Dating and genesis of the upper Weihe River terraces in Longxi basin, China*

Pan Baotian**, Liu Xiaofeng, Gao Hongshan, Wang Yong and Li Jijun

(Key Laboratory of Western China's Environmental System, Ministry of Education, Lanzhou University, Lanzhou 730000, China)

Accepted on May 21, 2007

Abstract Seven terraces along the Weihe River in Longxi basin have been investigated. These terraces all consist of archetypal duality in structure, namely the floodplain deposits and the layer of gravels overlaid by varying thickness of the loess. By resorting to various dating approaches such as palaeomagnetic, optically stimulated luminescenece (OSL), ^{14}C and loess-paleosol sequence, we provide preliminary timing of these seven terraces along upper Weihe River. Analysis on sedimentation characteristics and dating of these terraces showed that seven terraces may be jointly generated by tectonic uplifts and climatic changes. Tectonic uplifts may accommodate initial river incision, and climatic change may be responsible for processes of subsequent channel widening and aggradation. Aggradation normally occurs during glacial periods, in contrast to down-cuttings during transitions from glacial to interglacial period. Moreover, on the basis of the timings and heights of these terraces, we infer that the long-term rate of river incision was determined to be 0.2 m/kyr during the last 870 kyr, which differs from other river incision rates. This discrepancy may reflect spatio-temporal differentiation of tectonic activities in the Qinling orogenic belt during the Pleistocene.

Keywords: loess stratigraphy, river terraces, climate change, Upper Weihe River.

Weihe River belongs to the classic tributary of Yellow River, whose formation and evolution had been widely studied during the last century, but the results drew different conclusions. Clapp[1] and Babour[2] considered that Weihe River may very likely be the paleo-channel of the Yellow River. Ding[3] proposed that the Yellow River flowed into Weihe River via Taohe River during the Miocene-Pliocene, and the upper reaches of these two rivers had been separated in response to the uplift of Longxi region during early Pleistocene. But Xu[4] argued that this uplift event occurred during the late stage of early Pleistocene. Based on the research for Cenozoic sediment strata, Lin et al.[5] indicated that the current river channel of Weihe River was very likely occupied by the Yellow River during the Eocene, and the Yellow River bending around the Ordos block came into being during late Miocene to early Pliocene. Chen et al.[6] proposed that Weihe River cut through the Baoji gorge around 0.5 Myr. BP. In view of the prevailing opinion that river terraces have been regarded as direct evidence for the existence of river channels and fluvial geomorphological evolutions, great efforts to improve our understanding toward Weihe River terraces have been made by both Chinese and international scholars. Five terraces have been identified along Weihe River in Baoji, being interpreted as a result of the collision between Indian and Eurasian plates. Among these terraces, the highest terrace T_5 was dated to 1.2 Myr by Lei et al.[7, 8], and to about 2.6 Myr by Sun[9]. By investigating the terraces of Bahe River, a tributary of Weihe River, Porter et al.[10] proposed that these terraces were the result of the actions of climatic changes during the Pleistocene. However, for the upper Weihe River above Baoji gorge, an area located at the junction of the Tibet Plateau, the Loess Plateau and the Qinling mountains (Fig.1), and also situated in margin of "monsoon triangle"[11], there was almost no precise dating of terraces formation[4, 12], therefore a clear evolution history is unknown. In this region active tectonic movements and frequent climate changes controlled terrain formation and evolution[13—15], making this region suitable for the study of the process of terrace formation.

* Supported by National Natural Science Foundation of China (Nos. 40401007, 40471016, 40421101), and the National Program on Key Basic Research Project (No. 2005CB422001)

** To whom correspondence should be addressed. E-mail: panbt@lzu.edu.cn

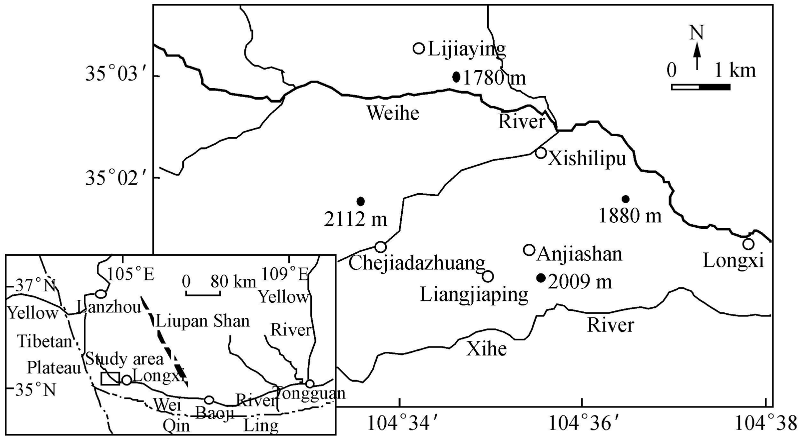

Fig. 1. Location of the study area and sites referred to in the text.

