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Climatic and tectonic controls on strath terraces along the upper Weihe River in central China

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ABSTRACT

The Weihe River in central China is the largest tributary of the Yellow River and contains a well-developed strath terrace system. A new chronology for the past 1.11 Ma for a spectacular flight of strath terraces along the upper Weihe River near Longxi is defined based on field investigations of loess–paleosol sequences and magnetostratigraphy. All the strath terraces are strikingly similar, having several meters of paleosols that have developed directly on top of fluvial deposits located on the terrace treads. This suggests that the abandonment of each strath terrace by river incision occurred during the transition from glacial to interglacial climates. The average fluvial incision rates during 1.11–0.71 Ma and since 0.13 Ma are 0.35 and 0.32 m/ka, respectively. These incision rates are considerably higher than the average incision rate of 0.16 m/km for the intervening period between 0.71 and 0.13 Ma. Over all our results suggest that cyclic Quaternary climate change has been the main driving factor for strath terrace formation with enhanced episodic uplift.

Introduction

River terraces are common landforms composed of alluvial deposits that occur along the flanks of river valleys in a wide range of climatic and tectonic settings (Bridgland and Westaway, 2008; Pazzaglia, 2013). River downcutting into former active channels and floodplains results in river terrace formation. Aggradation and degradation occur when rivers depart from conditions of equilibrium, which can result in river terraces formation (Bull, 1990). Strath terraces that form when rivers incise into bedrock capping the rock with thin deposits of alluvium are of particular note (Pazzaglia, 2013). Terraces can be used as a geodetic marker to infer climatic, tectonic and other environmental changes that alter the erosional capacity and sediment load of a river when numerically dated (Schumm, 1977; Bull, 1990; Merritts et al., 1994). Yet understanding and quantifying terrace formation, abandonment and any subsequent preservation, remains one of long-standing challenges in geomorphology (Gilbert, 1877; Howard, 1959; Schumm, 1977; Bull, 1990; Bridgland, 2000; Vandenberghe, 2008, 2015; Finnegan and Dietrich, 2011).

In their classic work, Penck and Brückner (1909) concluded that river terraces in the European Alpine foreland correlated with glacial moraines in the Alps. Moreover, in unglaciated regions, terrace formation can be triggered by changes in precipitation, vegetation cover and sediment load during glacial–interglacial climate oscillations (Huntington, 1907). The traditional view of a one-to-one correlation between fluvial activity and climate change has been pervasive for many decades (Büdel, 1977; Starkel, 2003). This view was promoted by Zeuner (1935), who suggested that terrace formation in the lower reaches of rivers is driven by fluctuating sea levels, whereas in areas remote from the sea, climate change produces a contrasting effect, with aggradation during glacial and incision during interglacial climates. Process-related thinking has suggested that sea-level fluctuations significantly affect shelf area but have little effect on drainage basins (Schumm, 1993; Koss et al., 1994). There is now a general consensus that long-time scale flights of river terraces relate to regional uplift and climatic fluctuations (Antoine et al., 2000; Starkel, 2003; Cordier et al., 2006; Bridgland and Westaway, 2008, 2014; Vandenberghe, 2008, 2015). Moreover, Vandenberghe (1995, 2008, 2015) suggested a non-linear model whereby river incision generally occurs during

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times of climatic instability. Abundant geological evidence and numerical models confirm this view (Bridgland and Allen, 1996; Antoine et al., 2000; Mol et al., 2000; Cordier et al., 2006; Vandenberghe et al., 2011).

The northeastern region of the Tibetan Plateau formed as a distant response to the Indian-Eurasian collision zone (Fig. 1a) and is a transitional zone in terms of its lithospheric structure, topography and climate (Li et al., 2014). The Yellow River and its large tributaries, such as the Daxiahe, Taohe, Huangshui and Weihe rivers, originate in this region (Fig. 1a). Most previous work in this region has focused on the history of punctuated Quaternary uplift, proposing that uplift occurred: 1) from 3.6 to 1.5 Ma, named the Qingzang Movement, which resulted in massive molasse deposits around the Tibetan Plateau's margin and the synchronous occurrence of faulted basins within the Tibetan Plateau (Li, 1991; Li et al., 2014, 2015); 2) from 1.2 to 0.6 Ma, named the Kunhuang

