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Geomorphological observations of active faults in the epicentral region of the Huaxian large earthquake in 1556 in Shaanxi Province, China

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Abstract—The Huaxian magnitude 8 great earthquake of January 23, 1556, is the largest one recorded in the Weihe basin, Shaanxi Province, China and caused 830,000 people either injury or death. The epicenter is located in the southeastern part of the Weihe basin, around Huaxian City. Earthquakes are closely related to active faults and active faults are well developed in the epicentral area of the Huaxian large earthquake. Thus we will discuss the activity of the major faults in the epicentral area by geomorphological observations.

There are three major fault sets in the study area: striking approximately east–west, northeast and northwest. These are inhomogeneous in spatial distribution, rates and manners of faulting, as shown by geomorphological observations such as faulted fluvial terraces and alluvial fans. The ages of the second and first terraces are around 20,000 and 5,000 years B.P. by thermoluminescent dating, Carbon-14 dating and archeology. The terraces were faulted by the North Huashan fault (F_1), the main boundary fault of Weihe basin and the Piedmont fault (F_2) after the second and the first terraces formed. The distribution of the displacement shows that the intersections of the North Huashan fault and the Chishui fault (F_4) striking northwest, and the western margin fault (F_5) of Tongguan loess tableland, have the largest in offsets in the area. Perhaps the Huanxian great earthquake in 1556 A.D. had a close relation to the North Huashan fault. The Weihe fault (F_3) striking east–west is also an active fault by analysis of the flood plain structure. Thus we should pay attention to the activities of the faults to take precautions against another possible large earthquake in this region. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

The Weihe basin, a trans-tensional basin at the south end of the Fenwei graben system (including Shanxi and Shaanxi Provinces) (Wang, 1965) (Fig. 1), is located in the central part of Shaanxi Province, China. It is half-crescent shaped, about 350 km in length from Baoji in the west to Yellow River in the east, and about 30–80 km in width from Qinling Mountain and Huashan Mountain in the south to the Ordos block to the north (Fig. 2).

The basin has fertile land, abundant products and a prosperous economy, and also had an ancient civilization 3000 years ago. Thirteen feudal dynasties were founded in the basin area. Many precious historical records remain from this time, which enable us to understand great historical events. Twenty-six destructive earthquakes have occurred in the basin since 1177 B.C. according to the historical records of Local Chronicles (Guo *et al.*, 1988). The largest one is the Huaxian magnitude 8 great earthquake on January 23, 1556 A.D. The Huaxian large earthquake caused about 830,000 people either injury or death (Kuo, 1957). The epicenter is located in the southeastern part of Weihe basin, around Huaxian City (Hou, 1985), by inference from "Substantial record of Jiajing Period (from 1522 to 1556 A.D.) of Ming Dynasty" (Guo *et al.*, 1988).

Earthquakes occur on active faults. Active faults are well developed in the epicentral area of the Huaxian large earthquake, and show inhomogeneity in spatial distribution, rates and manners of faulting. This paper will discuss the activity of the major faults in the epicentral area by geomorphological observations.

THE MAJOR ACTIVE FAULTS IN THE EPICENTRAL AREA OF THE HUAXIAN EARTHQUAKE

The Weihe basin stretching approximately east–west is an extensional basin since it is located in the south end of the Fenwei graben system which experiences the shear-tensional action in a north-northeast direction,

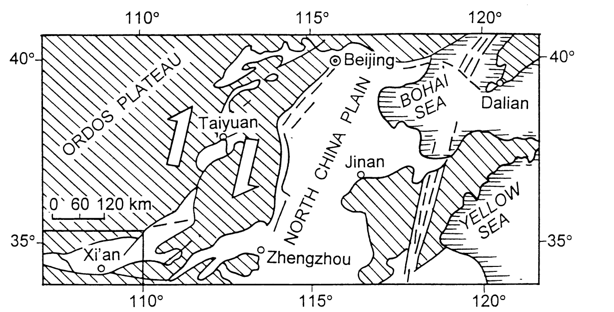

Fig. 1. The location of the Weihe basin (small rectangle in the lower left corner) which is a trans-tensional basin at the south end of the Fenwei graben system in North China block. Xi'an city is located in the center of the basin. The rectangle shows the location of Fig. 2. Diagonal lines: uplift; blank space: subsidence; blank arrow: shear direction of the Fenwei graben system.

