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Late Quaternary Activity of the Huashan Piedmont Fault and Associated Hazards in the Southeastern Weihe Graben, Central China

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Abstract: The Weihe Graben is not only an important Cenozoic fault basin in China but also a significant active seismic zone. The Huashan piedmont fault is an important active fault on the southeast side of the Weihe Graben and has been highly active since the Cenozoic. The well–known Great Huaxian County Earthquake of 1556 occurred on the Huashan piedmont fault. This earthquake, which claimed the lives of approximately 830000 people, is one of the few large earthquakes known to have occurred on a high–angle normal fault. The Huashan piedmont fault is a typical active normal fault that can be used to study tectonic activity and the associated hazards. In this study, the types and characteristics of late Quaternary deformation along this fault are discussed from geological investigations, historical research and comprehensive analysis. On the basis of its characteristics and activity, the fault can be divided into three sections, namely eastern, central and western. The eastern and western sections display normal slip. Intense deformation has occurred along the two sections during the Quaternary; however, no deformation has occurred during the Holocene. The central section has experienced significant high–angle normal fault activity during the Quaternary, including the Holocene. Holocene alluvial fans and loess cut by the fault have been identified at the mouths of many stream valleys of the Huashan Mountains along the central section of the Huashan piedmont fault zone. Of the three sections of the Huashan piedmont fault, the central section is the most active and was very active during the late Quaternary. The rate of normal dip–slip was 1.67–2.71±0.11 mm/a in the Holocene and 0.61±0.15 mm/a during the Mid–Late Pleistocene. As is typical of normal faults, the late Quaternary activity of the Huashan piedmont fault has produced a set of disasters, which include frequent earthquakes, collapses, landslides, mudslides and ground fissures. Ground fissures mainly occur on the hanging–wall of the Huashan piedmont fault, with landslides, collapses and mudslides occurring on the footwall.

Key words: Weihe Graben, Huashan piedmont fault, late Quaternary, fault–related hazards, normal fault

1 Introduction

The Weihe Graben is a Cenozoic graben and is located between the Qinling Orogenic Belt and the Ordos Block in the central part of China (Fig. 1). The evolving of the Weihe Graben was closely related to the collision between the Indian Plate and the Eurasian Plate in the Cenozoic (Peltzer et al., 1985; Sun Jimin, 2005). Due to the eastward movement of the Qinghai–Tibetan Plateau along the Qinling Mountains, the fault zone at the northern margin of the Qinling Mountains is in general a sinistral strike–slip fault (Peltzer et al., 1985; Zhang Yueqiao et al., 1995, 1999). However, on the southern margin of the Weihe Graben, the fault zone on the northern margin of the Qinling Mountains is a high–angle normal fault and also a basin–controlling fault on the southern margin of the Weihe Basin in the Cenozoic (Han Hengyue et al., 1987; Hou Jianjun and Han Mukang, 1994; Zhang Yueqiao et al., 1995; Ren Jun et al., 2012, 2013; Li Dunpeng et al., 2015). The Huashan piedmont fault underwent high–angle normal faulting and strong activity

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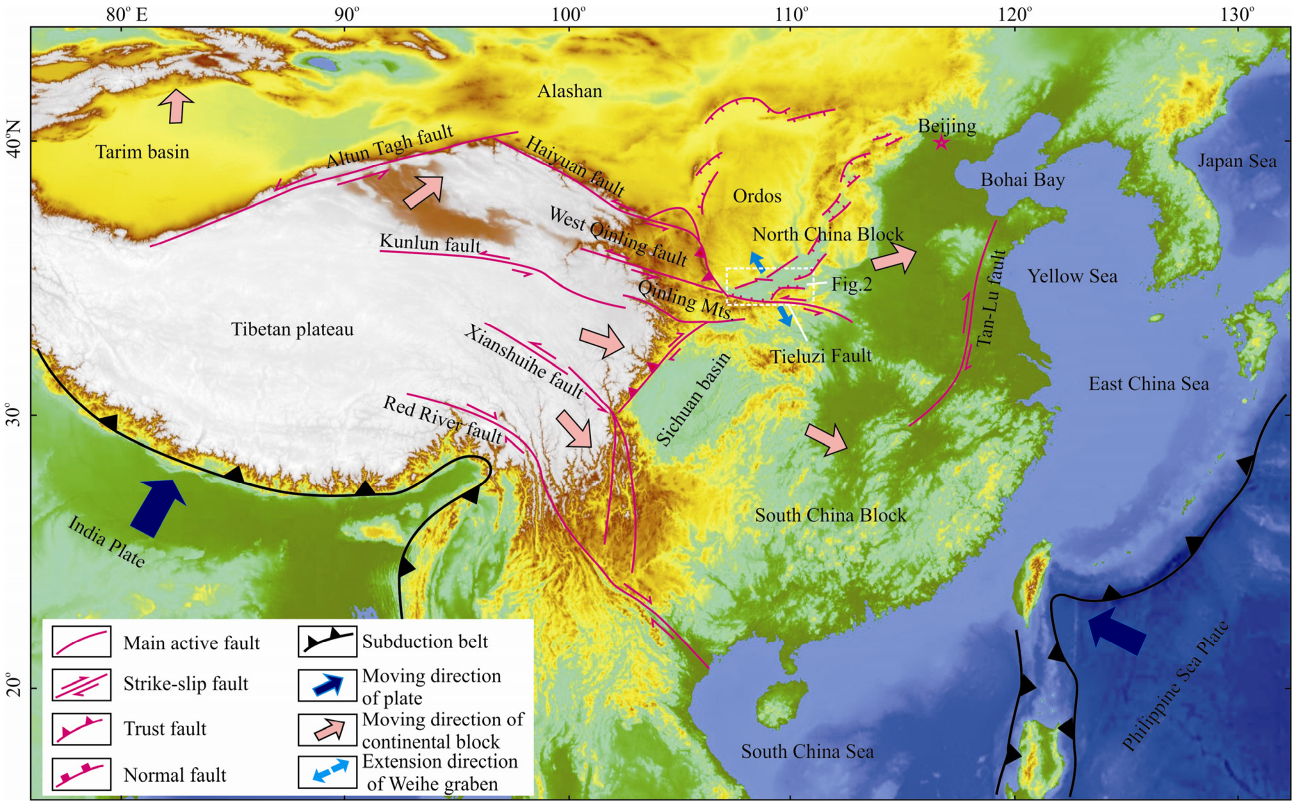

Fig. 1. Regional geological structure of the Weihe Graben.

in the Cenozoic with the rapid uplift of the Huashan Mountains. Currently, disasters caused by active faults are a major concern: these disasters include earthquakes, surface deformation, collapses, landslides, mudslides and ground fissures. Many ancient landslides and multiple collapse events took place in the late Quaternary along the Huashan piedmont fault zone. In addition, the Great Huaxian County Earthquake of 1556 occurred on the fault zone and is one of very few large earthquakes known to have occurred on normal faults (Zhang Anliang et al., 1989; Hou Jianjun et al., 1998; Yuan Tinghong and Feng Xijie, 2010; Rao Gang et al., 2014). Some researchers have focused on the response to disasters caused by the thrust and strike–slip faults (Chen Xiaoli et al., 2011; Xu Chong and Xu Xiwei, 2012). The Huashan piedmont fault is a key high–angle normal fault and even caused the Huaxian County magnitude 8.0 earthquake. Therefore, in this study the relationship between active normal faults and the disasters caused by these faults was studied using the Huashan piedmont fault in the south–eastern Weihe Graben as an example. This study will help us to understand high–angle normal fault and the associated hazards.