1 Weihe River terrace sequences in Longxi basin

Weihe River originates from Niaoshushan Mountains in Weiyuan, Gansu Province, flowing to the east along the northern flank of Qinling, and joining the Yellow River in Tongguan City, Shaan'xi Province, extending 818 km (Fig. 1). The upper Weihe River channel is narrow, where many basins are connected by valleys. Longxi basin lies in the mountains of upper Weihe River, and is only 50 km to the headwaters. The tertiary red clay is widely distributed in Longxi basin, and seven terraces are well developed at Anjiashan (Figs. 1 and 2).

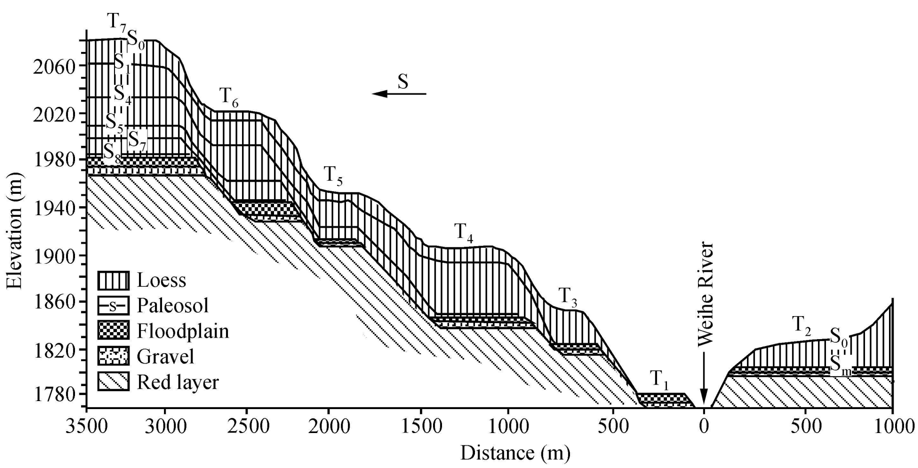

Fig. 2. Weihe River terrace sequences in Longxi Basin.

Terrace 7 (T_7) is a strath terrace with red clay as the bedrock, which is 1977 m above sea level (a.s.l) and 197 m above the modern river bed. This terrace is well exposed at Liangjiping along the southern bank of Weihe River. The thickness of the gravel layer is 5 m, which mainly consists of steel grey aleurite sandstone and red sandstone, and a few conglomerate and quartzite, and the biggest grain diameter is 40 cm. A 20 cm-thick red coarse sand layer is deposited on the gravel, overlaid by a 3 m-thick silt layer of floodplain deposits with horizontal bedding. These fluvial deposits are mantled by 104.5 m of aeolian loess.

The bedrock (red clay) of terrace 6 (T_6) is about 1922 m a.s.l in height, and the strath is about 142 m above the present Weihe River bed. This terrace is well exposed at Anjiashan along the southern bank of Weihe River. The 5 m-thick of river gravels and 4 m-thick of red and caesious coarse sand with horizontal bedding are deposited on the red clay. The gravels are mainly sub-round in shape, brownish in color and with a maximum diameter of 30 cm. The loess sequence is about 79 m-thick overlying on the gravel and sand layers.

The bedrock of terrace 5 (T_5) has an elevation of about 1922 m a.s.l, and 126 m above the present river bed. The terrace fill consists primarily of 2 m-thick fluvial gravel and 2 to 3 m-thick alluvial silt, overlaid by a 33.5 m-thick loess. The gravel layer is characterized by a mixture of gravels and clay, and the biggest gravel is over 20 cm in diameter, whose lithological feature is composed of sandstone and fine quartzite.