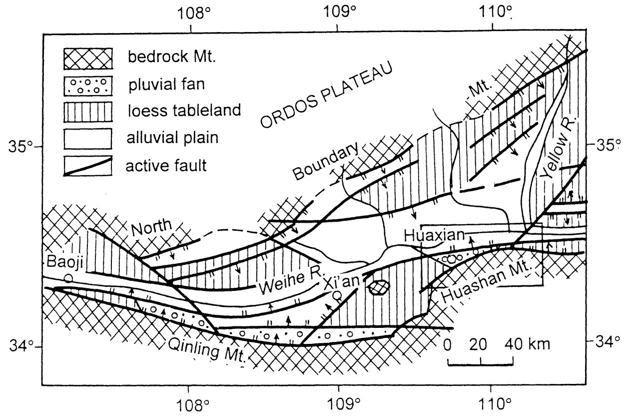

Fig. 2. The landform and tectonics of the Weihe basin. The study area including Huaxian city is located to the east of Xi'an city. See Fig. 3 for the location of Huaxian city.

as shown in Fig. 1. There are three major normal fault sets in the research region defined by fault strikes: approximately east–west, northwest and northeast (Fig. 3).

The EW-striking fault set

Three major faults strike east–west in the study area: the North Huashan fault (F_1), the Piedmont fault (F_2) and the Weihe fault (F_3) (Fig. 3). The North Huashan fault forms the southeastern border of Weihe basin. It strikes east–west between the Shidiyu and Huangpuyu rivers, northeast to the west of Shidiyu river, and northwest to the east of Huangpuyu river. The total length of the fault is about 180 km, but the middle part between Shidiyu and Huangpuyu rivers is the most active segment (Fig. 3). The dip of the fault at the surface is steeper than 65°. The North Huashan fault has been active throughout the Quaternary, forming the Huashan Mountain uplift and its frontal alluvial fan on the Piedmont plain. The Piedmont fault

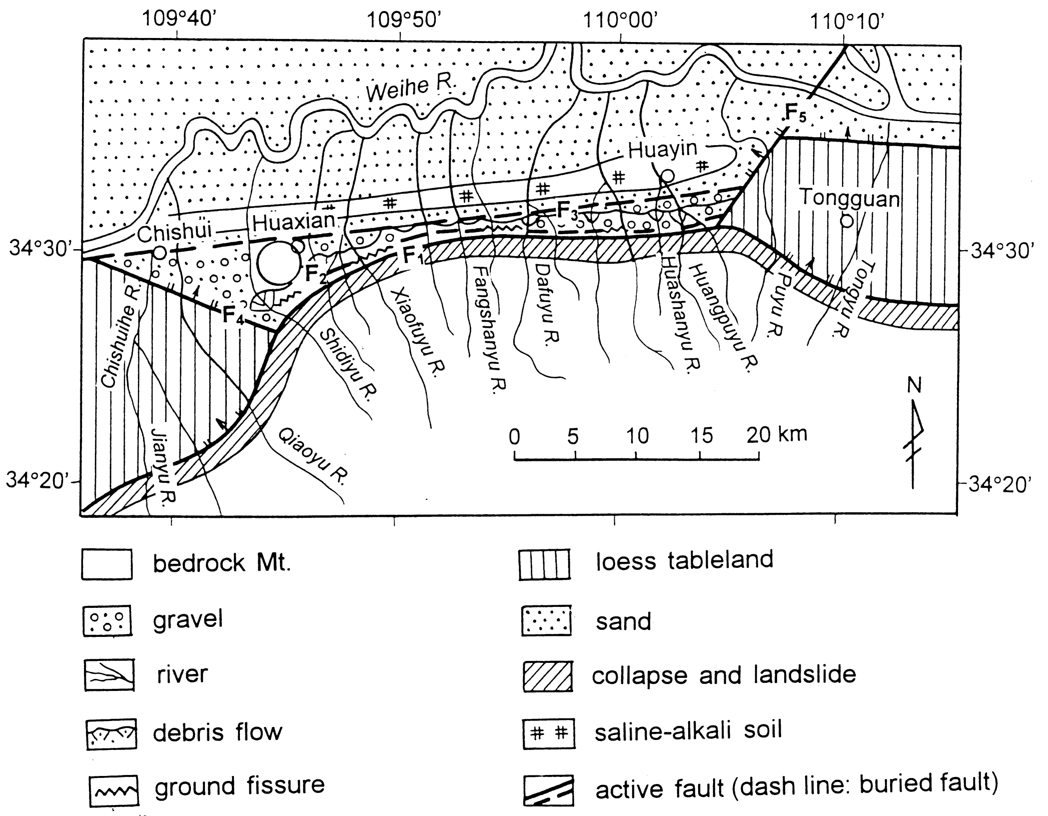

Fig. 3. Distribution of active faults, Huaxian large earthquake and geological hazards in the southeastern part of Weihe basin. F_1: North Huashan fault; F_2: Piedmont fault; F_3: Weihe fault; F_4: Chishui fault; F_5: western margin fault of Tonnguan loess tableland.