2 Tectonic Setting

The evolution of the Weihe Graben has been closely related to the tectonic activity in the region; in particular, the collision between the Indian Plate and the Eurasian Plate (Sun Jimin, 2005; Zhang Qin et al., 2012). The Indian Plate collided and subducted under the Eurasian Plate from southwest to north along the Himalaya suture zone at 55–50 Ma. One result of this event was that during the Cenozoic western China or all of East Asia underwent the most intense tectonic deformation that has ever occurred on the earth (Molnar and Tapponnier, 1975; Searle et al., 1987). The Himalayan movement both resulted in rapid vertical uplift of the Qinghai–Tibet Plateau and also stimulated the eastward movement of large amounts of crust and mantle of the plateau (Molnar and Helene, 1989). The eastward movement of the Gansu–Qinghai Block resulted in compression of the western Weihe Graben and sinistral strike–slip movement along the fault zone on the northern margin of the Qinling Mountains. In addition, due to the combined action of high–angle obduction and collision of the Philippines Plate and the conspicuous back–arc extension of the Ryukyu Island arc, the two major plates (the North China Plate and the South China Plate) in eastern China engendered a pushing effect towards the southeast. Furthermore, the south–eastward horizontal movement of the South China Plate was significantly faster than that of the North China Plate, and there was also a dragging effect caused by simultaneous small–scale convection in the deep mantle under the basin. Thus, a northwest–southeast–

trending extensional environment developed between the Ordos Block and the South China Block, which, together with the differential uplift of the Qinling Orogenic Belt, resulted in the formation of the relatively deep Weihe Graben between the Qinling Fold Belt and the Ordos Block (Tapponnier and Molnar, 1977; Peltzer et al., 1985; England and Houseman, 1989; Clark and Royden, 2000). The Weihe Graben is a typical Cenozoic fault basin near to the Ordos Block; in addition, the Weihe Graben together with its neighbouring Fenhe Graben comprises the Fenhe–Weihe Seismic Belt, which is well known in China and worldwide for many strong earthquake ever occured on this area.

The Huashan piedmont fault is located at the northern foot of the Huashan Mountains in the eastern part of the Weihe Graben. Topographically, the Huashan piedmont fault is the boundary between the Qinling Mountain and the Weihe Plain (Fig. 2). The Huashan piedmont fault is also a lithological boundary. The upthrown (southern) block consists of Archaean deeply metamorphosed rocks and Mesozoic granitic intrusive rocks. The downthrown (northern) block consists of the Cenozoic Weinan and Tongguan loess tablelands and Quaternary alluvial–diluvial fans. Similarly to the fault in the northern section of the Qinling Mountains, the Huashan piedmont fault is a deep fault. Radon anomalies, crust–mantle–derived helium and mantle–derived methane have been detected along the fault zone (Zhang Jun et al., 2001; Zhang Xue et al., 2014; Lu Jincai et al., 2005).

The Huashan piedmont fault has a sinuous trace and a total length of approximately 160000 m. On the basis of its geographical position, geomorphologic characteristics and activity, the Huashan piedmont fault can be divided into three sections: the eastern, central and western sections. The Huashan piedmont fault, a normal fault, extends in a northeast to approximately north–east east to approximately southeast direction along the Huashan piedmont. Clear triangular facets and large variations in the terrain along the fault zone are apparent. The fault surface of the Huashan piedmont fault has good continuity. In addition, multiple earthquakes have occurred along the fault zone; in particular, a large earthquake with a magnitude of 8.0 in 1556. The Huashan piedmont fault is the most active fault in the Weihe Graben.

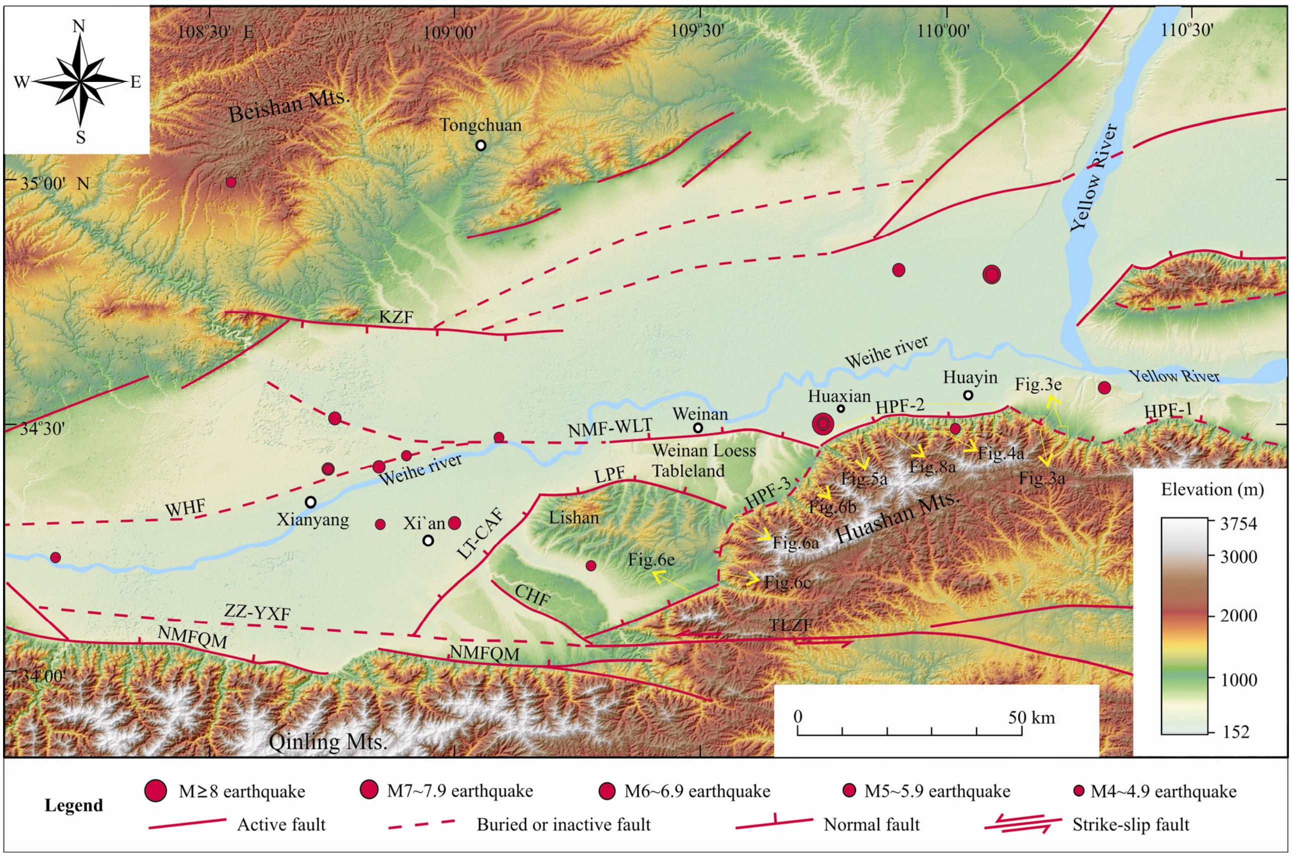

Fig. 2. Active faults and DEM of the Weihe Graben.

HPF, Huashan piedmont fault; HPF–1, Eastern section of the Huashan piedmont fault; HPF–2, Central section of the Huashan piedmont fault; HPF–3, Western section of the Huashan piedmont fault; NMF–WLT, North Margin fault of the Weinan Loess Tableland; WHF, Weihe fault; KZF, Kouzhen fault; LPF, Lishan Piedmont fault; LT–CAF, Lintong–Chang'an fault; NMFQ, North Margin fault of the Qinling Mts.; CHF, Changhe fault; ZZ–YXF, Zhouzhi–Yuxia fault; TLZF, Tieluzi fault.

3 The Huashan Piedmont Fault

3.1 Eastern section

The eastern section of the Huashan piedmont fault strikes north–northwest to north–northeast and has a length of 70 km. The eastern section generally dips to the northeast, northwest or north at angles of 45°–70°. The south of the fault is the bedrock of the Huashan Mountains, which is composed of the Archaean Taihua Formation and Yanshanian (Mesozoic) granitic intrusive rocks. The north is covered by Quaternary loess tablelands (Figs. 3a, 3b, 3e, 3f). Triangular facets and fault cliffs are still clearly visible along the fault zone (Figs. 3a, 3c, 3e). The loess deposited on the fault plane remains intact; the top surfaces of the loess tablelands along both sides of the river valley also remain intact and have not been cut (Fig3. 3b, 3f), indicating that the eastern section of the Huashan piedmont fault was inactive during the Holocene. Samples were collected from the bottom of the loess overlying the fault plane and were subjected to optically stimulated luminescence (OSL) dating. These loess samples yield OSL ages of 30.6±0.6, 24.9±0.6 and 20.4±1.2 ka, as