Terrace 4 (T_4) is a strath terrace with tertiary red clay as bedrock, which is 1830 m a.s.l and 52 m above modern water level. The gravel layer is about 10 m in thickness, which is divided into three layers. The bottom layer is 3 m-thick, composed of relatively small gravels (about 10 cm in diameter) with a good prephicity and sub-round gravels. In the middle is a 2 m-thick layer of red coarse sand. On the top is a 4 m-thick gravel layer. The gravel in this layer is big, generally sub-round or sub-angular, and the biggest one reaches 30 cm in diameter, but with a worse psephicity. The lithological feature is dominated by steel grey aleurite sandstone and red sandstone, and with a few conglomerate and quartzite. A 6 m-thick floodplain sands and a 58.5 m-thick loess are overlying the gravel layer.

Terrace 3 (T_3) is a strath terrace with red clay as bedrock, which is 1808 m a.s.l. and 30 m above modern water level. This terrace is well exposed at Xishilipu along the southern bank of Weihe River. The thickness of gravel layer is 2 m, up to 40 cm, and it is mainly composed by steel grey aleurite sandstone. A 3-m-thick coarse sand unit is interbedded with small gravels, on top of which are 3 m-thick floodplain silt and 32.5 m-thick aeolian loess.

Terrace 2 (T_2) is a strath terrace with red clay as bedrock, which is 1801 m a.s.l and 23 m above modern water level. This terrace is well exposed at Lijiaying along the northern bank of Weihe River. The thickness of gravel layer is about 3 m, over which are a 8 m-thick river silt with horizontal beddings and 15 m deposition of aeolian loess.

Terrace 1 (T_1) is distributed along both banks of Weihe River, which is the main locations for modern human activities. The bottom of gravel layer is unexposed, over which is a layer of 3.3 m-thick loess, intermingled with sand layer and small gravels. Two peat layers lie at the height of 0.5 m and 1.3 m, respectively.

2 Timing of Upper Weihe River terraces in Longxi basin

Dating the loess strata capping the river terraces is an effective method to infer the age of terrace formation, and the basal age of these loess strata can indicate the age of river incision[6—10]. Weihe River terraces in Longxi basin, with varying thickness of loess overlaying the terraces (Fig. 3), provided useful materials for dating river terrace formation. Long-sequence Chinese loess chronologies have been well established mainly by using a combination of dating approaches of magnetostratigraphy, climatostratigraphy, optically stimulated luminescenece (OSL) and ^{14}C dates. These approaches can make us easily identify the loess and paleosol units and determine the terraces age along upper Weihe River. Palaeomagnetic analysis was performed in the Paleomagnetism and Geochronology Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS), and optically stimulated luminescenece (OSL) experiment was carried out in Key Laboratory of Desert and Desertification of Cold and Arid Regions Environmental and Engineering Research Institute, CAS, and the ^{14}C age was dated in the ^{14}C laboratory of Lanzhou University.

The seventh terrace (T_7): There is a 104.5 m-thick loess with 10 loess-paleosol cycles/layers (S_0, S_m—S_8) capping this terrace. The bottom paleosol can be correlated with S_8, according to loess stratigraphy and grain size curve of T_7 profile (Fig. 4). Paleomagnetic samples were taken in T_7 profile at intervals of 0.5 m in the lower part of the profile (0—16 m in thickness) and of 1 m in the middle part (17—60 m in thickness) and of 2 m in the upper part (61—99.5 m in thickness), and 97 groups (291 samples) were collected altogether. Progressive demagnetizations were carried out by an incremental step of 50 ℃ till to 550 ℃ or 580 ℃. The results demonstrated that the secondary magnetization could be removed and the primary magnetization can be isolated with a temperature of 300 ℃, with the exception of some samples that needed to be heated to 350 ℃. Compared with the standard geomagnetic polarity timescale, the transition from normal to inverse magnetization at 5 m height above the bottom of the profile may correspond to the B/M boundary with an age of 780 kyr[16]. We noticed that the B/M boundary falls well within L_8, in agreement with the magnetostratigraphy elsewhere from the Loess Plateau[17, 18]. On the basis of grain size data, a layer of paleosol occurs at 3—5 m above the gravel layer, corresponding to paleosol S_8. Floodplain materials and gravel layer below paleosol S_8 should have been deposited during glacial period[10], namely L_9. By analyzing the age of the T_7, the normal polarity event located between 1.5—3 m on top of the gravel layer should correspond to the so-called post-Jaramillo event[19] (Fig. 4), equivalent to the Lantian event in the eastern Liupanshan Mountains[20], whose formation age corresponds to L_9. Therefore, the basal age of S_8 can represent the age when T_7 was created. Its orbitally tuned age is about 865 kyr[21]. It could be assured that the age of T_7 formation is about 870 kyr.

