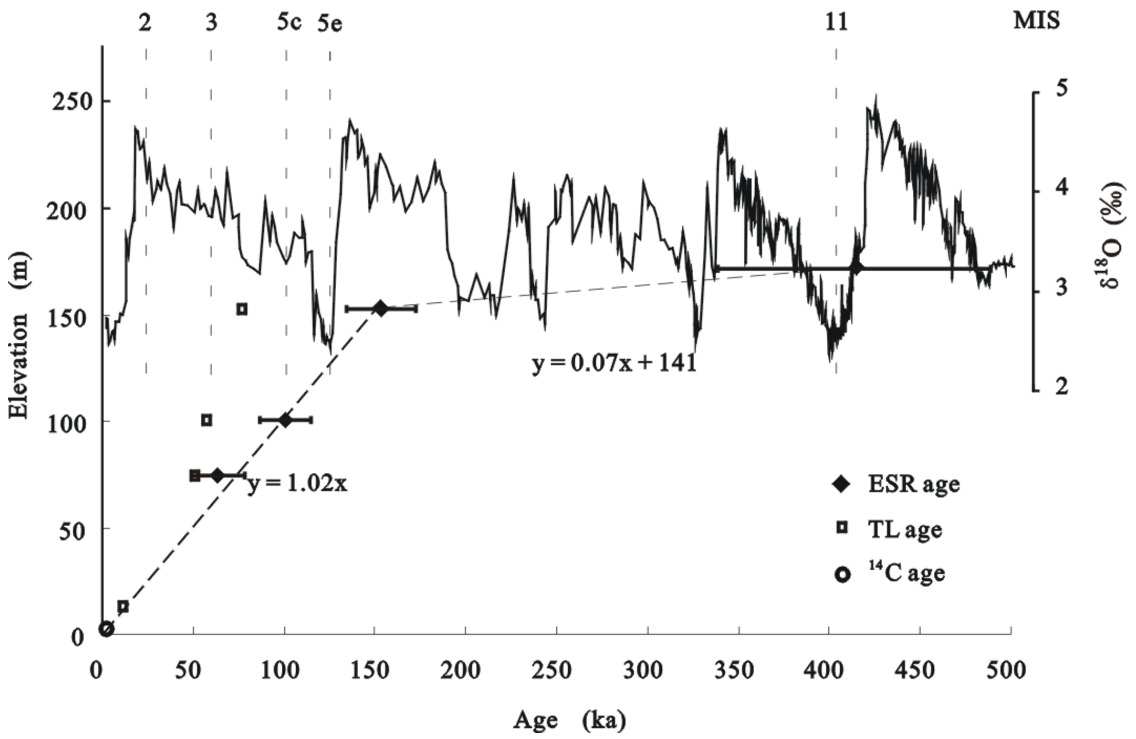

Fig. 7. *The linear relationship observed between terrace elevations and the ages, with marine oxygen isotope changes (Alexander* et al., *2009). The elevation is relative to river.*

While the climate change does affect the terrace development, in this profile T2 addressed MIS2/1, T3 addressed MIS4/3, T4 is for MIS5d/5c, T5 is for MIS6/5e, which is consistent with the results at north margin (Li, 1991, 1996; Liu *et al*., 2010b) and north-east margin (Porter *et al*., 1992) of the Tibet Plateau. This indicated synchronization with other areas of the Tibetan Plateau (Porter *et al*., 1992; Pan *et al*., 2009) and all these lay in glacial to interglacial transition periods as suggested by Pan *et al*. (2009). At Longmen Shan, moisture precipitation is mainly supported by Indian monsoon. During such climatic shift period, the Indian monsoon is strongly controlled by the change in the amount of the glacier at high latitude zone (An *et al*., 2011). At the entrance into an interglacial stage, the increase of precipitation due to the strengthened Indian Monsoon causes larger river incision and forms the terraces if this incision is associated with tectonic uplift.

In Qilian and Lanzhou region, no terrace was discovered between 830 ka and 130 ka accounting for the climate change (Pan *et al*., 2009). It was suggested that, without rapid tectonic uplift, climate change did not form stepped terrace systems at the margin of the Tibet Plateau (Pan *et al*., 2009). However, at the Minjiang River, an age of 423±115 ka, which can be correlated with MIS12/11 period, was obtained for T6 for the first time in this region. An older river terrace, documented by Xu and Zhou (2008) at the Yazheku River, at the eastern margin, was addressed to MIS16. It implies that additional uplifting phases could be taken into account. At the east margin of the Tibet Plateau, Longmen Shan area contains regional erosion uplifting due to the isostasy as suggested by Li *et al*. (2005). This regional uplifting caused by erosion could be temporarily accelerated by the rapid melting of glacier and strengthen of precipitation with regional enhancement of erosion rate during the transition of glacial to interglacial period. This could be another non-negligible driving factor for terrace formations in this region.

5. CONCLUSION

Six terrace levels were investigated in the Wenchuan profile at the upper reach of Minjiang River. The ESR dating method was used to obtain the age of the four higher terraces (T3-T6). Combined with previous research, it showed that T1-T5 was formed since 150 ka ago and T6 was formed at MIS12/11 stage. Both tectonic and climate influenced the formation of these terraces. The river terrace formation exit high synchronization with the uplifting of the Tibet plateau at the different margins. Apart from the whole uplifting of the Tibet plateau, the rapid uplifting due to isostasy is an additional regional tectonic factor to form the terrace in the eastern margin of the Tibetan plateau.

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