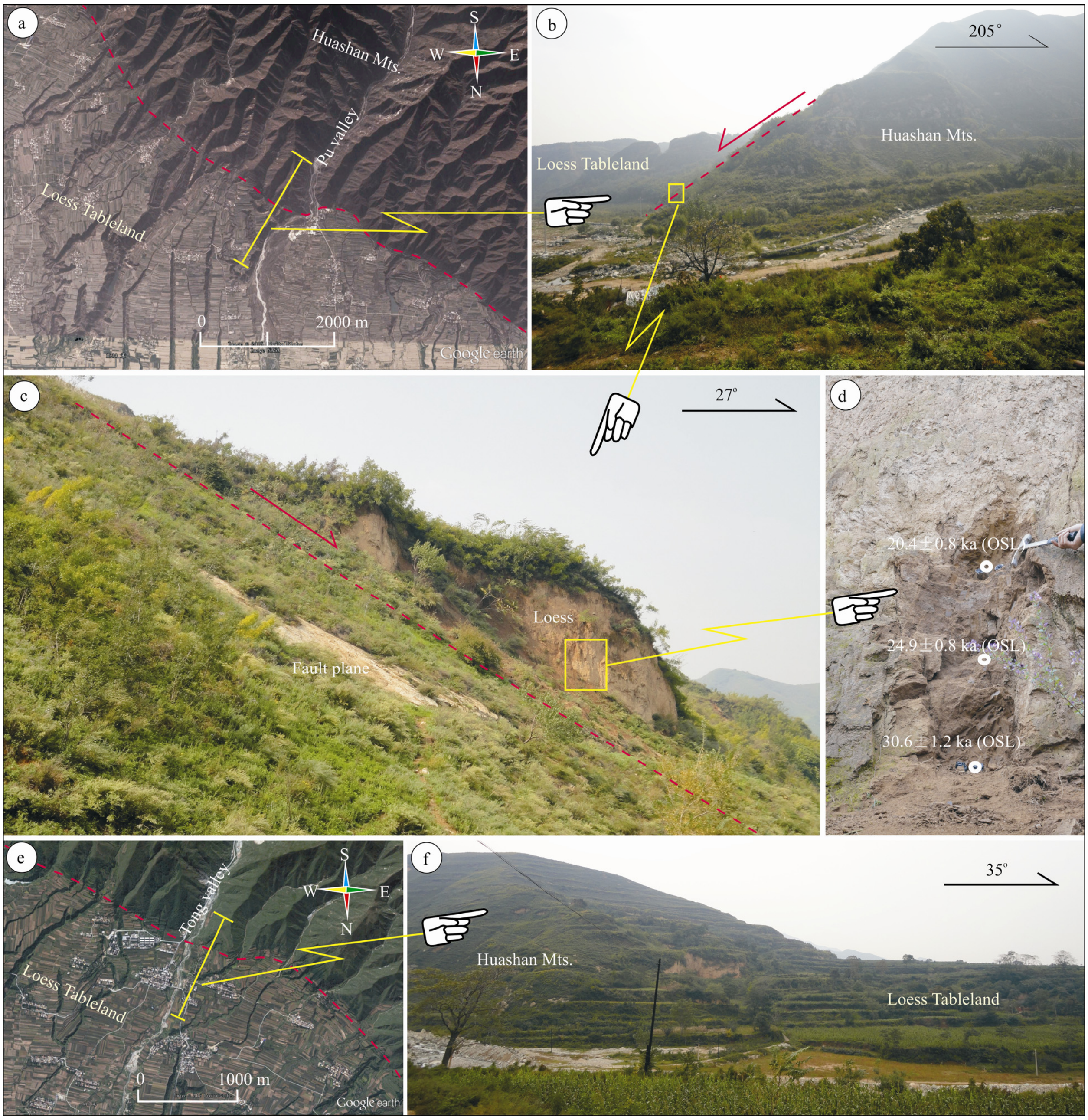

Fig. 3. The eastern section of the Huashan piedmont fault and associated features.
(a), Landforms near the investigation point, the mouth of the Pu valley; (b), Non–deformed loess tableland at the mouth of the Pu valley; (c), Residual accumulated loess overlying the fault plane at the mouth of the Pu valley; (d), Sampling sites and OSL ages of the loess samples; (e), Landforms near the investigation point, the mouth of the Tong valley, shown in a Google Earth image; (f), Non–offset, non–deformed loess at the mouth of the Tong valley.

shown in Fig. 3c and Fig. 3d, indicating that the latest activity of the Huashan piedmont fault took place during the Late Pleistocene.

3.2 Central section

3.2.1 Fault properties

The nearly east–west–trending central section of the Huashan piedmont fault is located north of the Huashan Mountains and has a length of approximately 40 km. The fault plane generally dips to the north or north–northwest at angles of 50°–80° (Fig. 4). The central section of the fault is a normal fault with the upthrow descending towards to the north or north–northwest (Fig. 2).

The presence of triangular facets and faulted cliffs along the fault zone are direct evidence of fault activity. This section has been highly active since the Late Pleistocene based on its geomorphology (Fig. 4). The steep Huashan Mountains are located south of the fault and the flat Weihe Alluvial Plain is located north of the fault: intact triangular facets that are steep, smooth and laterally continuous along the piedmont are still visible on the bedrock surface (Figs. 4a, 4b). Fault activity was accompanied by headward erosion of the rivers at their mountain outlets, and knick points have been identified at the mouth of each piedmont valley (Fig. 4c). A fractured zone of faulting is the most direct evidence of the presence of a fault. A clear fractured zone can still be seen along the central section of the piedmont fault zone. In general, the fault–fractured zone is not very thick, and the section of the fault–fractured zone in the area of relatively low terrain is covered by loess. Earthquake wedges are also evident next to the fractured fault zone (Figs. 4d, 4e, 4f). Striations have been preserved in a few areas; statistical analysis of these striations indicates that the fault is a normal fault (Fig. 4g).

3.2.2 Period of activity and rates of fault movement

Along the central section of the Huashan piedmont fault, many alluvial fans composed of alluvial–diluvial deposits of loess or streams of Late Pleistocene–Holocene age occur. Several periods of intense activity occurred along the central section of the Huashan piedmont fault in the late Quaternary, and most of these alluvial fans were cut and formed one to three fault scarps (Figs. 4h, 5).

At the mouth of the Weng valley (Fig. 4h), the last activity of the fault cut the Holocene alluvial fan and resulted in formation of a scarp with a height of approximately 6 m. Charcoal from the top of the alluvial fan yielded a ^{14}C age of 2215±95 cal. a BP (Fig. 4h). The rate of movement of the Weng valley during the Holocene is calculated to have been 2.71±0.11 mm/a (Figs. 4h, 4j). In addition, it is evident in this profile that the fault has also cut the sand and gravel layer of the third terrace. The top of the gravel layer yields an OSL age of 65.2±3.0 ka. The difference in elevation between the top of the gravel layer and the base of the latest fault scarp is 40±10 m (Figs. 4h, 4i). The rate of movement since the Late Pleistocene is calculated as 0.61±0.15 mm/a.

The Holocene alluvial fans located at the mouths of the Tan valley, the Shui valley and the Taiping valley were cut and formed 2–3 scarps: the youngest scarps generally have heights of 2–5 m, and the secondary scarps have heights of 4–5 m (Figs. 5b, 5c, 5d). The secondary scarps have ages of 5920 a BP (Fig. 5c) and 7670 a BP (Fig. 5d) (Yang Yuanyuan et al., 2012). The rate of movement during the Holocene is calculated to have been 1.67–2.53 mm/a.

Geological investigations of the Huashan piedmont fault have demonstrated that the fault zone has been relatively active since the Middle Pleistocene, and at least two relatively intense periods of fault activity occurred along the fault zone at approximately 7670 a BP (Fig. 5d) and 2215±95 cal. a BP (Fig. 4h). Based on the ^{14}C dating and displacement of fault measurements, the Huashan piedmont fault had a rate of normal dip–slip of 1.67–2.71±0.11 mm/a during the Holocene and a normal dip–slip rate of 0.61±0.15 mm/a since the Mid–Late Pleistocene.

3.3 Western section

The western section of the Huashan piedmont fault, also known as the fault at the western foot of the Huashan Mountains, is approximately 50 km long. Its trace is sinuous and generally trends northeast. It dips to the northwest at angles ranging from 62° to 80°. The western section of the Huashan piedmont fault is a normal fault with the upthrow down towards the north–northwest. The footwall is composed of Archaean migmatite and Mesozoic granites, and the hanging–wall is Weinan loess tableland.

Triangular facets are aligned along the west section of the Huashan piedmont fault and negative terrain is also present, indicating that the fault is still active (Figs. 6a, 6b, 6c). A well–preserved fault profile can be seen at the location illustrated in Fig. 6d. The fault gouge has an ESR age of 29.7±1.0 ka BP (Fig. 6e); thus, the fault was active in the Late Pleistocene. The top of the fault is covered by Holocene slope–wash deposits, indicating that the fault was not highly active during the Holocene. Associated stream terrace deposits are well preserved and have not been cut (Fig. 6a), further suggesting that this fault was not particularly active in the Holocene.