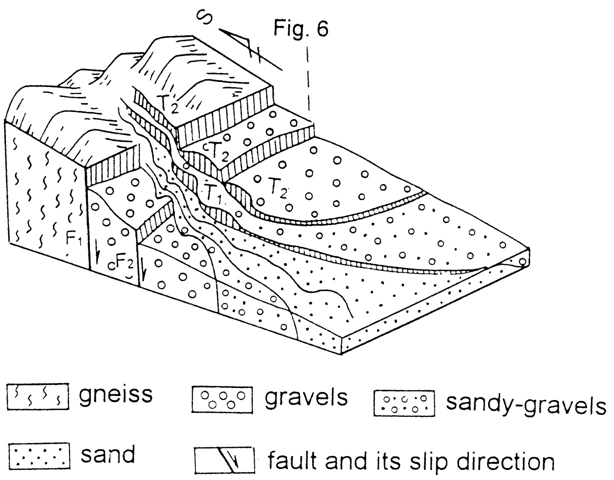

Fig. 4. The faulted spatial relations between river terraces and alluvial fans along the Shidiyu river in the Huashan Mountain front by the North Huashan fault (F_1) and the Piedmont fault (F_2).

(F_2) is about 300 m from the North Huashan fault to the north. Its strike is parallel to the boundary fault of the basin (i.e. the North Huashan fault) and its dip direction is the same as the North Huashan fault. Thus, we consider that this fault is a synthetic fault on the hangingwall of the boundary. North of the Piedmont fault is the Weihe fault (F_3) buried by Holocene unconsolidated sediments.

The NW- and NE-striking fault sets

The NW-striking fault, the Chishui fault (F_4), and the NE-striking fault, the western marginal fault of the Tongguan loess tableland (F_5), are developed only in the hangingwall of the North Huashan fault. Downthrow of hanging walls during normal faulting is commonly accompanied by the formation of minor accommodation structures, such as hangingwall cross faults (Hancock and Barka, 1987). Hangingwall cross faults are generally located near the lateral tips of active fault zones, distributing deformation at the proximal part of the hangingwall block (Stewart and Hancock, 1991). The two cross faults here (F_4 and F_5) divide the hangingwall block of the North Huashan normal fault into three segments. The middle segment between the two cross faults has subsided to form a flat buried alluvial fan plain. The eastern and western segments, with less subsidence, are now loess tablelands (Fig. 3). The fan scarp formed by the synthetic fault (F_2) in the alluvial fan plain extends to the west and east and sharply ends at the two cross faults. Therefore, the development of the two cross faults strongly influences the active characteristics of the hangingwall block of the North Huashan normal fault.

OBSERVATIONS OF RIVER TERRACES AND ALLUVIAL FAN ACROSS THE ACTIVE FAULTS

Geomorphological patterns along the range front may reflect large scale variations in the net displacement and structural geometry of the range front fault zone (Menges, 1987). Therefore, we measured in detail the terraces of 10 main rivers crossing the North Huashan fault and the Piedmont fault. There are 6 or

Fig. 5. The faulted spatial relations between the second river terrace (T_2) and the alluvial fan along the Huangpuyu river in the Huashan Mountain front by the North Huashan fault (F_1). The camera points east. South of the railroad (right) is the Huashan Mountain and the second terrace (T_2) of the Huangpuyu river. North of the railroad (left) is the alluvial fan which corresponds to the second terrace, but faulted by F_1. The location refers to Fig. 10(h).

Fig. 6. The alluvial fan along the Shidiyu river in the Huashan Mountain front displaced by the Piedmont fault (F_2) to form a fault scarp about 4 m in height. The camera points south. The location refers to Figs 4 and 8.

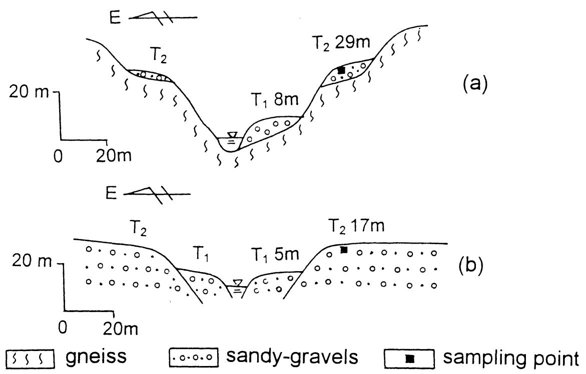

Fig. 7. Two cross sections of the Huangpuyu river. (a) In the Huashan Mountain; the age of the second terrace is 22,569 ± 1375 y B.P. by TL dating. (b) In the Mountain front; the age of the second terrace is 20,122 ± 1329 y B.P. by TL dating.