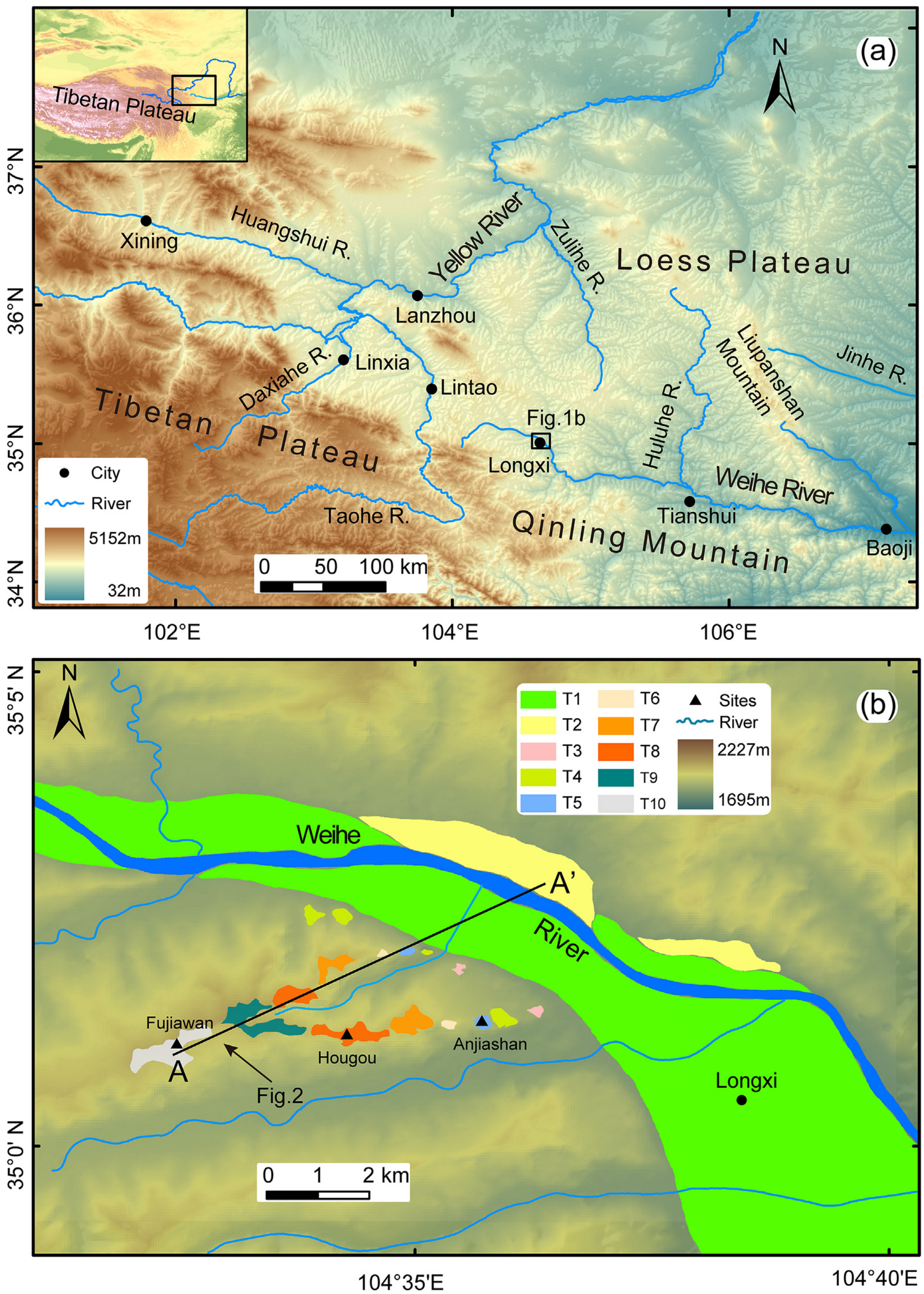

Figure 1. (a) Location of the Longxi Basin in central China. The small black rectangle highlights the study area. (b) Weihe River terraces in the Longxi Basin. Line A–A' defines the cross-valley profile (see Fig. 2).

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Movement, during which the Yellow River entered the Tibetan Plateau by cutting through the Jishi Gorge (Li, 1991), and the Kunlun Pass area was uplifted to >3000 m above sea level (asl) (Cui et al., 1998); and 3) at ~0.15 Ma, named the Gonghe Movement, which is represented by the unconformity into the folded fluvial sediments of the Gonghe Formation, and rapid downcutting of the Yellow River into the Gonghe Formation to form the Longyang Gorge (Li, 1991).

The northeastern Tibetan Plateau has attracted considerable interest in recent decades because it provides one of the most complete terrestrial records of Quaternary environmental and climatic change (Li et al., 1997; Lu et al., 2004; Sun, 2005; Vandenberghe et al., 2011; Wang et al., 2014, 2015). Nevertheless, the nature of the change in climate or rock-uplift that initiated the incision of the rivers in this region remains controversial. According to Lu et al. (2004) and Sun (2005), river terraces in this region reflect elements of the systems attendant on the Indian–Eurasian tectonic collision, in which terraces define episodes of an accelerated northward movement of India towards Asia during the Late Cenozoic. However, the effects of uplift cannot be fully separated from incisions caused by climate change (Li et al., 1997). Climate change driven by variations in Earth's orbital geometry is the major factor that modulates fluvial systems in central China (Porter et al., 1992). Our previous studies have shown that fluvial aggradation occurred during glacial times while river incision between successive terraces took place during the transition from glacial to interglacial times (Pan et al., 2003, 2009). In contrast, Vandenberghe et al. (2011) suggested that the Huangshui River incised slightly during the transition from glacial to interglacial times, while the main incision took place during the next interglacial–glacial transitions. Further studies have shown that terrace abandonment could have occurred during both cold–to–warm and warm–to–cold climatic transitions (Wang et al., 2014, 2015).

In this paper, we examine the Early to Late Pleistocene strath terrace record along the upper Weihe River within the Longxi Basin, and discuss the responses of the river system to climatic variations and tectonic movements during the Quaternary. Strath terraces in this region form in Neogene bedrock, that is beveled and capped by thin alluvium and loess. The ages of the basal units of the capping loess are used to represent the time when rivers incised into the strath terrace. Coupled with detailed magnetostratigraphic studies, grain-size analysis and paleosol investigations at multiple localities, allow us to reconstruction the nature of the terrace formation.

River terraces along the Weihe River in the Longxi Basin

The Weihe River, which is the largest tributary of the Yellow River, rises in the western Qinling Mountains (Fig. 1). The main stream of the Weihe is 818 km in length, and has a drainage area of 1,348,000 km^2. The upper reaches of the main stream are 430 km long, and drain an area of 30,660 km^2, including the western portion of the semiarid Chinese Loess Plateau, and the Qinling and Liupanshan mountain ranges (Fig. 1a). The elevation decreases from over 2500 m asl in the headwaters of the Weihe River to 600 m asl at Baoji, where the river cuts through the mountains and flows into the Guanzhong Basin. The climate of the Weihe catchment is of continental monsoon type. Mean annual precipitation varies between 400 and 600 mm, and ~70% of the rainfall occurs in the form of rainstorms between June and September. The Weihe River is recharged by rainfall, and its inter-annual runoff varies considerably.

The study area focused primarily on the Longxi Basin, which is located at the junction of the Tibetan Plateau, the Chinese Loess Plateau and the Qinling Mountains (Fig. 1). The Longxi Basin developed on the northern side of the north frontal fault zone of the western Qinling Mountains. Thick layers (hundreds of meters) of Cenozoic sequences were deposited from the Oligocene to the Late Miocene, influenced by the northward over-thrust of the fault zone, which depressed the Longxi Basin and thus accommodated any deposition (Z.C. Wang et al., 2006). The deposition in the Longxi Basin underwent strong tectonic deformation that has petered out in successive stages since the Late Miocene. Thick (>250 m) layers of Quaternary loess cap landforms at different elevations in the Longxi Basin. Previous geomorphic studies in the region have revealed a series of step-like planation surfaces and seven river terraces (Gao et al., 2008). More recently, we identified three strath terraces located above terrace T7 and below the step-like planation surfaces, which we call T8–T10 in descending order from lowest to highest (Figs. 1b and 2).