4 Fault–related Hazards

As is typical of normal faults, late Quaternary activity

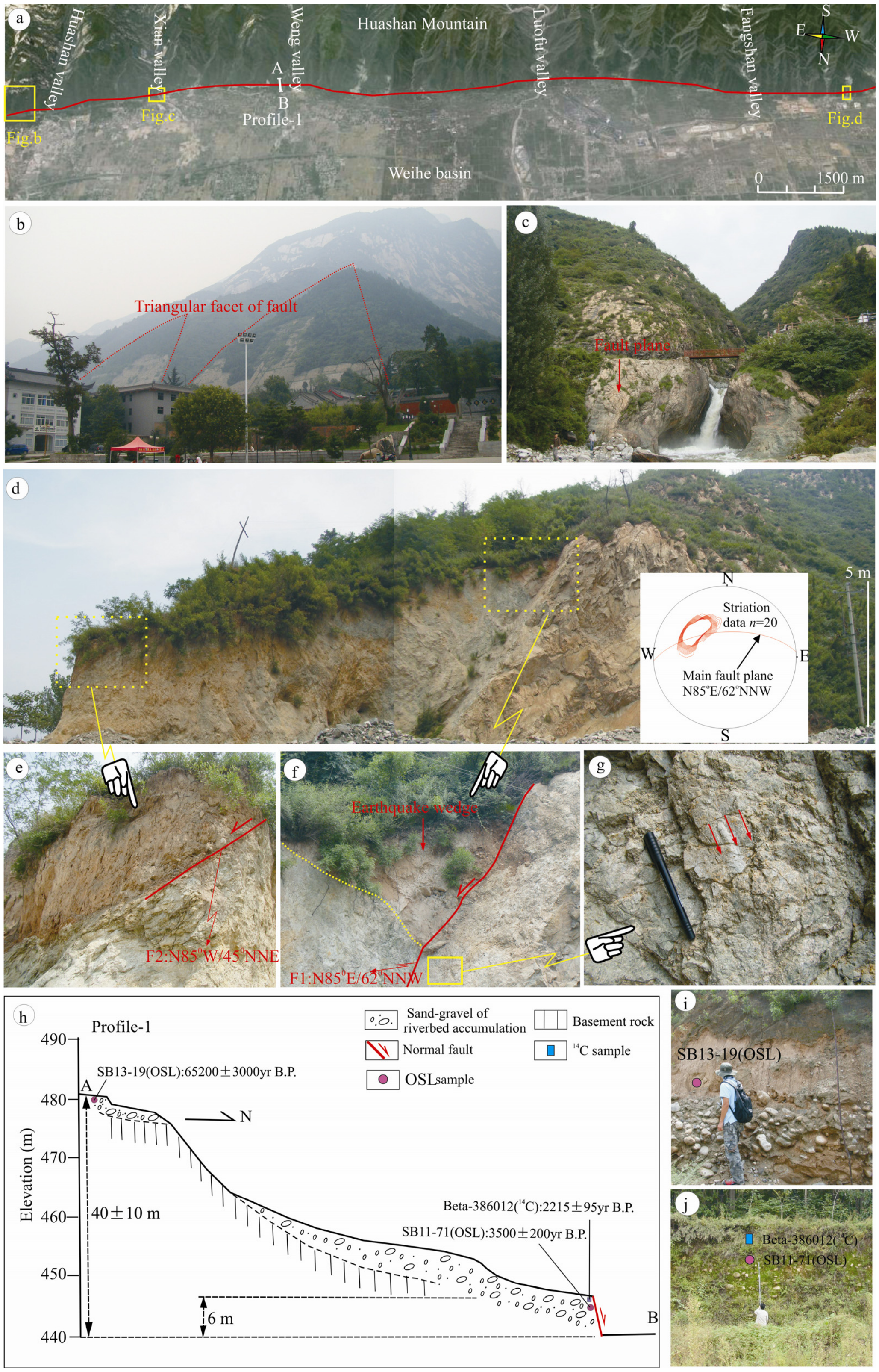

Fig. 4. Digital elevation model graph of the Weng valley–Fangshan valley along the central section of the Huashan piedmont fault and a representative profile.

(a), Location of the Weng valley–Fangshan valley in the Huashan piedmont fault shown in a Google Earth image; (b), Triangular facets along the fault at the mouth of the Huashan Mountains valley; (c), Fault plane and knick point in the Xian valley; (d), Fault zone at the mouth of the Liu valley and stereographic projections (lower–hemisphere projections) of the fault plane and striations; (e), Contact between loess and fractured fault rocks; (f), Colluvial wedge between fractured fault rocks and fractured rocks; (g), Vertical striations; (h), Fault profile in the Weng valley; (i), Location of the OSL dating sample collected at location A on the profile; (j), Location of the OSL dating sample collected at location B on the profile.

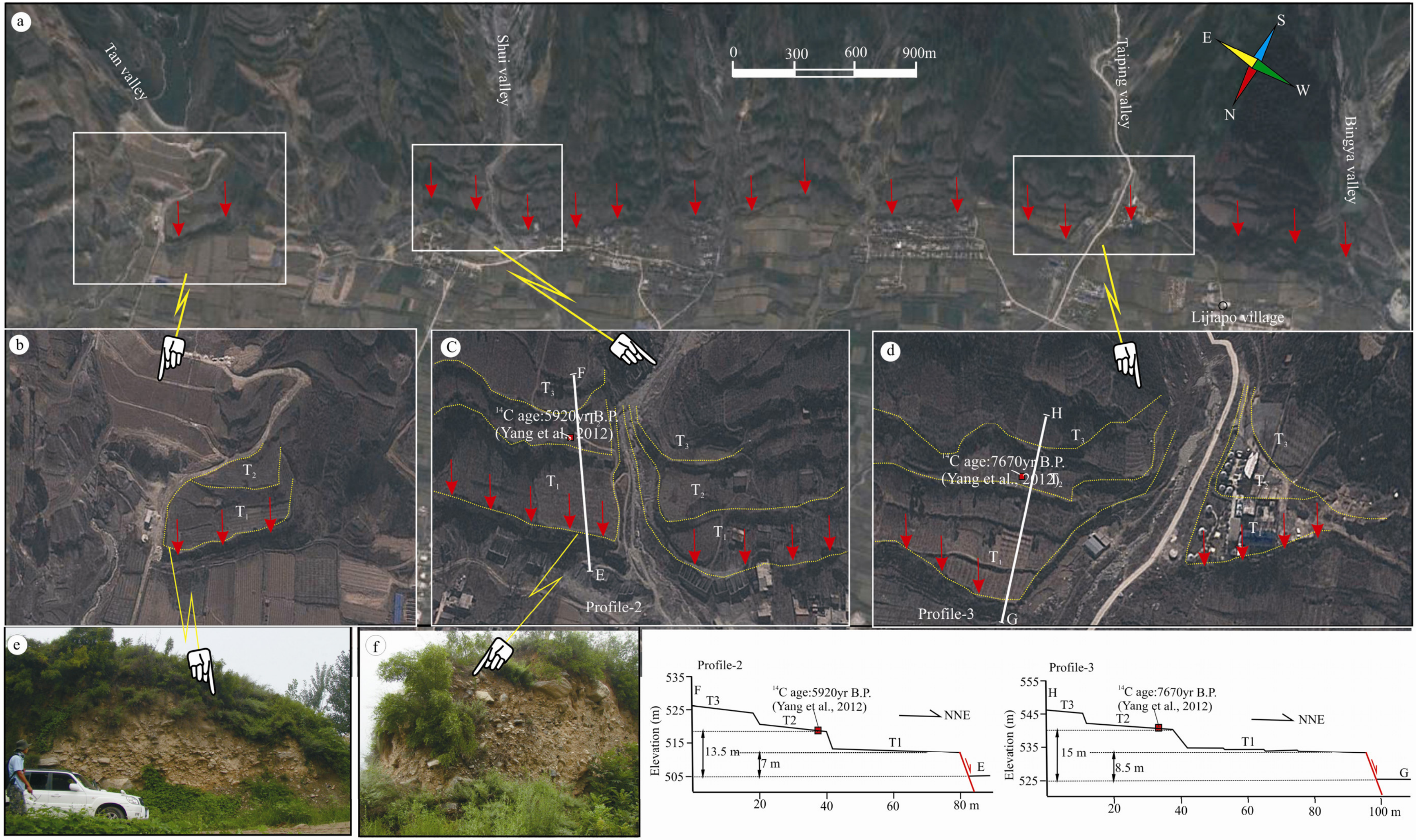

Fig. 5. Geomorphologic characteristics of alluvial fans in the Tan valley and Taiping valley on the central section of the Huashan piedmont fault and corresponding fault profiles.