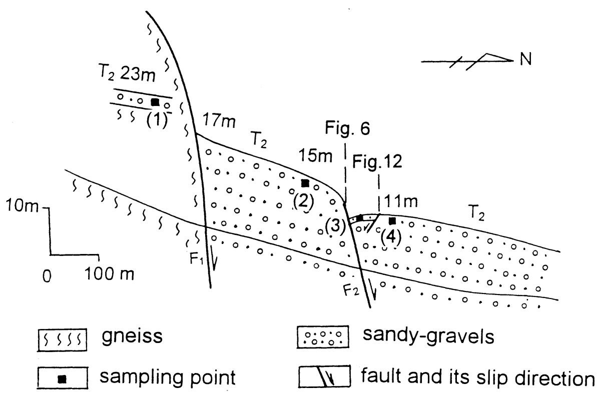

Fig. 8. Longitudinal profile along the Shidiyu river. The ages of the samples by TL dating are: (1) 21,267 ± 1586 y B.P.; (2) 19,000 ± 661.8 y B.P.; (3) 14,702 ± 605.1 y B.P.; (4) 18,654 ± 601.1 y B.P.

7 river terraces developed on the flank of the North Huashan Mountain. However, only the second and first terraces are widely distributed and well enough preserved to be used for quantitatively calculating the history of fault displacements. The terraces in the Mountain have clear spatial relations to the Piedmont alluvial fans, or in other words, the alluvial fans are extensions of the river terraces in the Mountain. Our observations revealed that the terraces and alluvial fans were faulted by the North Huashan fault (F_1) and the Piedmont fault (F_2) (Figs 4–6).

The ages of the river terraces and alluvial fans

For further comparison of the river terraces and alluvial fans in the front of North Huashan Mountain,

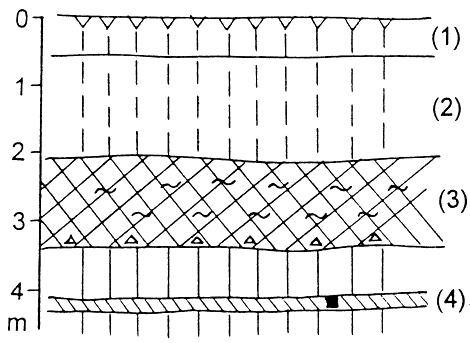

Fig. 9. Section of the first terrace of the Dafuyu river. (1) Farming soil bed 0.6 m in thickness; (2) pale yellow soil bed, 1.5 m in thickness; (3) black earth bed, 1.3 m in thickness, bearing grey pot shards which are identified as from the Longshan Culture of the Chalcolithic period 4,000–5,000 y ago; (4) brown earth bed bearing a plant ash earth of the Longshan Culture Period, whose age is 3,730 ± 140 y B.P. by C^{14} dating (after Li, 1992).

Table 1. Vertical displacements in meters of the first and second terraces along north Huashan fault (F_1) and the Piedmont fault (F_2)

No.	Names of rivers	TD of F_1+F_2		TD of F_1		SD of F_1		TD of F_2		SD of F_2	
		T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1
1	Jianyu	6	2	6	2	4	2	0	0	0	0
2	Qiaoyu	4	2	4	2	2	2	0	0	0	0
3	Shidiyu	10	3	6	2	4	2	4	1	3	1
4	Xiaofuyu	10	3	7	2	5	2	3	1	2	1
5	Fangshanyu	8	3	8	3	5	3	0	0	0	0
6	Dafuyu	7	4	7	4	3	4	0	0	0	0
7	Huashanyu	15	7	15	7	8	7	0	0	0	0
8	Huangpuyu	19	6	12	3	9	3	7	3	4	3
9	Puyu	6	1	6	1	5	1	0	0	0	0
10	Tonguy	7	1	7	1	6	1	0	0	0	0

Notes: TD of F_1+F_2: total displacement of the North Huashan fault (F_1) and the Piedmont fault (F_2). TD of F_1: total displacement of F_1. SD of F_1: separate displacement in different stages of F_1. TD of F_2: total displacement of F_2. SD of F_2: separate displacement in different stages of F_2, T_2: the displacement of the second terrace. T_1: the displacement of the first terrace. River numbers are referred to in Fig. 11.

we studied their formation by using the methods of thermoluminescent dating (TL), carbon-14 dating (C^{14}) and archeology. We collected fine sand samples at points 50 cm below the top surfaces of the fluvial terraces, and had the selected quartz grains measured in the laboratory of the Institute of Geodynamics, the State Seismological Bureau of China. We followed the method and the results of carbon-14 dating (C^{14}) and archeology of Li (1992).

The ages of second terraces are from 14,702 to 22,569 y B.P. by the method of thermoluminescent dating. Generally speaking, the higher the second terrace above river level, the older the age. For example, the height of the second terrace of Huangpuyu river on the upthrow block in Huashan Mountain is 29 m above the river level, with an age of $22{,}569 \pm 1375$ y (Fig. 7a). The height of the second terrace on the downthrow block in the Huashan Mountain front is 17 m above the river level with an age of $20{,}122 \pm 1329$ y, by TL dating (Fig. 7b). Thus we deduce 12 m in vertical displacement faulted by the North Huashan fault (F_1), there. The heights and the ages of the second terrace of Shidiyu river can be taken as another good example (Fig. 8). The second terrace of the Shidiyu river is 23 m in height and $21{,}267 \pm 1586$ y in age on the upthrow block of the North Huashan fault in Huashan Mountain, and 17 m in height on the downthrow block in the front. So the vertical displacement of the North Huashan fault here is 6 m, after the second terrace formed. The alluvial fan scarp of Shidiyu river is about 4 m in height as shown in Fig. 6. The second terrace is 15 m in height above the Shidiyu river and $19{,}000 \pm 661.8$ y in age on the upthrow block of the Piedmont fault (F_2). The height of the second terrace is 11 m on the downthrow block of F_2 with the TL dating of $18{,}654 \pm 601.1$ y, but the age is $14{,}702 \pm 605.1$ y by TL dating near the Piedmont Fault. The reason is that the strong subsidence near the fault (F_2) may have allowed deposition of younger sediments.