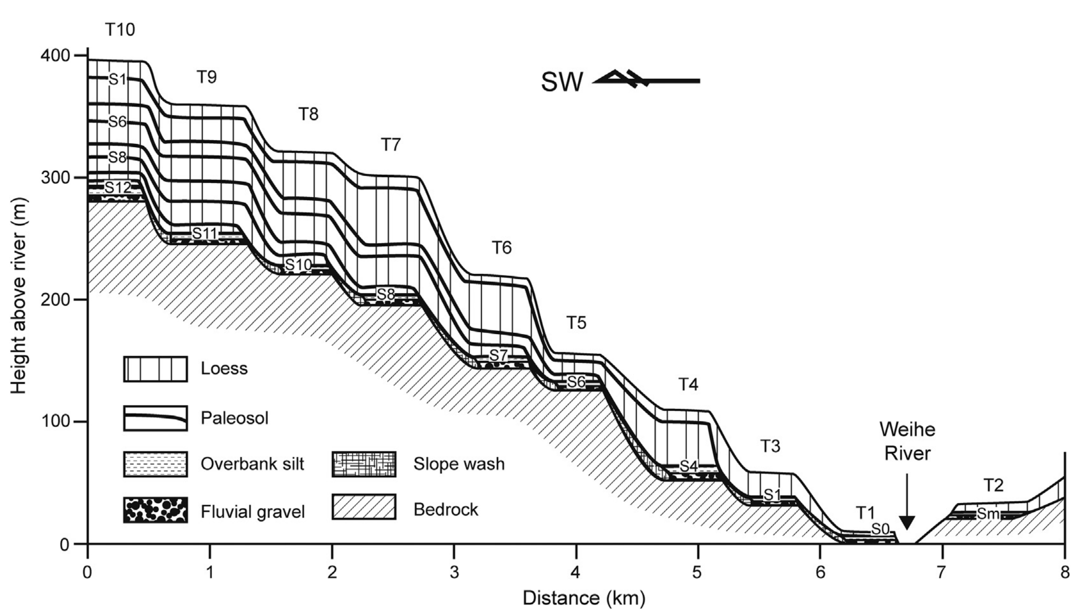

Figure 2. Schematic cross-section of the alluvial terrace sequences along the Weihe River valley, showing the superjacent loess/paleosol stratigraphy that constitutes the basis for assigning ages to alluvial fills. The location is shown in Fig. 1b.

Methods

We conducted field observations to identify the position of each of the three strath terraces, the thickness of capping gravels, overbank deposits and overlying loess, and the number, character and distribution of paleosols within the loess. Strath and gravel elevations were surveyed using a differential GPS system, and uncertainties were estimated to be <5 cm. Basal gravel layers are 282, 246 and 221 m above the modern river level and are covered by ~110, 115 and 100 m of loess, respectively (Fig. 2 and Table 1).

The chronology of the Chinese loess and paleosol units has been established by astronomical tuning, and constrained by use of a revised paleomagnetic polarity timescale (e.g., the bottom age of S1 is 130 ka; Ding et al., 2002; Lisiecki and Raymo, 2005). Therefore, the sedimentary sequence can be used as a dating tool in much the same way that marine oxygen isotope records can be used to provide a continuous chronological framework of climate and associated changes (Bridgland, 2000; Nádor et al., 2003; Maddy et al., 2012). The ages of the strath terraces were estimated by correlating the loess–paleosol successions on terraces of unknown ages with those of the southern and central Chinese Loess Plateau. This provided an estimate to within a Marine Isotope Stage (MIS) of ±10–40 ka. This approach has proven especially useful in assessing the ages of river terraces in the Chinese Loess Plateau, and in the correlation of these terraces with those along the Yellow (Li et al., 1997; Pan et al., 2009), Huangshui (Vandenberghe et al., 2011) and Weihe (Sun, 2005; Gao et al., 2008) rivers. When numeric ages are provided, strath terraces can be used as a geodetic marker to infer tectonic and climatic processing rates. On the basis of strath terrace heights and ages, the measured rates of river incision into bedrock are commonly interpreted as proxies for rates of rock uplift (Maddy, 1997) and indices of the strength of climatic forcing of erosion over time (Porter et al., 1992). The incision rate was measured from the height of one terrace to the next.

We used paleomagnetism and paleosol stratigraphy to establish the chronology of terraces T10, T9 and T8. In a well-exposed natural outcrop, oriented 1000 cm^3 cubic blocks of loess were collected, with geographic north marked on the top surface. In the laboratory, each bar was cut into 8 cm^3 cubic samples using an electric saw. Treatment and testing of samples were conducted in the Paleomagnetic Laboratory of the Key Laboratory of Western China's Environmental Systems (Ministry of Education). All of the samples were measured on 2G-755 cryogenic magnetometers in magnetically-shielded conditions, and were progressively demagnetized to 550 or 580°C. Magnetizations were effectively removed at 250–300°C, such that characteristic remanence directions could be clearly identifiable at temperatures >300°C.

We analyzed the grain-size characteristics of the basal units and loess–paleosol samples of the capping aeolian stratigraphy of terraces T10, T9 and T8 to help characterize loess–paleosol successions in the field (Fig. 3). Samples for particle size analysis were collected at 5 cm intervals. The particle size was measured using a U.K. Mastersizer 2000 laser particle sizer in the Key Laboratory of Western China's Environmental Systems (Ministry of Education) following the methods proposed by Ding et al. (2002) and Prins et al. (2007).

Timing of terrace formation

Grain-size analysis shows that the loess and paleosol samples can be clearly separated into the >16 μm and clay fractions. Further, the samples from the bases of the loess profiles are mostly located in the same zones as the paleosol samples (Fig. 3). Using field investigation results and grain-size analysis, we were able to establish the loess–paleosol stratigraphy of the loess sequences on the three terraces.

Age of terrace T10

Only the lower 25 m of the section was sampled for grain-size analysis due to the development of artificial agricultural terraces, which has disturbed the upper portion of the section. Five paleosol units were identified based on field observation and grain-size analysis (Fig. 4). Approximately 83 paleomagnetic sites (249 subsamples) were sampled at intervals of 0.5 m in the lower portion of Section T10 (0–5 m), and at intervals of 1 m in the upper portion (5–79 m). The magnetostratigraphic results show that the Section T10 contains three normal polarity zones (N1–N3) and three reversed polarity zones (R1–R3; Fig. 4). N1 spans the upper 53.5 m of the sequence; we interpreted the N1/R1 transition as representing the Brunhes–Matuyama (B/M) boundary dated at ~780 ka (Cande and Kent, 1995). Previous magneto-pedostratigraphic studies of the Chinese Loess Plateau have demonstrated that the B/M boundary appears within loess L8 (Liu, 1985; Zhu et al., 1998), and, therefore, we assigned the paleosol unit directly below the B/M boundary to S8. Based on pedostratigraphy, the lower four paleosol units are probably S9–S12. Previous studies have demonstrated that the post-Jaramillo subchron (Kamikatsura and Santa Rosa) and Jaramillo subchron appear typically in intervals within loess L9 and intervals between S10 and S12, respectively (X.S. Wang et al., 2006; Liu et al., 2010). Combining the loess–paleosol stratigraphy with the geomagnetic stratigraphy we obtained, we found that levels corresponded to intervals within L9 for N2, and from S10 to S12 for N3. We, therefore, correlated N2 with the post-Jaramillo subchron (Kamikatsura and Santa Rosa), and N3 with the Jaramillo subchron (0.99–1.07 Ma). The lowermost paleosol S12, corresponding to MIS 33 (Ding et al., 2002), developed at ~1.11 Ma (Lisiecki and Raymo, 2005). We would argue that this

Table 1
Characteristics of the Weihe River terraces near Longxi.