(a), Locations of the Tan valley and the Taiping valley along the Huashan piedmont fault and the piedmont alluvial fans shown in a Google Earth image; (b), Second alluvial–fan terrace and scarp on the front of the terrace on the west bank of the mouth of the Tanyu valley; (c), Third alluvial–fan terrace and scarp on the front of the terrace at the mouth of the Shui valley; (d), Third alluvial–fan terrace and scarp on the front of the terrace at the mouth of the Taiping valley; (e), Scarp on the front of the first terrace on the west bank at the mouth of the Tan valley; (f), Scarp on the front of the first terrace on the east bank of the mouth of the Shui valley.

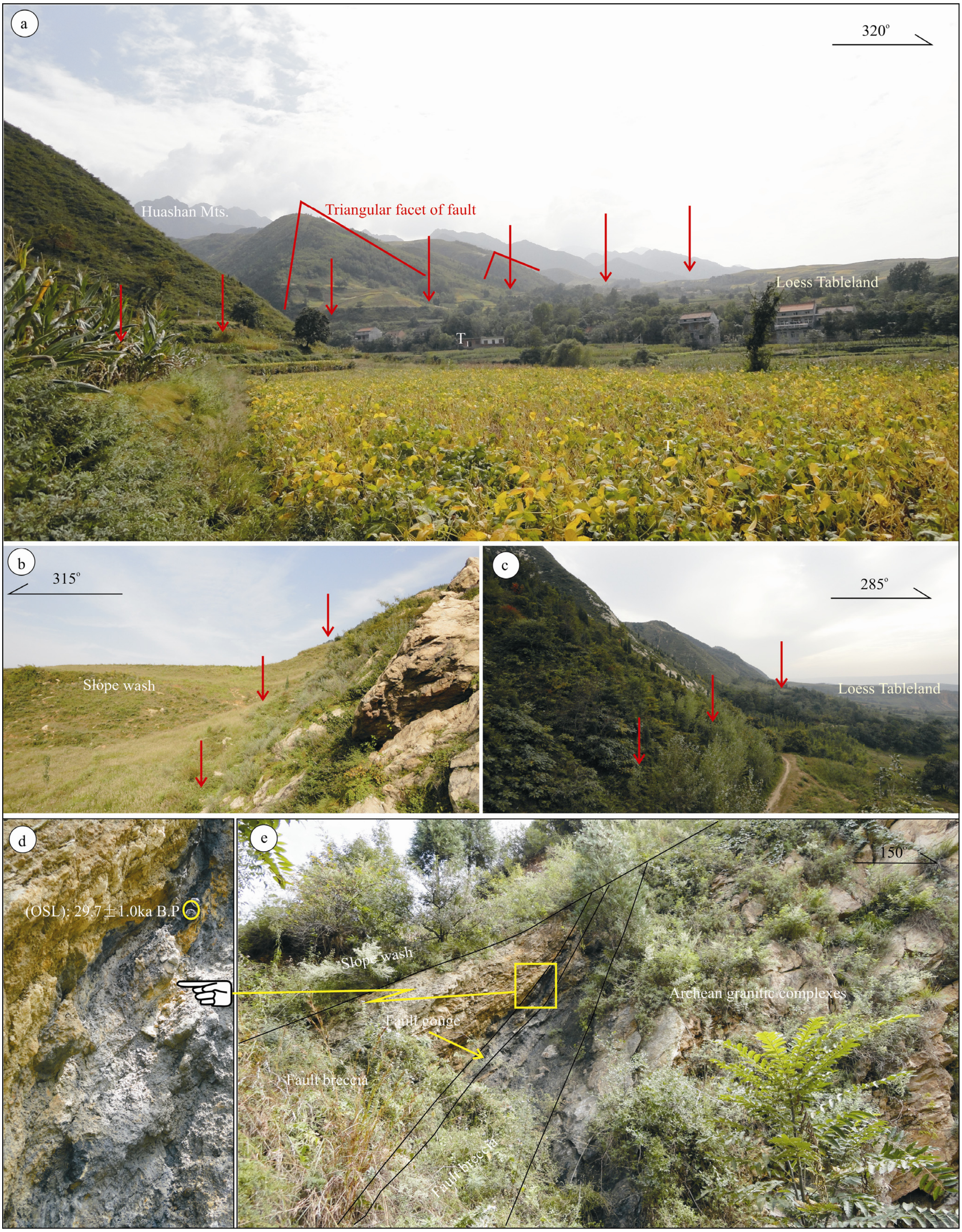

Fig. 6. Fault–related features of the western section of the Huashan piedmont fault.

(a), Triangular facet of the fault and non–offset Holocene first stream terrace; (b), Negative terrain and Holocene slope–wash deposits in the fault zone; (c), Triangular ridge facets along the fault and non–deformed loess tableland; (d), Fault gouge; (e), Profile of the early fault and fault gouge sampling locations.

of the Huashan piedmont fault has produced great earthquake and geological hazards. Along the Huashan piedmont fault zone, many palaeoearthquakes and ancient landslides are apparent.

4.1 Earthquake activity

4.1.1 Contemporary and modern earthquakes

According to historical records, multiple contemporary and modern earthquakes have occurred in the Weihe Graben; in particular, the eastern Weihe Graben has been very active compared to other areas of the graben. As seismic activity often occurs along active fault zones, the frequency and intensity of seismic activity tends to reflect the continuity and intensity of fault activity. An analysis of earthquake data in the study area indicates that multiple earthquakes have occurred in the Huashan piedmont fault zone (Table 1; Fig. 7). Most of these earthquakes were small; only a few were destructive. The M_w 5.5 earthquake in 1072 and the M_w 8.0 earthquake in 1556, which resulted in great economic losses and many casualties, are the strongest known historical earthquakes attributed to this fault zone.

During the M_w 5.5 earthquake of 1072, a landslide occurred on Futou Mountain in the northern slope of the Huashan Mountains. This landslide formed a quake lake, named Baiya Lake, on the Huashan Mountains piedmont. The landslide was 2–3 km from wide east to west and 5 km long from north to south. Its surface was strewn with falling rocks resulting from the earthquake, and houses and trees in the area were completely destroyed.

The M_w 8.0 earthquake of Huaxian County in 1556 had a seismic intensity level of XI and the main disaster region had an area of 280000 km^2. This earthquake affected an area of 900000 km^2, which included most of southern and northern China. The earthquake was responsible for 830000 deaths and is still the earthquake responsible for the greatest number of casualties worldwide (Yuan Tinghong and Feng Xijie, 2010). The earthquake created a 70–km–long surface rupture zone with a vertical displacement of more than 5 m (Wang, 1980). Intense deformation phenomena were formed during this earthquake, and a few earthquake relics are visible today, e.g. seismic fractures, earthquake faults and secondary geological hazards such as collapses and landslides (Wang Jingming, 1980; Zhang Anliang et al., 1989; Hou Jianjun et al., 1998). The earthquake also elevated the riverbed of the Tongguan section of the Yellow River, which resulted in post–earthquake flooding in the eastern Weihe Basin: these effects continued for more than 400 years (Wang Rudiao, 2006).

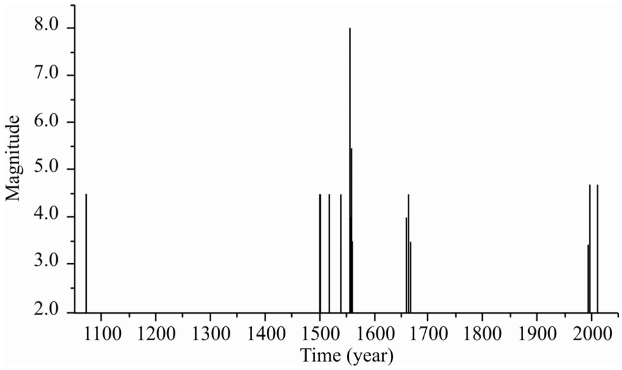

Fig. 7. Magnitudes and timing of earthquakes along the Huashan piedmont fault belt (data from (1) and (2)).