The ages of the first terrace are from 3,730 y to 5,000 y old by the method of C^{14} dating and archeology. The section of the first terrace at the mouth of the Dafuyu river revealed that the first bed from the surface is farming soil, 0.6 m thick; the second bed is pale yellow soil, 1.5 m thick; the third bed is black earth, 1.3 m thick, bearing grey pot shards which are identified as from the Longshan Culture of the Chalcolithic period 4,000–5,000 y ago; the fourth bed is brown earth bearing plant ash earth of the Longshan Culture Period whose age is $3{,}730 \pm 140$ y B.P. by C^{14} dating (Li, 1992) (Fig. 9). The first terrace of Huashanyu river in Huayin County is $4{,}535 \pm 126$ y B. P. by C^{14} dating (Li, 1992). Combining the method of C^{14} dating and archeology, we may infer that the first terrace might have been formed after 5,000 y B.P.

The vertical displacements movement along the faults

The results of measuring river terraces in the Huashan Mountain and alluvial fan plain show that the North Huashan fault moved vertically after the second terrace-forming event (Table 1). Displacements of the first and the second terraces show that vertical down throw displacements are low, about 4–7 m and 1–2 m, respectively, in loess tablelands of the western and eastern segments of the North Huashan fault (Fig. 10a, b, i & j). Displacements of the second and first terraces, however, are large; about 7–19 m and 3–7 m, respectively, in the middle segment of the fault (Fig. 10 c–h). Fault displacements are larger in the eastern part, where the Huangpuyu river crosses the fault, than in the western part where the Shidiyu and Xiaofuyu rivers cross the fault. The second terrace is approximately 20,000 years old, according to thermoluminescent dating. The first terrace is formed approximately 5,000 y B.P. using methods of C^{14} dating and archeology. These data show that the North Huashan fault was active in late Pleistocene and middle Holocene time and caused geological hazards such as collapse, landslides and debris flows in Huashan Mountains and its Piedmont (Hou *et al*., 1994). Our further field investigations reveal that recent tectonic movement is not just concentrated along the boundary fault (i.e. the North Huashan fault) but locally migrates towards the basin center to form the