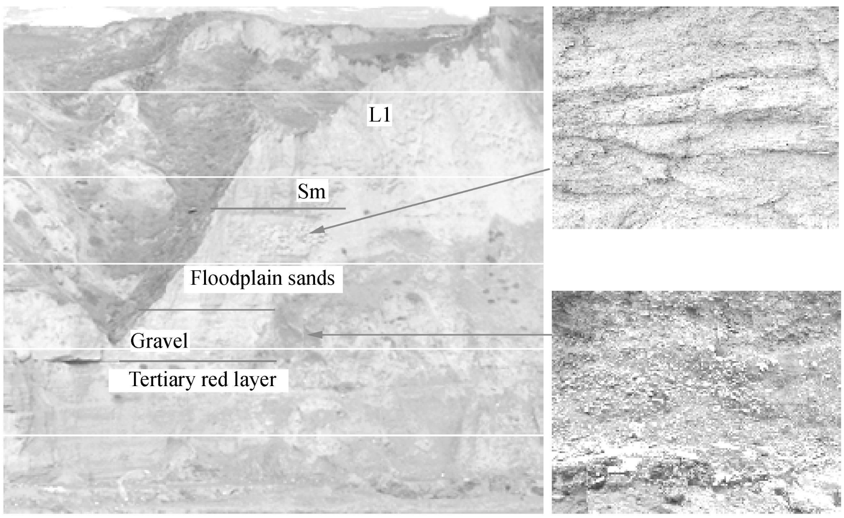

Fig. 3. Loess-paleosol sequence overlying Weihe River terrace (T_2).

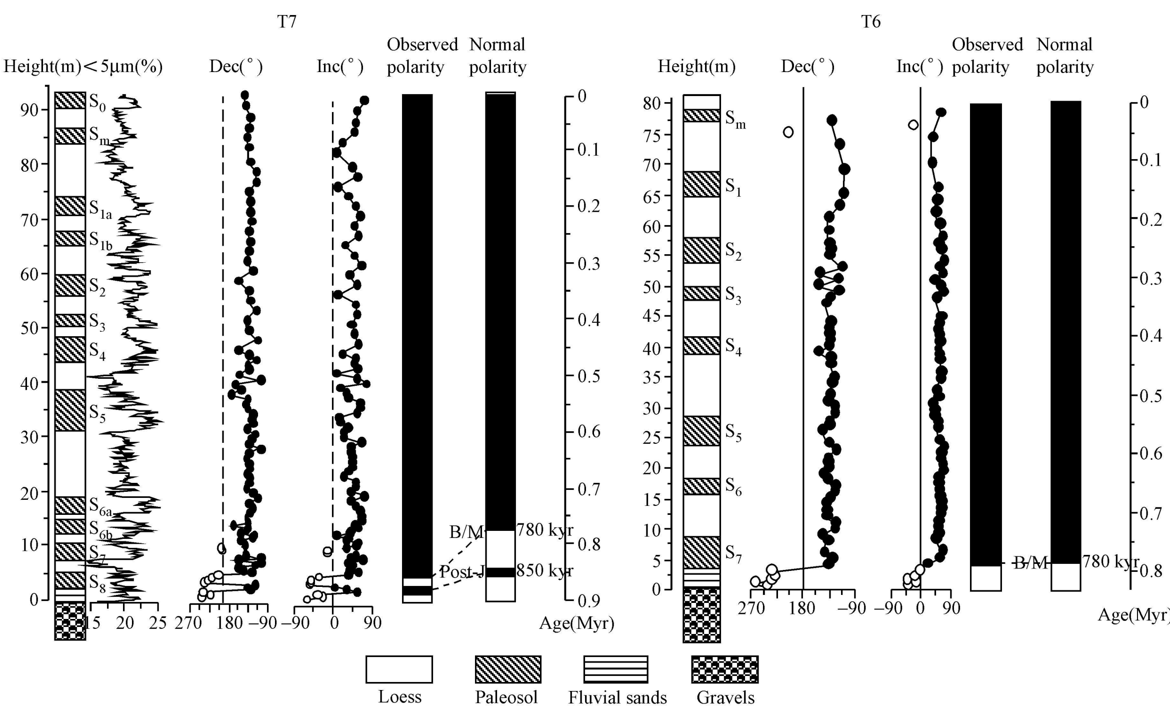

Fig. 4. Loess stratigraphy and palaeomagnetism of T_7, T_6 profiles.