Currently, the collapsed accumulations that were formed from the aforementioned two earthquakes are still present. Large fallen rocks can be seen everywhere in Huaxian County on the Huashan piedmont. These fallen rocks are generally 4–5 m in diameter, but a few exceed 10 m in diameter (Figs. 8a,8b, 8c, 8d, 8e, 8f). There is an old cypress tree (height 5.6 m; maximum circumference 1.25 m) growing on a large fallen rock (length 9 m; width 8 m; height 5 m) near the piedmont: this cypress tree is approximately 400 years old and has been named

Table 1 List of earthquakes along the Huashan piedmont fault belt

Sequence number	Date	Epicenter	earthquake magnitude	The source of date
1	1072/11/03	N34.5°, E109.8°	$5^{1}/_{2}$	(1)
2	1502/08/03	N34.5°, E109.7°	$4^{1}/_{2}$	(1)
3	1520/07/06	N34.5°, E109.8°	$4^{1}/_{2}$	(1)
4	1541/08/25	N34.7°, E109.8°	$4^{1}/_{2}$	(1)
5	1556/01/23	N34.5°, E109.7°	8	(1)
6	1557/01/31	N34.5°, E109.7°	4	(1)
7	1558/11/21	N34.5°, E109.7°	$5^{1}/_{2}$	(1)
8	1560/10	N34.5°, E109.7°	$3^{1}/_{2}$	(1)
9	1661/01/12	N34.5°, E109.7°	4	(1)
10	1661/01/25	N34.3°, E109.8°	$4^{1}/_{2}$	(1)
11	1668/09/30	N34.5°, E109.8°	$3^{1}/_{2}$	(1)
12	1992/02/16	N34.43°, E109.13°	3.4	(2)
13	1996/11/06	N34.38°, E110.76°	3.1	(2)
14	1998/01/05	N34.46°, E109.07°	4.7	(2)
15	2009/11/04	N34.48°, E109.14°	4.7	(2)
16	2009/11/20	N34.48°, E109.13°	3.6	(2)

(1)http://www.sxsdq.cn/dqzlk/dfz_sxz/huaxz/
(2)http://www.csndmc.ac.cn/newweb/data.htm#

Fig. 8. Rockfall deposits caused by the earthquakes of 1072 and 1556.
(a)–(f), Rockfall deposits on the piedmont plain that resulted from the earthquakes of 1072 and 1556 (locations of rocks are shown in Fig. 9).

'Shibaobai' by local residents (Fig. 8c). Based on the growth of this tree, the rocks rolled down to this area more than 400 years ago. The earthquake responsible for other fallen rocks cannot be determined. However, according to historical records, in surrounding areas collapses occurred only during the M_w 5.5 earthquake of 1072 and the M_w 8.0 earthquake of 1556; therefore, these falling rocks are most likely to be related to these two earthquakes.

The frequent seismic activity along the Huashan piedmont fault zone is indicative of the activity of the fault. Most of the earthquakes were on the central section of the fault zone, indicating that the central section is the most seismically active section of the three sections.

4.1.2 Palaeoearthquakes

The palaeoearthquakes is generally used to refer to earthquake events that occurred in the Quaternary, particularly the Holocene. As seismic activities often occur along faults, seismic activity is generally considered to be the result of stick–slip movement of the fault. Therefore, frequent palaeoearthquakes in a fault zone are another sign of fault activity. Certain geological and geomorphologic features (e.g. surface ruptures, fault scarps, ground fissures, surface bulges and earthquake–induced landslides) that resulted from earthquakes and have since been preserved provide valuable data for identifying palaeoearthquakes.

No destructive earthquake has ever been recorded in the Huashan piedmont fault zone in modern times; however, an M_w 8.0 earthquake did occur in the Huashan piedmont fault zone in 1556 (Zhang Anliang et al., 1989; Hou Jianjun et al., 1998; Yuan Tinghong and Feng Xijie, 2010; Rao Gang et al., 2014). Therefore, particular attention has been paid to palaeoearthquakes that occurred in the Huashan piedmont fault zone. Due to intense human activity and the fact that the most intense fault activity has occurred in the Huayin City–Huaxian County region, many palaeoearthquake relics on the ground have been destroyed and are difficult to identify. However, a large number of underground buried fissures have been discovered in the Huashan piedmont fault zone. These underground fissures are generally developed in Upper Pleistocene sandy clay and are filled with cultural remains such as ancient pottery fragments, broken tiles and charcoal chips; in addition, the underground fissures are covered by a layer of cultured soil 1.2–2.5–m thick. From ^{14}C dating analysis of charcoal chips from inside two buried underground fissures, located at Shaohua Middle School and in the village of Chongchen in Huaxian County, two palaeoearthquakes occurred in 2715 a BP and 5610 a BP, and the earthquake period of the fault zone has been determined to be 2300–2900 years (Xu Xiwei et al., 1988). Multiple seismic wedges were discovered in an exploratory trench in Shamagou Village, Taoxia County, Huayin City (Zhang Anliang et al., 1989). This exposure revealed that four palaeoearthquake events, including the Great Huaxian County Earthquake of 1556, occurred in the Huashan piedmont fault zone; in addition, the period of large earthquakes during the Holocene has been estimated to be approximately 2000–2500 years.

These findings indicate that palaeoearthquakes occurred relatively frequently along the Huashan piedmont fault zone and that the fault has been active during the Holocene.

4.2 Ancient high–speed, long–runout landslides

As a result of modern quarrying activities, a mixed accumulation underlying the loess has been discovered in the Huashan piedmont fault zone. Geological investigations have indicated that the accumulation is mostly composed of Archaean metamorphic rocks (more than 10 m thick, approximately 2 km wide and approximately 5 km in length) derived from bedrock in the Huashan Mountains area. The accumulation is relatively fractured but still contains large blocks. No clay is mixed into the accumulation. An approximately 9–m–thick layer of loess has been deposited on the mixed accumulation of the landslide. Clearly, this accumulation represents a palaeolandslide (Fig. 9).

The palaeolandslide might be related to palaeoseismic activity along the Huashan piedmont fault zone (Du Jianjun et al., 2013). As this large landslide is located in the meizoseismal area of the two large earthquakes that occurred in Huaxian County in 1072 and 1556, most researchers have believed that the formation of this landslide was related to these two earthquakes (Li Xianggen and Ran Yongkang, 1983; He Mingjing, 1986; Yin Yueping, 2007; Zhou Qunying, 2010). To determine the age of the palaeolandslide, samples were collected from five loess profiles that covered the mixed accumulation of the landslide, and the OSL method was used for systematic dating. The loess samples collected from the bases of the five profiles have OSL ages between 130.2±5.6 and 187.3±7.7 ka (Fig. 10). Based on the OSL ages of the loess, this high–speed, long–runout landslide occurred at least 187000 years ago. The existence of this palaeolandslide demonstrates that the Huashan piedmont fault experienced strong activity 187,000 years ago.

4.3 Disasters (e.g. collapses, landslides and mudslides)

The Huashan Mountains area lies south of the Huashan piedmont fault zone and consists of metamorphic complexes of the Archaean Taihua Formation. As a result