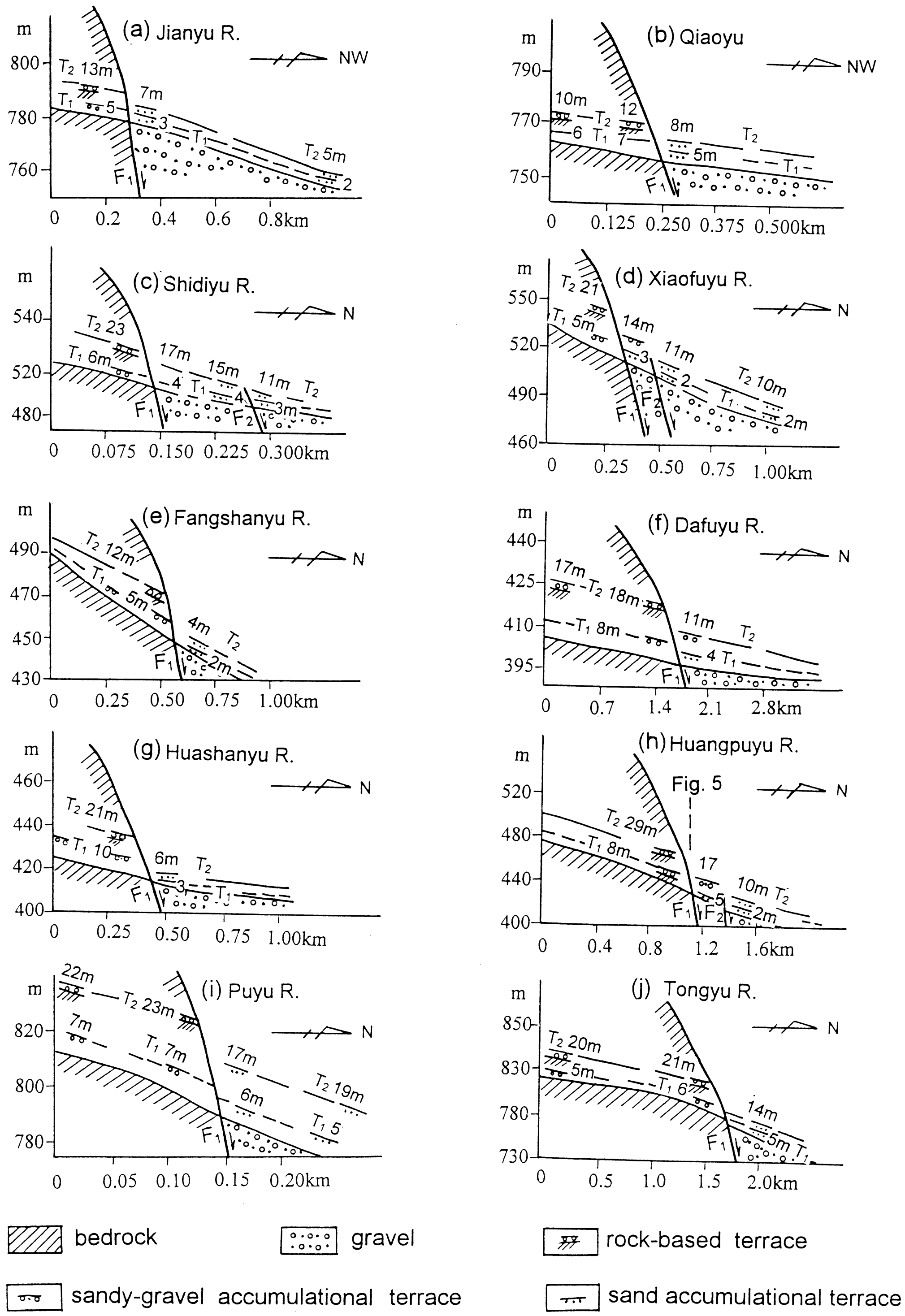

Fig. 10. Longitudinal profiles of river terraces across the North Huashan fault (F_1) and fan scarp fault (F_2). T_2 and T_1: the second and first terraces. Numbers on the terraces: relative height in meters above river level.

Piedmont fault scarp (F_2) in the alluvial fan plain (Figs 3, 4 & 8). The fault strike is parallel to the boundary fault and its dip directions the same as the North Huashan fault. Thus, this is a synthetic fault in the hangingwall of the boundary fault. The Piedmont fault offset the first and the second terraces about 3–4 m and 1 m vertically where the Shidiyu and Xiaofuyu rivers cross the fault (Fig. 10c & d), but about 7 m and 3 m where Huangpuyu crosses the fault (Fig. 10 h). Thus the Piedmont fault displacements are smaller in the western part than in the eastern part of the study area.

To understand the displacement variations of the North Huashan fault (F_1) and the Piedmont fault (F_2),