The sixth terrace (T_6): T_6 profile is composed of 79 m-thick loess with 8 paleosol cycles/layers (S_m—S_7), and the bottom paleosol can be correlated with S_8. Paleomagnetic samples were taken in the T_6

profile at intervals of 0.5 m in the lower part of the profile (0—5 m in thickness, including a 3 m-thick floodplain deposit) and of 1 m in the upper part (6—79 m in thickness), and 83 groups (249 samples) were collected. Pretreatment and measurement of T_6 samples were the same as T_7. Transition from normal to inverse magnetization at 3 m height above the bottom of the profile should represent the B/M boundary, with an age of 780 kyr (Fig. 4), and the floodplain materials should have been deposited during L_8. Based on macroscopic profile description, 3-m height above the bottom is the paleosol S_7. The basal age of S_7 is 787 kyr[21], so the formation age of T_6 was estimated to be about 790 kyr.

For lower terraces (T_5, T_4, T_3, T_2), overlying loess is much thinner than that of older terraces. Grain size data and optically stimulated luminescence (OSL) dates show that the bottom of the loess capping those terraces (T_5, T_4, T_3, T_2) may correspond to the paleosols S_5, S_4, S_1, S_m (Fig. 5), ages of which was estimated to be about 620 kyr, 420 kyr, 130 kyr and 60 kyr, respectively[21]. Two ^{14}C samples were taken at 0.5 m and 1.3 m of T_1 profile, with their ages given at about 3381 ± 68a BP and 1519 ± 90a BP. It is certain that terrace T_1 was formed during the Holocene, thus the age of the terrace is no earlier than 10 kyr, i.e. the age of T_1 is about 10 kyr.

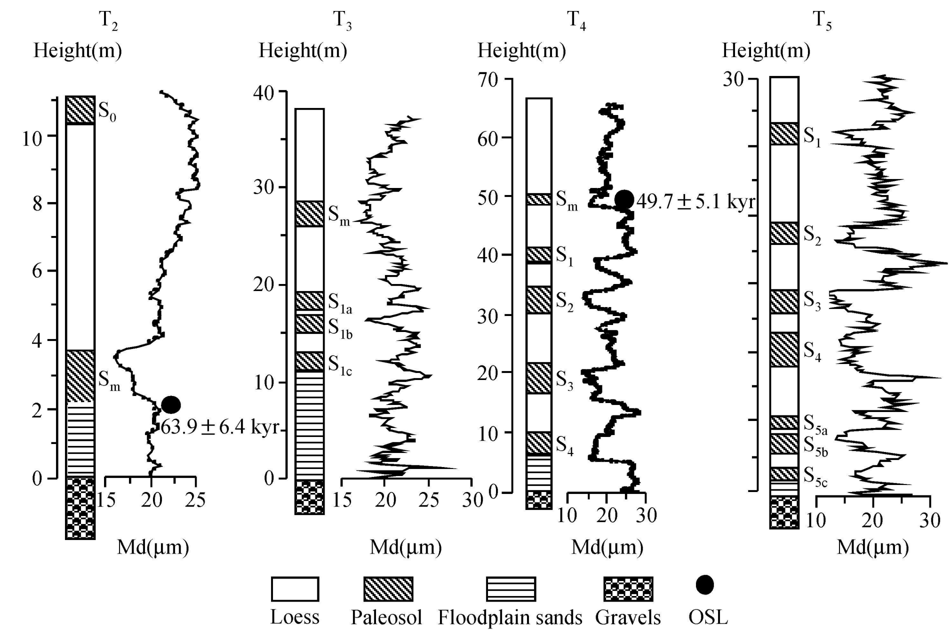

Fig. 5. Loess stratigraphy capping T_2, T_3, T_4, T_5 along Weihe River in Longxi basin.