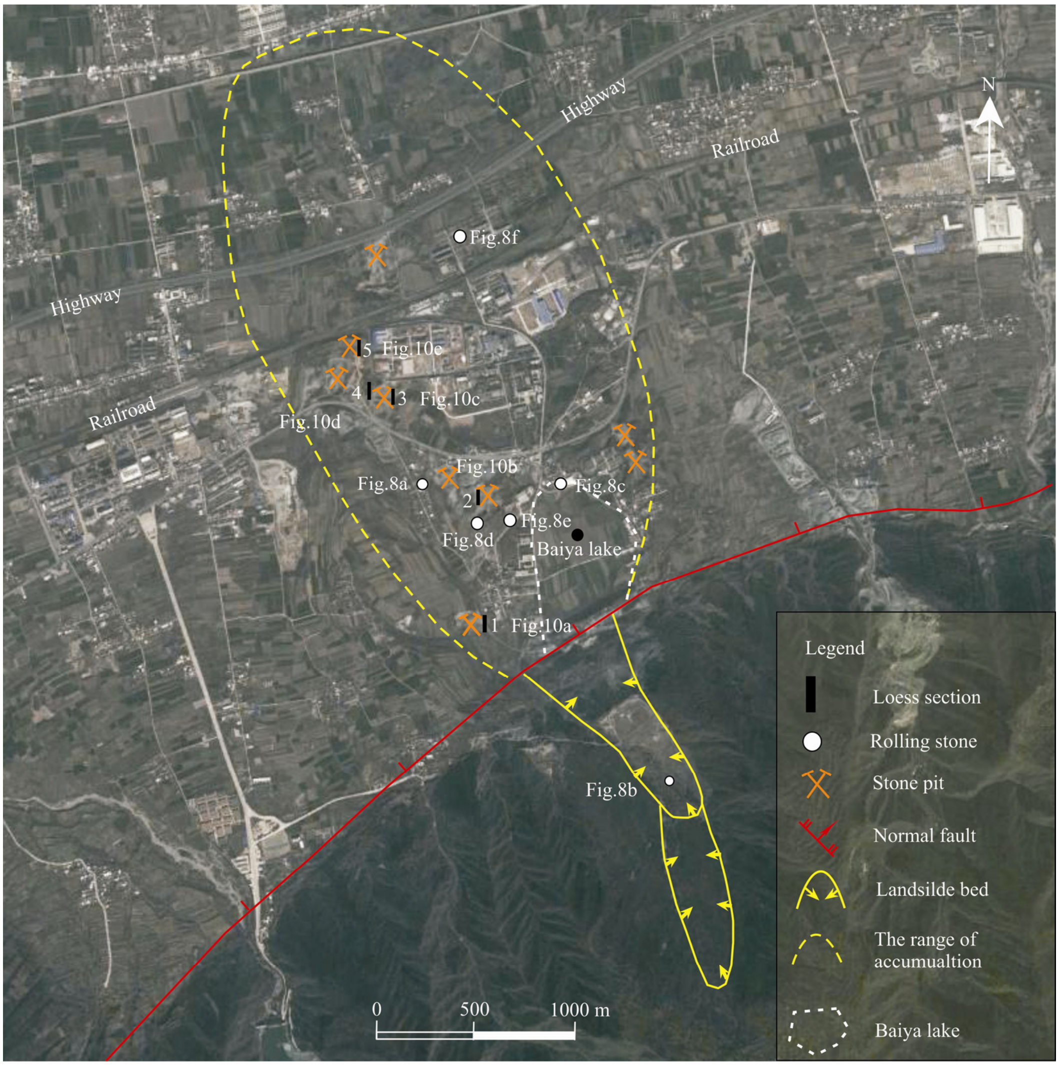

Fig. 9. Extent and features of the ancient high–speed, long–runout landslide in Huaxian County, Shaanxi Province, China.

of long–term tectonism in the region, the bedrock has been fractured and jointed. Following this tectonism, the Huashan Mountains area and the Qinling Mountains were rapidly uplifted and the rocks became more fractured due to weathering. In particular, the normal fault movement of the Huashan piedmont fault resulted in steep triangular facets and slopes on the footwall of the fault. These landforms provided sufficient source materials and the prerequisite locations for the development of collapses, landsides and mudslides; thus, geological disasters have been frequent in the Huashan piedmont fault zone.

Collapses mainly occur on steep slopes with gradients of more than 45° on the northern slope of the Huashan Mountains. The secondary disasters induced by the large earthquakes in Huaxian County in 1072 and 1556 were the most intense collapse disasters. Falling rocks affected an

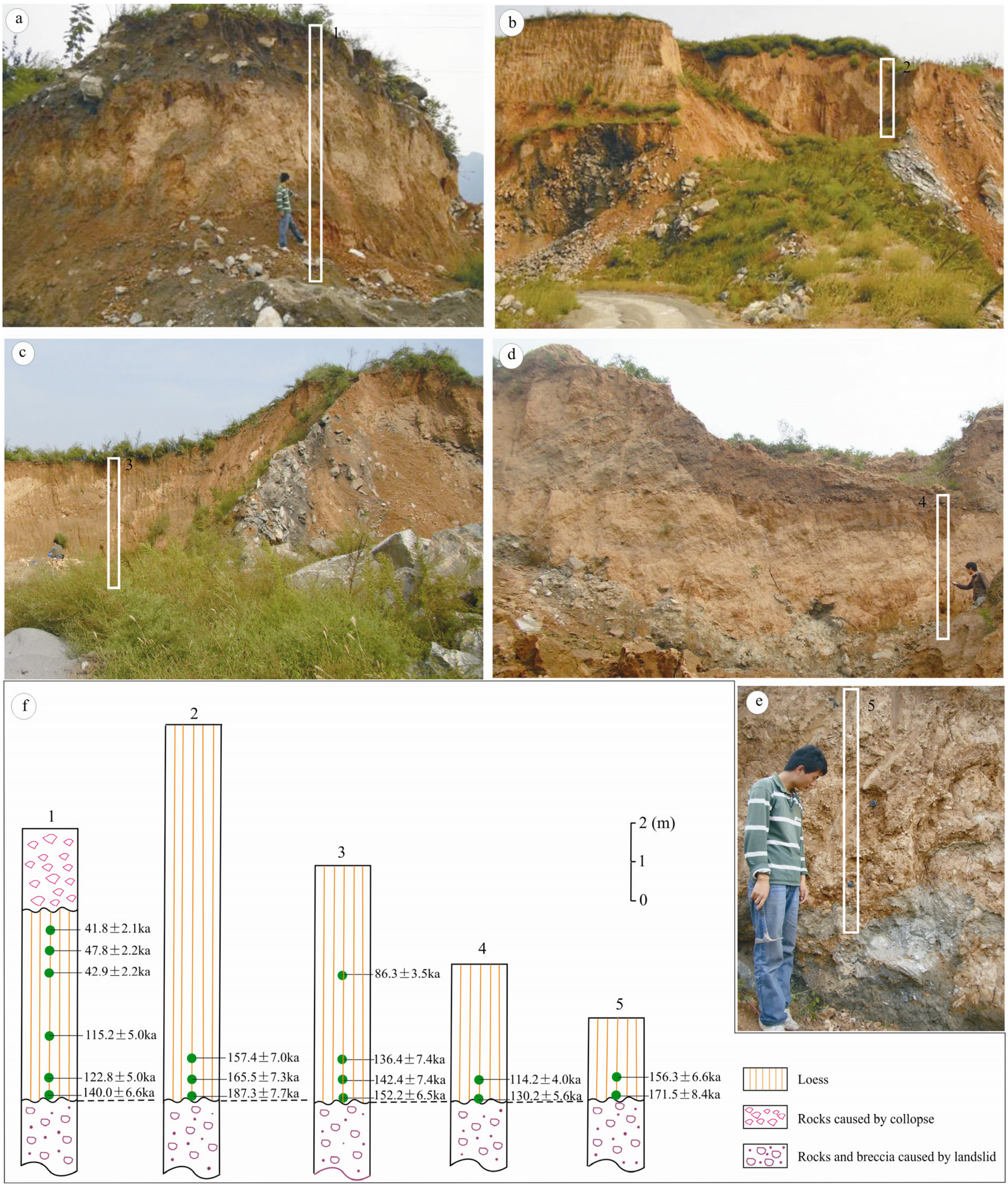

Fig. 10. Loess and its age where it overlies the ancient landslide.

(a)–(e), Loess covering the palaeolandslide and loess sampling sites (the locations of these loess sampling sites are shown in Fig. 9); (f), Sketch profiles and OSL ages of loess covering the palaeolandslide.

area greater than 10 km across on the northern slope of the Huashan Mountains and in the piedmont area, resulting in huge economic losses and casualties (Fig. 8; Wang Jingming, 1980; Zhang Anliang et al., 1989; Hou Jianjun et al., 1998). In addition, mountain body collapses occasionally occur on both sides of the mountain streams due to flowing water and erosion.

From the long–term activity of the Huashan piedmont fault, the streams on the northern slope of the Huashan Mountains have been eroding the mountain and transporting abundant sedimentary material to the mountain mouth, thereby creating frequent mudslides and causing development of alluvial fans at gully mouths during rainstorms. In addition, the rivers have been eroding and destabilizing the side slopes of the gullies, resulting in sliding of soil or rock masses along certain sliding surfaces under gravity. Currently, many gully mouths along the fault zone are hazardous areas for mudslides.

4.4 Ground fissure disasters

Ground fissures are well developed in the Weihe Graben (Peng Jianbing et al., 2007, 2008). Ground fissure disasters are primarily distributed along the fault zone on the northern margin of the Qinling Mountains and in the plain area to the north of the fault zone. There are two prominent movement characteristics of the ground fissures in the Weihe Graben: vertical differential movement and horizontal tensional movement. Vertical differential movement of ground fissures generally involves normal–fault movement; horizontal tensional movement of ground fissures often forms tensional fissures 0.3–8 cm wide. The widths of these fissures gradually decrease to zero with increasing depth (Peng Jianbing, 2012).