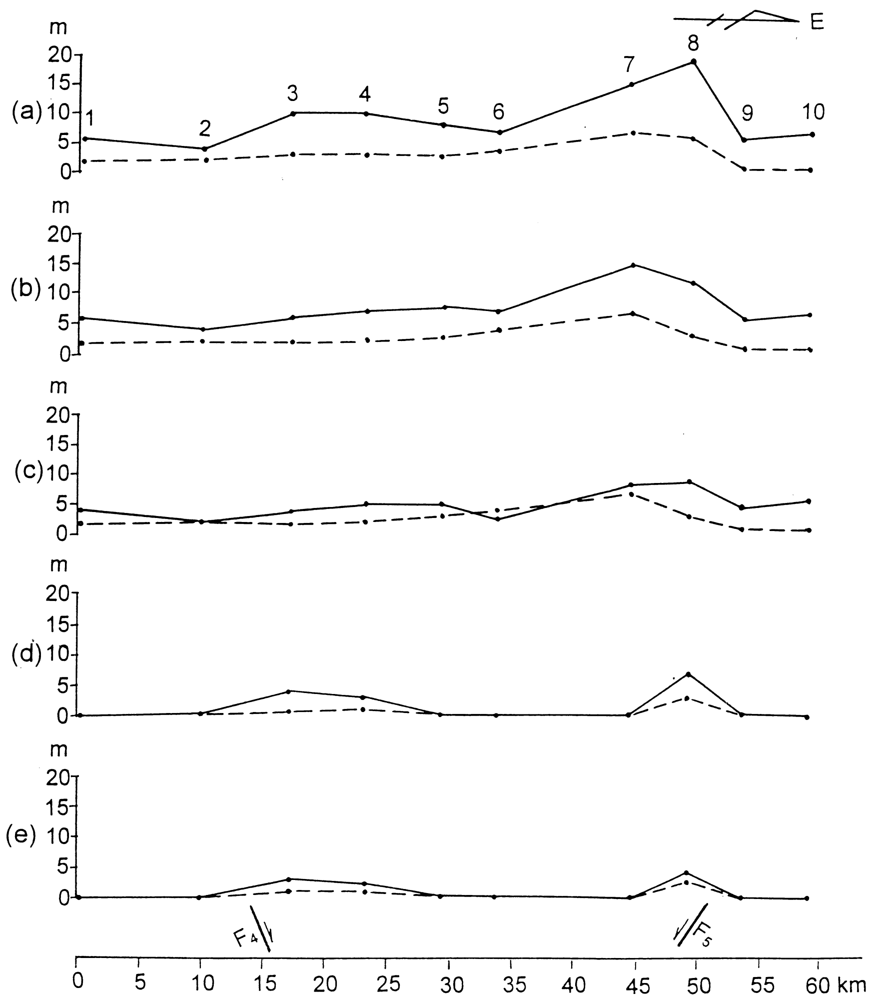

Fig. 11. The curves of displacements in time-space of the North Huashan fault (F_1) and/or the Piedmont fault (F_2) reflected by river terraces across the faults. (a): Total displacement of F_1 and F_2 since 20,000 y B.P. (stage 1, solid line) and after 5,000 y B.P. (stage 2, dotted line). (b): Total displacement of F_1 after stage 1 (solid line) and stage 2 (dotted line). (c): Separate displacement of F_1 in stage 1 (solid line) and in stage 2 (dotted line). (d): Total displacement of F_2 after stage 1 (solid line) and stage 2 (dotted line). (e): Separate displacement of F_2 in stage 1 (solid line) and in stage 2 (dotted line). Numbers 1–10 refer to the measured rivers in Table 1.

we draw five kinds of curves to reflect the difference along the two faults. We may divide the slip history of the two faults into two stages according to the observations of the second and first terraces (T_2 and T_1). Stage 1 was the period the second terrace formed between 20,000 and 5,000 y B.P. Stage 2 was the period the first terrace formed after 5,000 y B.P.

The fault slip variations are shown in Fig. 11. The total displacements of the North Huashan fault (F_1) and the Piedmont fault (F_2) between the Chishui fault (F_4) and the western margin fault (F_5) of Tongguan loess tableland since stage 1 (solid line) and since stage 2 (dotted line) show that the largest offsets are located in the western part where the Shidiyu and Xiaofuyu rivers cross the two faults, and in the eastern part where the Huangpuyu river crosses the two faults (Fig. 11a). The total displacements of the North Huashan fault (F_1) since stage 1 (solid line) and since stage 2 (dotted line) also show similar characteristics to the total displacement curves of the two faults, but the curves are smoother (Fig. 11b) than those in Fig. 11(a). The displacements of the North Huashan fault in different stages between 20,000 y and 5,000 y B.P. (stage 1, solid line) and since 5,000 y B.P. (stage 2, dotted line) show that the largest displacements are still in the western and eastern parts, but the displacement in stage 2 is 1 m larger than in stage 1 along Dafuyu river (Fig. 11c). The total displacements of the Piedmont fault since stage 1 (solid line) and since stage 2 (dotted line), and the separate displacements of the Piedmont fault in stage 1 (solid line) and stage 2 (dotted line), show that the fracture offsets only

Fig. 12. A gravel bed was faulted by an antithetic fault whose strike is parallel to the Piedmont fault (F_2). The position refers to Fig. 8. The camera points west.

occurred in the western and eastern parts; the displacements in the other parts are near zero (Fig. 11d & e).

OBSERVATIONS OF FLOOD PLAIN STRUCTURES ACROSS THE ACTIVE FAULTS

Ground subsidence is concentrated along the front of the Piedmont fault scarp (F_2) and the northern side of the Weihe fault (F_3). The depression along the front of the Piedmont fault scarp made the fan surface dip reversely towards the Huashan Mountain to produce an antithetic fault which displaced a gravel bed by about half a meter (Figs 8 & 12). The other depression is located on the northern side of the Weihe fault (F_3). The fault is buried by Holocene unconsolidated sediments. Therefore, this kind of fault trace is hard to identify in a trench (Bonilla *et al*., 1990), and the buried fault is also not clearly expressed in the topography. However, it is obvious in the structure of the flood plain, with the feature of a gravel flood plain sharply changing to a sand–mud flood plain (Fig. 13). That means that the northern side of the fault is in relative subsidence without any expression on topography, because of subsidence having been compensated by deposition. Dykes were built along the Chishui river on the north side of the fault to prevent flood because of the subsiding. The scene of a younger bridge built above an older bridge (Fig. 14) demonstrates the subsidence on Chishui river in Chishui town to the west of Huaxian City. The older bridge, now submerged to near ground surface, was built in 1660 A.D. and the younger one in 1832 A.D. according to the "Huaxian County Annals" (Han *et al*., 1987).