Terrace	Terrace seat (m)*	Thickness of gravel layer (m)	Thickness of fluvial silt (m)	Thickness of loess (m)	Oldest aeolian stratigraphic unit	MIS	Age of incision (ka)
T1		1.5	3–4	1.5–2	S0	1	14
T2	23	3	6	9	Sm	3	57
T3	30	2	6	30	S1	5	130
T4	52	10	6	58.5	S4	11	424
T5	126	2	2–3	33.5	S6	17	712
T6	142	5	4	79	S7	19	790
T7	197	5	3	104.5	S8	21	866
T8	221	2–3	1	100	S10	29	1031
T9	246	6–7	0.5	115	S11	31	1081
T10	282	8–9	2	110	S12	33	1114

* Terrace seat is the elevation (in meters) of the bedrock surface in a terrace.

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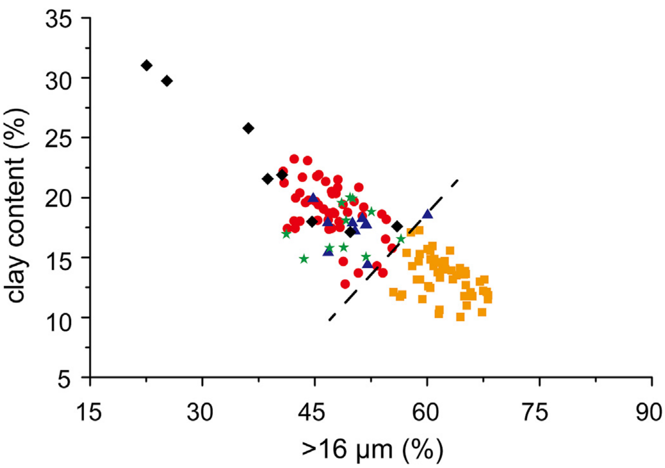

Figure 3. Grain-size properties of overlying aeolian loess deposits identified in this study. The yellow squares and red circles indicate loess and paleosol samples, respectively. Samples taken from the bases of the aeolian loess profiles of terraces T10 (green five-point stars), T9 (black rhombuses) and T8 (blue triangles) are plotted in the photograph. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

age represents the best estimate of terrace abandonment, given that this paleosol lies directly atop fluvial silt, with no intervening loess.

Age of terrace T8

Only the lower 20 m of the Section T8 was sampled because the upper portion of the section was heavily disturbed by farming activity. Five paleosol units within the lower 10 m of the section were identified on the basis of field observations and grain-size analysis (Fig. 4). Approximately 60 paleomagnetic sites (180 subsamples) were sampled at intervals of 0.25 m in the lower portion of the section (0–11 m), and at intervals of 0.5 m in the upper portion (11–19 m). Three normal polarity zones (N1–N3) and two reversed zones (R1–R2) were evident in Section T8 (Fig. 4). As mentioned above, the N1/R1 transition in loess L8 represents the B/M boundary (~780 ka; Cande and Kent, 1995). Therefore, we assigned the paleosol unit at ~5 m above the fluvial silts to S8, and the lowermost paleosol unit to S10. Based on previous studies, we correlated N2 with the post-Jaramillo subchron (Kamikatsura and Santa Rosa), and N3 with the upper Jaramillo subchron. The lowermost paleosol S10, corresponding to MIS 29 (Ding et al., 2002), developed at 1.03 Ma, allowing us to argue that terrace T8 was formed at ~1.03 Ma (Lisiecki and Raymo, 2005).

Age of terrace T9

The fluvial deposits of Terrace T9 were overlain by ~115 m of loess. Calcium cementation was evident within the lower 20 m of the section, which was influenced by the groundwater (Fig. 5). Paleo-gullies were evident in the lower portion of the section (12–20 m) (Fig. 5b). These buried gullies are ubiquitous features of the landscape in the loess regions of central China (Porter and An, 2005). These disturbances might be responsible for the problematic magnetostratigraphic results recorded within this section. Our magnetostratigraphic results show that the reverse stratigraphy contains only one normal polarity zone (N1), except for two reversed samples found at 20 m above the fluvial silts. We deduced that the lowermost paleosol is probably S11, corresponding to MIS 31, based on the geomorphic relations between terraces T10, T9 and T8, field identification of the loess stratigraphy, and grain-size data (Ding et al., 2002). Thus, we estimated that terrace T9 was abandoned at ~1.08 Ma (Lisiecki and Raymo, 2005).

Discussion

A strath terrace surface can be either the top surface of the filled alluvial deposits, or a scour surface formed during lateral channel migration. The terrace forms when the river attains a temporary equilibrium profile and is followed by renewed downcutting. Increasing discharge, or decreasing sediment supply, or a higher channel slope enhances downcutting (Maddy et al., 2012). The changing discharge and sediment supply are generally triggered by climatic fluctuations, while higher channel slopes can be attributed

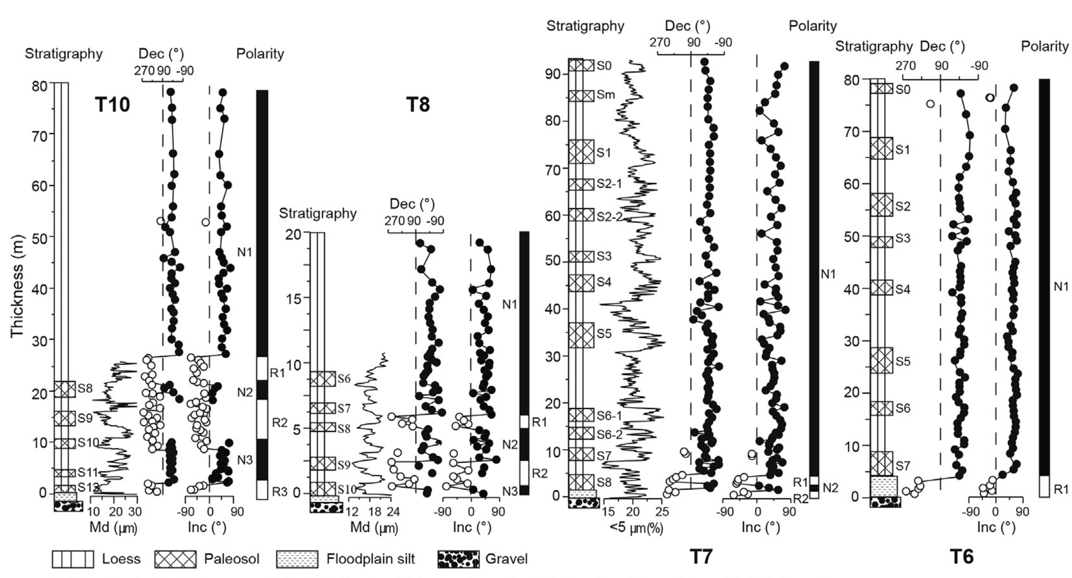

Figure 4. Stratigraphy, grain size, declination, inclination and observed polarity patterns for the loess sequences of terraces T10, T8, T7 and T6. Md denotes median grain size. Terraces T7 and T6 are modified from Gao et al. (2008).