3 The genesis of Weihe River in Longxi basin

River terrace formation is controlled by climatic change, tectonic activity and base level change[22]. It is shown that the distance that base level changes influencing fluvial geomorphology is no longer than 400 km[23]. The study area is 1500 km away from China's marginal seas. Even taking the Yellow River as a local base level, its distance still exceeds 400 km. It is obvious that terrace formation of the Weihe River in Longxi basin has no bearings on base level changes. Moreover, the study area is located at the junction of the Tibetan Plateau, the Loess Plateau and the Qinling Mountains where tectonic movement is active[13] and climatic change is frequent[14,15]. In this region river terraces formation are necessarily influenced by tectonic movement and climatic change.

River incision rates cannot accurately represent the uplift rate, but reflect the general trend of uplift[24], and in some cases even reflect uplift rates[25]. Fig. 6 shows that incision rate of Weihe River is about 0.2 m/kyr since 870 kyr. By analyses of the karst cave along Qinyou River, Wang[26] obtained the average downcutting rate of 0.31 m/kyr in the middle part of Qinling Mountains since the late Quaternary, and the incision rate of Minjiang is about 1.5 m/kyr since the late Pleistocene[27]. The difference in estimated incision rates may result from differential uplift activities of Qinling Mountains during the Pleistocene, which may indicate that the uplift of the interior of Qinling Mounains is higher than that of the northern flank. But, uplift amount of the northern flank of Qinling Mountains was 197 m during Pleistocene, at the very least.

Paleosols lie in the bottom of the loess capping seven terraces along the upper Weihe River in Longxi basin, corresponding to S_8, S_7, S_5, S_4, S_1, S_m, S_0, respectively. These paleosols suggest that Weihe River incised during glacial-interglacial transitions or interglacial periods. When climates were at the beginning of warm periods, climate instability enhanced, river discharge became higher, the vegetation densely populated, sediment load lowered and incidences of floods increased[28]. All of these may empower the river to incise into the gravel layer to the strath. In contrast, during interglacial periods, the relatively stable climate and low incidences of the mega-floods decreased the power of river downcutting through the gravel layer. Great thickness of the gravels is found deposited on the terraces along Weihe River in Longxi basin. It can be inferred that terrace formation occurred during the transitional period from glacials to interglacials, and that tectonic uplifts accommodated to vertical incision for the Weihe River.

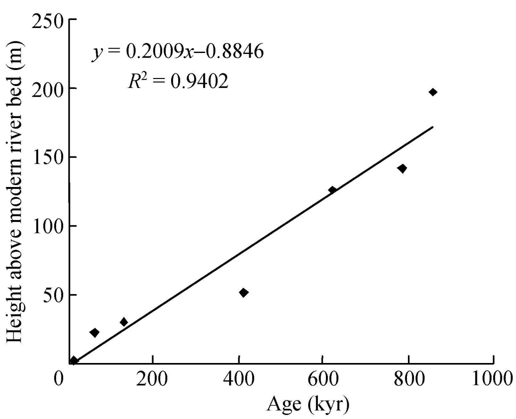

Fig. 6. Calculated river incision rates of the Weihe River in Longxi basin.

4 Conclusions

The seven terraces preserved along the upper Weihe River in Longxi basin were estimated to form about 870 kyr, 790 kyr, 620 kyr, 420 kyr, 130 kyr, 60 kyr and 10 kyr, respectively. Tectonic movements of the northern flank of Western Qinling Mountains may accommodate to vertical incisions for Weihe River. River incision and terraces formation may occur during periods of glacial-interglacial transitions.

Acknowledgements We thank Su H, Chen YY, Sun RH, Wang JP and Zhang H for field and laboratory assistance.