The ground fissures in the Weihe Basin are all concentrated near the active fault, and the trends of the fissures are generally consistent with the strike of the fault (Chen Zhixin et al., 2007). The strikes of the ground fissures are generally in good agreement with the parallel–distributed strike of the fault, and these ground fissures exhibit tensional characteristics.

The ground fissures in the Weihe Graben are hazardous. There is a general consensus that the formation and development of the ground fissures in the Weihe Graben has resulted from faulting in the graben and that groundwater pumping has promoted the formation and development of these ground fissures (Chen Zhixin et al., 2007; Peng Jianbing et al., 2007, 2008; Peng Jianbing, 2012; Zhang Qin et al., 2012; Deng Yahong et al., 2013).

5 Discussions

The Huashan piedmont fault is the boundary of the southeastern part of the Weihe Graben. The elevation difference between the footwall and hanging–wall of the Huashan piedmont fault is more than 1750 m. The Huashan Mountains, the footwall of the Huashan piedmont fault, have a highest elevation of 2160 m and contain outcrops of pre–Mesozoic bedrock. The hanging–wall of the Huashan piedmont fault is the Weihe Graben, which has a general elevation higher than 400 m and outcrops of Cenozoic sediments. The formation and dynamical mechanism of high–angle normal Huashan piedmont fault are related to both the differential uplift of the Qingling Mountains and the northwest–southeast–trending regional extensional environment. The Huashan Mountains experienced rapid uplift during the Cenozoic between ~50 and ~10 Ma according to apatite fission–track data (Liu Jianhui et al., 2013). This indicates that the Huashan piedmont fault commenced normal dip–slip activity in the Eocene with uplift of the Huashan Mountains.

The Huashan piedmont fault has been continuously active since the Late Pleistocene. The central section of the Huashan piedmont fault is the most active and was very active both during the late Quaternary and in the Holocene. Based on the age of the scarp from the Holocene fault, Zhang Anliang et al. (1989) calculated that the dip–slip rate was 0.6–2.0 mm/yr since 6000 yr BP and 0.5–2.3 mm/yr since 2700 yr BP. After a systematic investigation of these scarps, Li Yongshan (1992) confirmed that the river terraces and latest scarps on the alluvial–flood fan resulted from fault activities. The dip–slip rate is 2.4 mm/yr according to the ages of cultural relics and archaeology. On the basis of the dislocation distance and AMS ^{14}C dating of the T_1 and T_2 diluvial terraces by Yang Yuanyuan et al. (2012), the average dip–slip rate of the central section of the Huashan piedmont fault was 1.485 mm/yr from 6000 to 2000 yr BP and 3.72 mm/yr since 2000 yr BP. In that paper, the rate of normal dip–slip was 1.67–2.71±0.11 mm/a in the Holocene and was 0.61±0.15 mm/a during the Mid–Late Pleistocene.

Earthquake wedges record seismic events (Xu Xiwei et al., 1988) and Yang Yuanyuan et al. (2012) thought that the alluvial fan scarps resulted from seismic activity. Therefore, the central section of the Huashan piedmont fault must have experienced no fewer than three intensive periods of seismic activity during the Holocene, because of the existence of two diluvial scarps formed between 5920–7670 Cal yr BP (Yang Yuanyuan et al., 2012) and 2215±95–3105±105 Cal yr BP and relics of the great Guanzhong earthquake of 1556 AD (He Mingjing, 1986; Zhang Anliang et al., 1989; Hou Jianjun et al., 1998; Yuan Tinghong and Feng Xijie, 2010).

Active faults generally cause many types of geological hazards, such as earthquakes, collapses, landslides, mudslides and ground fissures. Active faults are both a direct and an indirect cause of geological disasters. The direct effects of active faults are earthquakes (Han Jinliang, 2015; Li Xi et al., 2015; Shi Zhigang et al., 2015; Sun Ping et al., 2015; Yin Zhiqiang et al., 2016). Indirect effects include destruction of the rock and soil structure, resulting in the development of large networks of structural fissures, fractured tectonites or large–scale fracture zones, which provide favourable conditions for the occurrence of collapses, landslides and mudslides (Fu Xiaofang et al., 2008; Huang Runqiu and Li Weile, 2009; Ma Yinsheng et al., 2009; Zhang Yongshuang et al., 2010a, 2013; Ni Huayong et al., 2014; Yang Wentao et al., 2015; Dou Aixia et al., 2016). Faults that have been active since the Late Pleistocene are particularly hazardous to buildings and engineering construction (Zhang Yongshuang et al., 2010b; Zhang Yongshuang et al., 2012). The continuous strong activity of the Huashan piedmont fault since the Late Pleistocene has resulted in the occurrence of several disasters with different magnitudes. Multiple palaeoearthquakes, palaeolandslides and palaeocollapse events have occurred in the fault zone. These disasters are attributed to the activity along the Huashan piedmont fault in the late Quaternary. In addition, multiple palaeoearthquakes, palaeolandslides and palaeocollapses have occurred in the fault zone on the northern margin of the Qinling Mountains south of the Weihe Graben (Zhang Anliang et al., 1990, 1992; Nan Ling and Cui Zhijiu, 2000; He Mingjing et al., 2006).

The distribution of geological hazards along a fault often varies with the type of fault. In general, geological disasters caused by compressional or thrust faults are located mostly on the hanging–walls of the faults and include landslides and collapses (Chen Xiaoli et al., 2011). The numbers and types of geological disasters along strike–slip faults are essentially distributed evenly on both sides of the fault (Xu Chong and Xu Xiwei, 2012). The main types of disaster caused by compressional and strike–slip faults are landslides, collapses and mudslides, which are distributed near the fault zones. Those disasters may occur on the hanging–wall or the footwall of a compressional or strike–slip fault. The Huashan piedmont fault was a highly active normal fault during the late Quaternary; however, the disasters that have occurred due to the fault have been distributed significantly differently between the hanging–wall and the footwall. Ground fissures parallel to the strike of the fault mainly occur on the northern (hanging) wall of the fault. The hanging–wall area is a wide plain with a high population density; therefore, during an earthquake, the hanging–wall will incur the greatest damage and largest losses. The disasters caused by the Great Huaxian County Earthquake of 1556 were mainly distributed in the Weihe plain area, where human activity was concentrated. The footwall of the Huashan piedmont fault is the mountainous area of the Huashan Mountains; disasters that occur in the footwall mainly include landslides, collapses and mudslides.

The hanging–wall of the Huashan piedmont fault dropped significantly in the late Cenozoic, whereas the footwall of the Huashan piedmont fault was rapidly uplifted. There are several–hundred–metre triangular facets and fault scarps along the fault zone. The terrain contains steep slopes (35°–65°) with a large topographic contrast. In addition, the continuous activity along the fault resulted in the formation of fault rocks (also called tectonites) of significant thicknesses, and these fault rocks are relatively fragmented. Multiple sets of structural joints in the Archaean strata provide internal conditions for formation of landslides; thus, landslides and mudslides may occur frequently under conditions of fault activity and heavy precipitation. Due to the alluvial fans, which were formed at the piedmont mountain stream outlets, along with long–term sedimentation in the Weihe River channel, a concave area developed between the Huashan piedmont and the Weihe River, where massive flooding frequently occurs during rainstorms.

6 Conclusions

As a result of the investigation of the types and activities along the Huashan piedmont fault during the late Quaternary and the analysis of the disasters on both the hanging–wall and footwall of the fault zone, the following conclusions were obtained:

(1) The Huashan piedmont fault can be divided into three sections: eastern, central and western. During the late Quaternary, all three sections of the Huashan piedmont fault displayed high–angle normal fault activity.

(2) The central section of the Huashan piedmont fault is the most active of the three sections and was very active during the late Quaternary. The rate of normal dip–slip was 1.67–2.71±0.11 mm/a in the Holocene and 0.61±0.15 mm/a during the Mid–Late Pleistocene.

(3) The Huashan piedmont fault was highly active during the late Quaternary. This activity has induced large–scale, long–runout palaeolandslides and devastating earthquakes. The Great Huaxian County Earthquake of 1556 is one of the few strong earthquakes worldwide that occurred because of a normal fault.

(4) The activity along the Huashan piedmont fault, a normal fault, has resulted in many types of disaster; however, the disasters that have occurred on the hanging–wall are different from those on the footwall. The hanging–wall of this normal fault has mainly experienced

ground fissures, whereas the footwall is mainly the location of landslides, collapses and mudslides.

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