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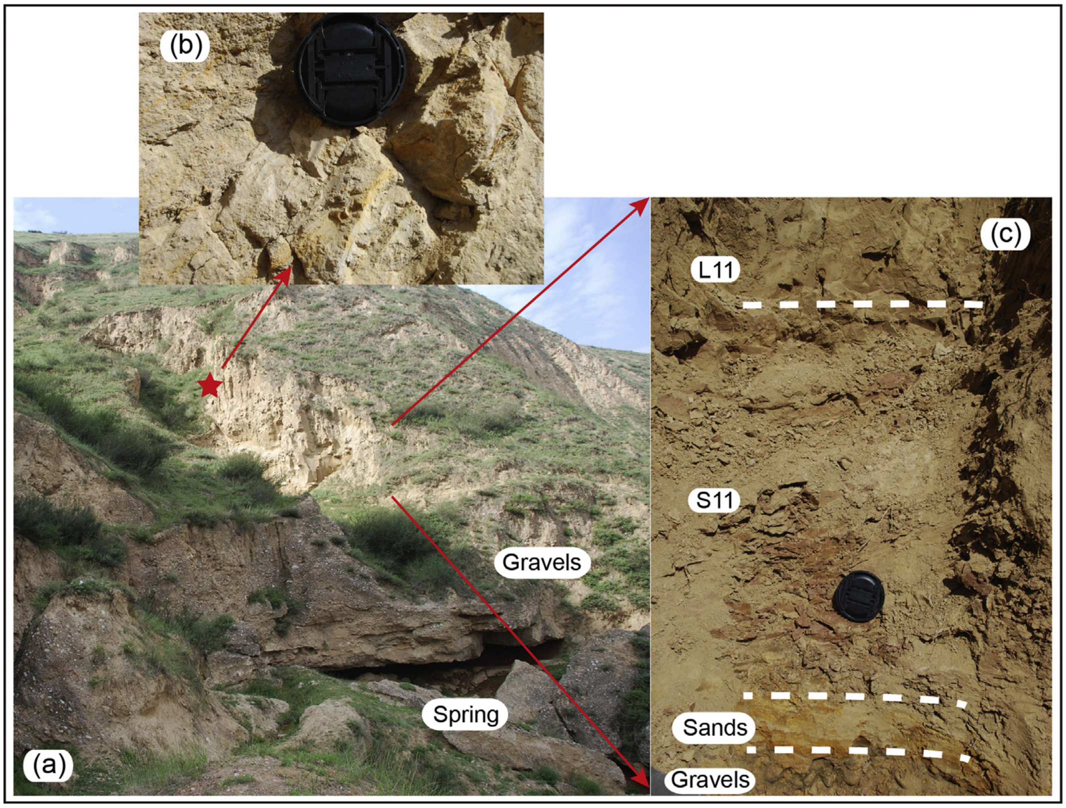

Figure 5. (a) Views of Terrace T9, showing the loess sequences, gravels and springs. (b) Paleo-gully deposits with cross bedding. (c) Lower portion of the T9 Section. The loess and paleosol units, and the overbank sediments, can be identified.

to tectonic uplift and/or base level lowering. Because our study area is located some 2000 km from the nearest coastline, our terraces cannot possibly be influenced by sea-level fluctuations. In this context, we focused on the impact of climate change and tectonic uplift on terrace formation in this area.

Climate change and strath terrace formation

The Weihe River has incised some 300 m into the Longxi Basin, and formed ten strath terraces over the past 1.11 Ma. The formation of six strath terraces (T10–T5) during the mid-Pleistocene transition is approximately consistent with the ~40 ka orbital cycle (with only S9 missing). Similarly, the frequency of the formation of three terraces (T3–T1) during the past 0.13 Ma is entirely consistent with the formation of one terrace per orbital cycle. The frequency of terrace formation appears to match the orbital-driven climate cycle reflected in the LR04 stacked $\delta^{18}O$ marine record (Fig. 6; Lisiecki and Raymo, 2005). However, not every climatic cycle has a corresponding terrace in our study area. Notable 'missing' strath terraces are evident for the glacial–interglacials that include L10–S9, L6–S5, L4–S3 and L3–S2 (Fig. 6). Terraces of these ages might exist in this or other basins, but have not yet been identified or studied. The missing strath terraces in the Longxi Basin might be a consequence of poor preservation, as they might have been destroyed by later fluvial activities.

The loess–paleosol stratigraphy of the terraces is strikingly similar in the way in which the basal paleosol on each terrace is typically developed directly above alluvial silts and sands (Figs. 2 and 3). The deposition of loess during glacial periods and formation of paleosols in warmer interglacial periods, on orbital time scale, has long been known (Liu and Ding, 1998). Our terrace sequences correspond with the orbitally-driven climatic changes which govern fluvial aggradation–incision activity. In this case, fluvial aggradation commonly occurred during glacial periods, whereas stream incision may have occurred during the transitions from glacial to interglacial climates. In general, fluvial behavior is related to climatically-induced changes in vegetation cover and catchment hydrology, which in turn affect the magnitude and frequency of discharge events and the rate of sediment supply (Leigh, 2008; Kasse et al., 2010).

Our study suggests that terrace abandonment largely coincided with the transitions from glacial to interglacial climates. This view is supported by previous studies conducted near the margins of the northeastern Tibetan Plateau (Li et al., 1997; Owen et al., 2006; Gao et al., 2008; Pan et al., 2009). However, Sun (2005) suggested that the lowermost units of the aeolian capping sediments for terraces in the Fenwei Graben are loess. In addition, some studies of the Huangshui River have shown that both loess and paleosols can be identified in the basal units of the aeolian profile, and that the Huangshui terraces were most probably formed during both warm–to–cold and cold–to–warm climatic transitions (Vandenberghe et al., 2011; Wang et al., 2014, 2015). In either case, we can reasonably argue that the general sequence of terrace deposits reflect climatic forcing, although the exact timing needs further investigation.