References

1 Clapp FG. The Huang Ho, Yellow River. The Geographical Review, 1933, 21(1): 1—18

2 Barbour G. Pleistocene history of the Huangho. Bulletin of the Geological Society of America, 1933, 44: 1143—1160

3 Ding S. Landform and river evolution. Yellow River Material Compiles (31922), the Geology and Soil in Yellow River Basin (in Chinese), 1952, 1—10

4 Xu SY. Some problems of terrace evolution of Huanghe River and its distributary in the western loess zone of Longxi basin. Journal of Lanzhou University (National Sciences) (in Chinese). 1965, 1: 116—143

5 Lin AM, Yang ZY, Sun ZM, et al. How and when did the yellow river develop its square bend? Geology, 2001, 29(10): 951—954

6 Chen Y, Tong GB, Cao JD, et al. Tectonic climate response in the geomorphology of the Weihe River valley around Baoji, Shaanxi province. Journal of Geomechanics (in Chinese), 1999, 5(4): 49—56

7 Yue LP, Lei XY, Qu HJ. The age of terrace development in the middle reaches of the Yellow River. Geological Review (in Chinese), 1997, 43(2): 186—192

8 Lei XY and Zhang MG. The age of terrace development in the middle reaches of the Weihe River. In: New Tectonic Movement and Environment (Ed. Lu YC.) (in Chinese), Beijing: Earthquake Press, 2001, 149—157

9 Sun JM. 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, 2005, 24(10—11): 1279—1286

10 Porter SC, An ZS, Zheng HB, et al. Cyclic Quaternary Alluviation and Terracing in a Nonglaciated Drainage Basin in the North Flank of the QinlingShan, Central China. Quaternary Research, 1992, 38: 157—169

11 Chen MX. The physiography in middle Gansu Province (in Chinese). 1947, 12(6): 545—556

12 Li JJ. The environmental effects of the uplift of QingHai-XiZang plateau. Quaternary Science Review, 1991, 10: 479—483

13 Peltzer G, Tapponier P, Zhang ZT, et al. Neogene and Quaternary faulting in and along the Qinling Shan. Nature, 1985, 317: 500—505

14 Fang XM, Pan BT, Guan DH, et al. A 60000-year loess-paleosol record of millennial-scale summer monsoon instability from Lanzhou China. Chinese Science Bulletin, 1999, 44(24): 2264—2266

15 Lu HY, Zhang FQ, Liu XD, et al. Periodicities of palaeoclimatic variations recorded by loess-paleosol sequence in China. Quaternary Science Review, 2004, 23: 1891—1900

16 Cande SC and Kent DV. Revised calibration of the geomagnetic polarity timescale for the late Cretaceous and Cenozoic. Journal of Geophysical Research, 1995, 100: 603—609

17 Rutter NW, Ding ZL, Evans ME, et al. Magnetostratigraphy of Baoji loess-paleosol section in north central China Loess Plateau. Quaternary International, 1991, 7: 97—102

18 Liu XM, Liu TS, Shaw J, et al. Paleomanetic and paleoclimatic studies of Chinaese loess, In: Loess, Environment and Global Change. Beijing: Science Press, 1991, 61—81

19 Chen FH and Zhang WX. The Problem of Loess Stratigraphy and Quaternary Glaciers in Gansu-Qinghai Zone (in Chinese). Beijing: Science Press, 1993, 24—34
20 Yue LP and Xue XX. Palaeomagnetism of Chinese Loess (in Chinese). Beijing: Geology Press, 1995, 38—41
21 Ding ZL, Derbyshire E, Yang SL, et al. 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, 2002, 17 (3): 5-1—5-21
22 Schumm SA. The Fluvial System. Hoboken: John Wiley and Sons, 1977, 338: 211
23 Schumm SA. River Response to Baselevel Change: Implications for Sequence Stratigraphy. The Journal of Geology, 1993, 101: 279—294
24 Li JJ, Fang XM, Rob Van der Voo, et al. 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, 1997, 102 (B5): 10121—10132
25 Maddy D, Bridgland DR, Green CP. Crustal uplift in southern England: evidence from the river terrace records. Geomorphology, 2000, 33: 167—181
26 Wang F, Li HC, Zhu RX, et al. Late Quaternary downcutting rates of the Qianyou River from U/Th speleothem dates, Qinling Mountains, China. Quaternary Research, 2004, 62(2): 194—200
27 Kirby E, Whipple KX, Burchfiel BC, et al. Neotectonics of the Min Shan, China: Implications for mechanisms driving Quaternary deformation along the eastern margin of the Tibetan Plateau. GSA Bulletin, 2000, 112(3): 375—393
28 Macklin MG, Benito G, Gregory KJ, et al. Past hydrological events reflected in the Holocene fluvial record of Europe. Catena, 2006, 66: 145—154