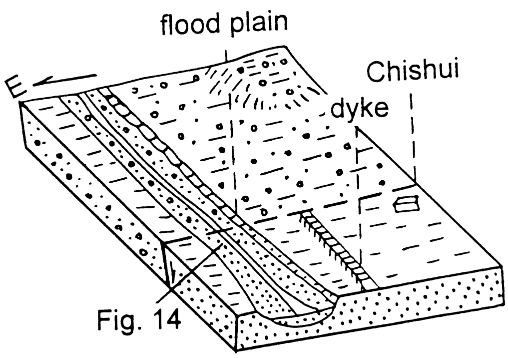

Fig. 13. The variation of flood plain structure from gravels to sands and muds where the Chishui river crosses the Weihe fault (F_3).

CONCLUSIONS

There are three active fault sets striking east–west, northeast and northwest in the epicentral area of Huaxian large earthquake in 1556 A.D. The North Huashan fault (F_1) is the largest one in the study region. Two hangingwall cross faults, the Chishui fault (F_4) striking northwest and the western margin fault (F_5) of Tongguan loess tableland striking northeast, divided the North Huashan fault into three segments: the western, the eastern and the middle segments. The middle segment has large displacement especially in the eastern and western parts, according to the analysis of fluvial terraces. The distribution of the Piedmont fault (F_2) scarp is restricted by the two hangingwall cross faults (F_4 and F_5). The highest fault scarps are

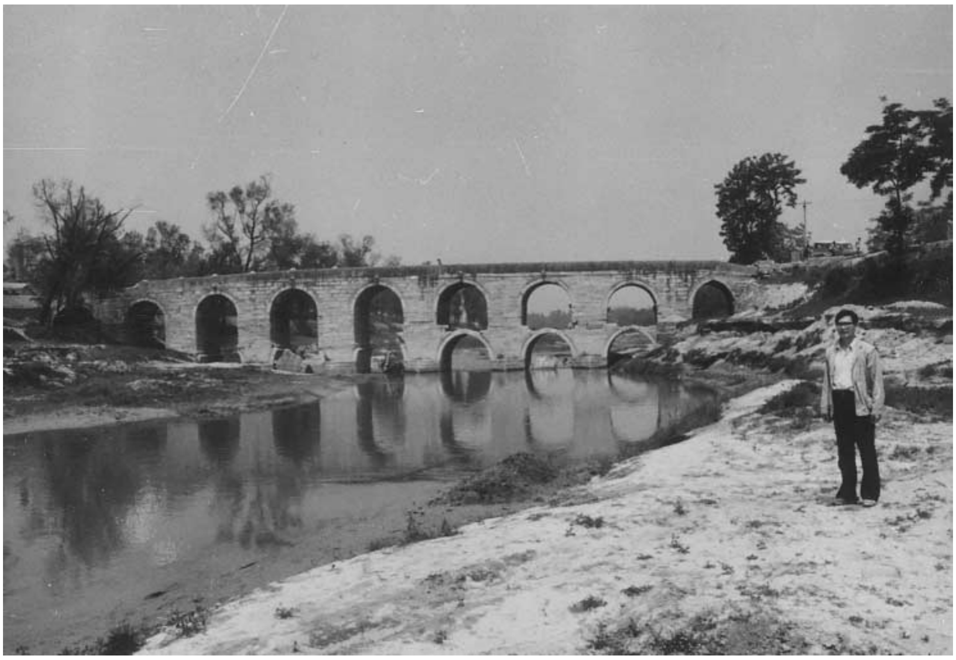

Fig. 14. A younger bridge on an older bridge on the Chishui river in Chishui town to the west of Huaxian City. The older bridge subsided to near ground surface, so a new bridge was built on the older one. The camera points south.

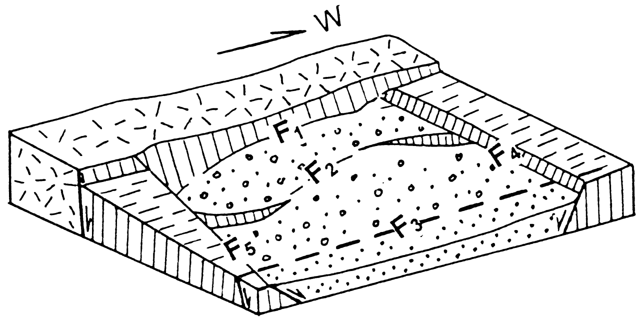

Fig. 15. Schematic diagram illustrating the distribution of the active faults and displacements in the study area. F_1 North Huashan fault; F_2; Piedmont fault; F_3 Weihe fault; F_4 Chishui fault; F_5 western margin fault of Tongguan loess tableland.

also located in the intersecting parts between the North Huashan fault and the two cross faults (Fig. 15). The Weihe fault (F_3) has been moving since the flood plain formed, according to the analyses of the flood plain structure. From the above analyses, we may infer that the North Huashan fault played an important role in the 1556 event, because its scale and displacements are the largest in the study area. Therefore, we need to consider the potential for active faulting, and prepare for another possible large earthquake in the region, since the faults are active now.

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