Temporal variations in rock uplift and terrace development

The collision of the Indian and Eurasian continental plates led to the tectonic uplift of Tibet and caused a series of large-scale strike-slip faults along the northern and northeastern margins of Tibet (Tapponnier et al., 2001; Li et al., 2014). The southeast-trending

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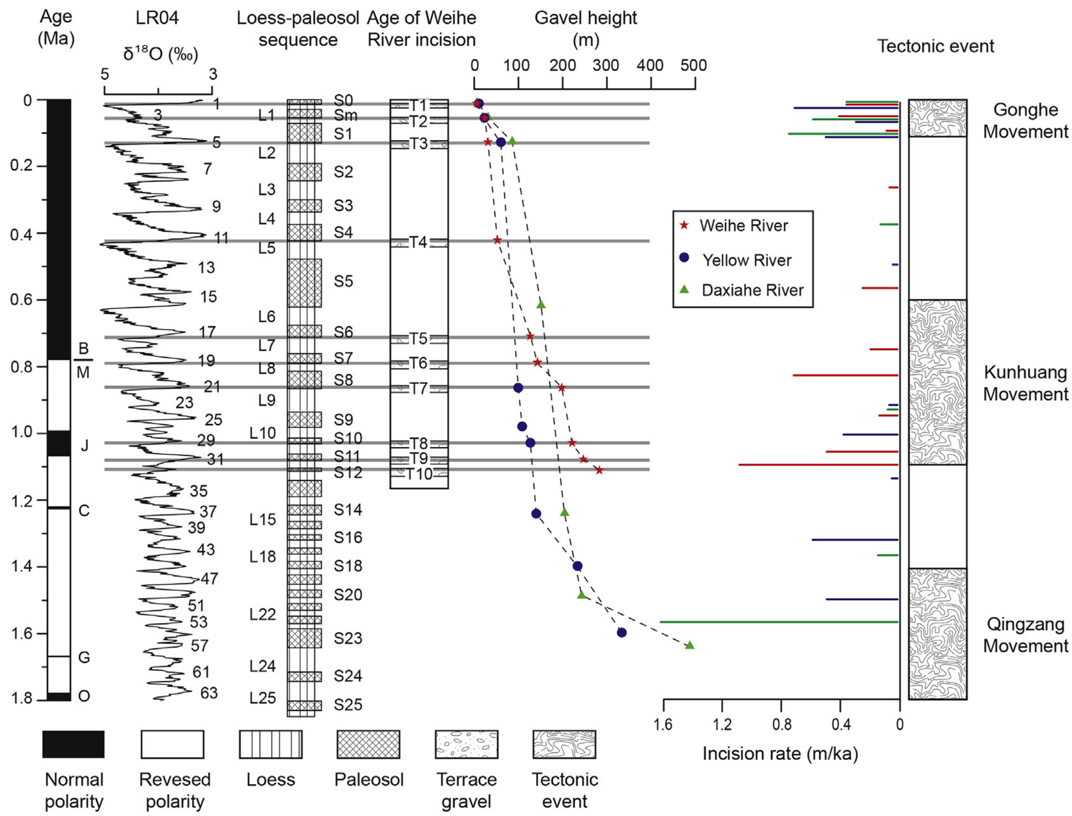

Figure 6. Correlation of the incision of river terraces in the Longxi, Lanzhou and Linxia basins compared to the global marine oxygen isotope climate record (Lisiecki and Raymo, 2005) and the paleosol development in the loess covering the terraces. The red, blue and green lines illustrate the incision rates of the Weihe, Yellow and Daxiahe rivers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sinistral fault, the West Qinling Fault along the Qinling Mountains, and Quaternary faulting in and around this area, all show that this region remains tectonically active (Peltzer et al., 1985; Kirby et al., 2007). In addition, crustal loading and unloading resulting indirectly from Quaternary climatic forcing might drive tectonic uplift (Westaway, 2002; Westaway et al., 2003). These crustal deformations create regionally elevated terrain that provides the potential energy for river incision, although tectonic uplift and any isostatic rebound are notoriously difficult to quantify (Molnar and England, 1990).

By comparing adjacent terrace ages and their elevation (Fig. 6), the amount of river incision can be inferred over a given time interval. The incision–aggradation cycles of the sequences of the Weihe River show large variances in their incision rates. From 1.11 to 0.71 Ma, a significant downcutting of the riverbed occurred; the average incision rate during this time was ~0.35 m/ka. A second episode of strong downcutting was initiated at 0.13 Ma (the formation of terrace T3), with an average incision rate of >0.32 m/ka. However, the rate of downcutting appears to have slowed to a fairly constant level of ~0.16 m/ka between 0.71 and 0.13 Ma. In the neighboring Lanzhou Basin, this change, involving two increases in the rate of incision, is recorded in the terrace sequences of the Yellow River, where defined by loess–paleosol stratigraphy, paleomagnetism and luminescence dating (Pan et al., 2009). We calculate average incision rates of 0.08 m/ka for the period between 1.2 and 0.8 Ma, and 0.35 m/ka for the period after 0.13 Ma. Between 0.8 and 0.13 Ma, the incision rate decreased to 0.03 m/ka. In the Linxia Basin, incision rates for the Daxiahe River also show that river incision has not been constant throughout the Quaternary. From 1.66 to 1.4 Ma, a significant downcutting occurred, with an incision rate of 1 m/ka (Li et al., 1997). Thereafter, the incision rate slowed to a fairly constant level of ~0.11 m/ka. A second episode of strong downcutting was initiated at 0.12 Ma, with an incision rate of 0.75 m/ka (Li et al., 1997).

Although river incision rates cannot be used directly to evaluate regional uplift (Finnegan et al., 2014), we can roughly estimate the tendency of regional uplift to affect incision rates on the assumption that the terrace gradients are similar to that of the contemporary river, i.e., each terrace represents a quasi-equilibrium profile adjusted to the regional uplift (Maddy, 1997). In such an active tectonic region, the two enhanced downcutting periods experienced by the Weihe River, during ~1.1–0.71 Ma, and from 0.13 Ma to the present, might be attributed to the accelerated uplift of the western Qinling Mountains during these periods, coinciding with the Kunhuang and Gonghe movements (Li et al., 2015), respectively. In addition, the ages of these Weihe river terraces also correlate with periods of accelerated northward movement of the Indian Plate towards the Eurasian Plate, providing some dating constraints on the Tibetan Plateau's episodic uplift during the Quaternary.

Conclusions

Ten strath terraces were mapped along the Weihe River within the Longxi Basin, and are composed of basal channel gravels and alluvial silts, and are overlain by thick loess–paleosol deposits. Stratigraphic loess–paleosol studies of the aeolian deposits on the top of the ten terraces (T10–T1) indicate that the basal layers of these loess deposits are S12, S11, S10, S8, S7, S6, S4, S1, Sm and S0, and correspond to MIS 33 (T10), 31 (T9), 29 (T8), 21 (T7), 19 (T6), 17 (T5), 11 (T4), 5 (T3), 3 (T2), and 1 (T1). This record indicates that the fluvial aggradation and incision in the upper Weihe River can be linked to climate change, with fluvial aggradation commonly occurred during glacial times, whereas river incision occurred during the transition from glacial to interglacial times.

Tectonic deformation provides additional forcing that amplifies elevational contrasts along the length of the Weihe River helping to drive long-term fluvial incision. Two enhanced downcutting periods are evident between ~1.1 and 0.71 Ma, and 0.13 Ma and the present day, possibly a consequence of accelerated uplift of the western Qinling Mountains.

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References

Antoine, P., Lautridou, J.P., Laurent, M., 2000. Long-term fluvial archives in NW France: response of the Seine and Somme rivers to tectonic movements, climatic variations and sea-level changes. Geomorphology 33, 183–207.

Bridgland, D.R., 2000. River terrace systems in north-west Europe: an archive of environmental change, uplift and early human occupation. Quaternary Science Reviews 19, 1293–1303.

Bridgland, D.R., Allen, P., 1996. A revised model for terrace formation and its significance for the early middle Pleistocene terrace aggradations of north-east Essex, England. In: Turner, C. (Ed.), The Early Middle Pleistocene in Europe. Balkema, Rotterdam, The Netherlands, pp. 121–134.

Bridgland, D.R., Westaway, R., 2008. Climatically controlled river terrace staircases: a worldwide Quaternary phenomenon. Geomorphology 98, 285–315.

Bridgland, D.R., Westaway, R., 2014. Quaternary fluvial archives and landscape evolution: a global synthesis. Proceedings of the Geologists' Association 125, 600–629.

Büdel, J., 1977. Klima-Geomorphologie. Gebrüder Bornträger, Berlin.

Bull, W.B., 1990. Stream-terrace genesis: implications for soil development. Geomorphology 3, 351–367.

Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research 100, 6093–6095.

Cordier, S., Harmand, D., Frechen, M., Beiner, M., 2006. Fluvial system response to middle and upper Pleistocene climate change in the Meurthe and Moselle valleys (Eastern Paris Basin and Rhenish Massif). Quaternary Science Reviews 25, 1460–1474.

Cui, Z.J., Wu, Y.Q., Liu, G.N., 1998. Discovery and character of the Kunlun-Yellow River movement. Chinese Science Bulletin 43, 833–836.

Ding, Z.L., Derbyshire, E., Yang, S.L., Yu, Z.W., Xiong, S.F., Liu, T.S., 2002. Stacked 2.6-Ma grain size record from the Chinese loess based on five sections and correlation with the deep-sea $\delta^{18}O$ record. Paleoceanography 17, 5–1–21.

Finnegan, N.J., Dietrich, W.E., 2011. Episodic bedrock strath terrace formation due to meander migration and cutoff. Geology 39, 143–146.

Finnegan, N.J., Schumer, R., Finnegan, S., 2014. A signature of transience in bedrock river incision rates over timescales of 10^4–10^7 years. Nature 505, 391–394.

Gao, H.S., Liu, X.F., Pan, B.T., Wang, Y., Yu, Y.T., Li, J.J., 2008. Stream response to Quaternary tectonic and climatic change: evidence from the upper Weihe River, central China. Quaternary International 186, 123–131.

Gilbert, G.K., 1877. Report on the Geology of the Henry Mountains. Geographical and Geological Survey, U.S.. Rocky Mountain Region, 160pp.

Howard, A.D., 1959. Numerical systems of terrace nomenclature: a critique. The Journal of Geology 67, 239–243.

Huntington, E., 1907. Some characteristics of the glacial period in non-glaciated regions. Geological Society of America Bulletin 18, 351–388.

Kasse, C., Bohncke, S.J.P., Vandenberghe, J., Gábris, G., 2010. Fluvial style changes during the last glacial-interglacial transition in the middle Tisza valley (Hungary). Proceedings of the Geologists' Association 121, 180–194.

Kirby, E., Harkins, N., Wang, E.Q., Shi, X.H., Fan, C., Burbank, D., 2007. Slip rate gradients along the eastern Kunlun fault. Tectonics 26, 1–26. TC2010.

Koss, J.E., Ethridge, F.G., Schumm, S.A., 1994. An experimental study of the effects of base-level change on fluvial, coastal plain and shelf systems. Journal of Sedimentary Research 64, 90–98.

Leigh, D.S., 2008. Late Quaternary climates and river channels of the Atlantic coastal plain, southeastern USA. Geomorphology 101, 90–108.

Li, J.J., 1991. The environmental effects of the uplift of the Qinghai-Xizang plateau. Quaternary Science Reviews 10, 479–483.

Li, J.J., Fang, X.M., Van der Voo, R., Zhu, J.J., Niocaill, C.M., Ono, Y., Pan, B.T., Zhong, W., Wang, J.L., Sasaki, T., Zhang, Y.T., Cao, J.X., Kang, S.C., Wang, J.M., 1997. Magnetostratigraphic dating of river terraces: rapid and intermittent incision by the Yellow River of the northeastern margin of the Tibetan plateau during the Quaternary. Journal of Geophysical Research 102, 10121–10132.

Li, J.J., Fang, X.M., Song, C.H., Pan, B.T., Ma, Y.Z., Yan, M.D., 2014. Late Miocene–Quaternary rapid stepwise uplift of the NE Tibetan plateau and its effects on climatic and environmental changes. Quaternary Research 81, 400–423.

Li, J.J., Zhou, S.Z., Zhao, Z.J., Zhang, J., 2015. The Qingzang movement: the major uplift of the Qinghai-Tibetan plateau. Science China: Earth Sciences 58, 2113–2122.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20, 1–17.

Liu, T.S., 1985. Loess and the Environment. Science Press, Beijing (in Chinese).

Liu, T.S., Ding, Z.L., 1998. Chinese loess and the paleomonsoon. Annual Reviews of Earth and Planetary Sciences 26, 111–145.

Liu, W.M., Zhang, L.Y., Sun, J.M., 2010. High resolution magnetostratigraphy of the Luochuan loess-paleosol sequence in the central Chinese loess plateau. Chinese Journal of Geophysics 53, 888–894 (in Chinese, with English Abstract).

Lu, H.Y., Wang, X.Y., An, Z.S., Miao, X.D., Zhu, R.X., Ma, H.Z., Li, Z., Tan, H.B., Wang, X.Y., 2004. Geomorphologic evidence of phased uplift of the northeastern Qinghai-Tibet plateau since 14 million years ago. Science in China (Series D) 47, 822–833.

Maddy, D., 1997. Uplift-driven valley incision and river terrace formation in southern England. Journal of Quaternary Science 12, 539–545.

Maddy, D., Demir, T., Veldkamp, A., Bridgland, D.R., Stemerdink, C., van der Schriek, T., Schreve, D., 2012. The obliquity-controlled early Pleistocene terrace sequence of the Gediz River, western Turkey: a revised correlation and chronology. Journal of the Geological Society 169, 67–82.

Merritts, D.J., Vincent, K.R., Wohl, E.E., 1994. Long river profiles, tectonism, and eustasy: a guide to interpreting fluvial terraces. Journal of Geophysical Research 99, 14031–14050.

Mol, J., Vandenberghe, J., Kasse, C., 2000. River response to variations of periglacial climate. Geomorphology 33, 131–148.

Molnar, P., England, P., 1990. Late Cenozoic uplift of mountain ranges and global climate change: chicke or egg? Nature 346, 29–34.

Nádor, A., Lantos, M., Tóth-Makk, Á., Thamó-Bozsó, E., 2003. Milankovitch-scale multi-proxy records from fluvial sediments of the last 2.6 Ma, Pannonian Basin, Hungary. Quaternary Science Reviews 22, 2157–2175.

Owen, L.A., Finkel, R.C., Ma, H.Z., Barnard, P.L., 2006. Late Quaternary landscape evolution in the Kunlun Mountains and Qaidam Basin, Northern Tibet: a framework for examining the links between glaciations, lake level changes and alluvial fan formation. Quaternary International 154–155, 73–86.

Pan, B.T., Burbank, D., Wang, Y.X., Wu, G.J., Li, J.J., Guan, Q.Y., 2003. A 900 ky record of strath terrace formation during glacial-interglacial transitions in northwest China. Geology 31, 957–960.

Pan, B.T., Su, H., Hu, Z.B., Hu, X.F., Gao, H.S., Li, J.J., Kirby, E., 2009. Evaluating the role of climate and tectonics during non-steady incision of the Yellow River: evidence from a 1.24 Ma terrace record near Lanzhou, China. Quaternary Science Reviews 28, 3281–3290.

Pazzaglia, F.J., 2013. Fluvial terraces. In: Shroder, J., Wohl, E. (Eds.), Treatise on Geomorphology, Fluvial Geomorphology, vol. 9. Academic Press, San Diego, CA, pp. 379–412.

Peltzer, G., Tapponier, P., Zhang, Z.T., Xu, Z.Q., 1985. Neogene and Quaternary faulting in and along the Qinling Shan. Nature 317, 500–505.

Penck, A., Brückner, E., 1909. Die Alpen im Eiszeitalter. Tauchnitz, Leipzig (in Italian).

Porter, S.C., An, Z.S., Zheng, H.B., 1992. Cyclic Quaternary alluviation and terracing in a nonglaciated drainage basin on the north flank of the Qinling Shan, central China. Quaternary Research 38, 157–169.

Porter, S.C., An, Z.S., 2005. Episodic gullying and paleomonsoon cycles on the Chinese loess plateau. Quaternary Research 64, 234–241.

Prins, M.A., Vriend, M., Nugteren, G., Vandenberghe, J., Lu, H.Y., Zheng, H.B., Weltje, G.J., 2007. Late Quaternary aeolian dust input variability on the Chinese Loess Plateau: inferences from unmixing of loess grain-size records. Quaternary Science Reviews 26, 230–242.

Schumm, S.A., 1977. The Fluvial System. John Wiley, New York.

Schumm, S.A., 1993. River response to baselevel change: implications for sequence stratigraphy. The Journal of Geology 101, 279–294.

Starkel, L., 2003. Climatically controlled terraces in uplifting mountain areas. Quaternary Science Reviews 22, 2189–2198.

Sun, J.M., 2005. Long-term fluvial archives in the Fen Wei Graben, central China, and their bearing on the tectonic history of the India-Asia collision system during the Quaternary. Quaternary Science Reviews 24, 1279–1286.

Tapponnier, P., Xu, Z.Q., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., Yang, J.S., 2001. Oblique stepwise rise and growth of the Tibet Plateau. Science 294, 1671–1677.

Vandenberghe, J., 1995. Timescales, climate and river development. Quaternary Science Reviews 14, 631–638.

Vandenberghe, J., 2008. The fluvial cycle at cold–warm–cold transitions in lowland regions: a refinement of theory. Geomorphology 98, 275–284.

Vandenberghe, J., 2015. River terraces as a response to climatic forcing: formation processes, sedimentary characteristics and sites for human occupation. Quaternary International 370, 3–11.
Vandenberghe, J., Wang, X.Y., Lu, H.Y., 2011. Differential impact of small-scaled tectonic movements on fluvial morphology and sedimentology (the Huang Shui catchment, NE Tibet Plateau). Geomorphology 134, 171–185.
Wang, X.S., Yang, Z.Y., Løvlie, R., Sun, Z.M., Pei, J.L., 2006. A magnetostratigraphic reassessment of correlation between Chinese loess and marine oxygen isotope records over the last 1.1 Ma. Physics of the Earth and Planetary Interiors 159, 109–117.
Wang, X.Y., van Balen, R., Yi, S.W., Vandenberghe, J., Lu, H.Y., 2014. Differential tectonic movements in the confluence area of the Huang Shui and Huang He rivers (Yellow River), NE Tibetan Plateau, as inferred from fluvial terrace positions. Boreas 43, 469–484.
Wang, X.Y., Vandenberghe, J., Yi, S.W., van Balen, R., Lu, H.Y., 2015. Climate-dependent fluvial architecture and processes on a suborbital timescale in areas of rapid tectonic uplift: an example from the NE Tibetan Plateau. Global and Planetary Change 133, 318–329.
Wang, Z.C., Zhang, P.Z., Zhang, G.L., Li, C.Y., Zheng, D.W., Yuan, D.Y., 2006. Tertiary tectonic activities of the north frontal fault zone of the west Qinling mountains: implications for the growth of the northeastern margin of the Qinghai-Tibetan plateau. Earth Science Frontiers 13, 119–135 (in Chinese, with English Abstract).
Westaway, R., 2002. Long-term river terrace sequences: evidence for global increases in surface uplift rates in the Late Pliocene and early Middle Pleistocene caused by flow in the lower continental crust induced by surface processes. Netherlands Journal of Geosciences 81, 305–328.
Westaway, R., Bridgland, D., Mishra, S., 2003. Rheological differences between Archaean and younger crust can determine rates of Quaternary vertical motions revealed by fluvial geomorphology. Terra Nova 15, 287–298.
Zeuner, F.E., 1935. The Pleistocene chronology of central Europe. Geological Magazine 72, 350–376.
Zhu, R.X., Pan, Y.X., Guo, B., Liu, Q.S., 1998. A recording phase lag between ocean and continent climate changes: constrained by the Matuyama/Brunhes polarity boundary. Chinese Science Bulletin 43, 1593–1598.