Knickpoint series of gullies along the Luoyunshan Piedmont and its relation with fault activity since late Pleistocene

Changbin Sun^{a,b,*} Tianfeng Wan^a Xinsheng Xie^b Xiaoming Shen^b Kuan Liang^{b,c}

^a School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China

^b Key Laboratory of Crustal Dynamics, Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, China

^c Institute of Geology, China Earthquake Administration, Beijing 100029, China

* Corresponding author at: Key Laboratory of Crustal Dynamics, Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, China. Tel.: +86 10 62846730; E-mail address: chbsun@163.com (C. Sun).

Abstract

The authors surveyed the longitudinal profiles of 28 gullies across the Luoyunshan Piedmont fault (LPF) by differential GPS and dating of sediments well preserved in the typical terraces and obtained 6-level knickpoint series of the gullies along the Luoyunshan Piedmont. The authors compared it with previous studies on the paleo-earthquakes of the LPF revealed by trenches and found that the paleo-earthquake events from knickpoint and trench studies are in good agreement in terms of the time of occurrence and vertical displacement of the fault. It shows studying the paleo-earthquake events of the fault by knickpoint series is feasible. At last, the authors established a more complete paleo-earthquake sequence of the LPF supported by geomorphologic and sedimentary evidence, i.e., six paleo-earthquake events happened on the LPF from about 28,000 years ago; the LPF has the characteristic of quasi-periodic recurrence and the average recurrence interval is 4585 years. The vertical displacement of the paleo-earthquake events is

2.4-3.0 m; according to the empirical equations between co-seismic displacement and earthquake magnitude the magnitude of these events is M_s 7.0-7.5. This study aims to complement and improve the traditional trenching method, provide theoretical and methodological support for the research of active tectonics, and contribute important information for the seismic hazard assessment of the densely populated Linfen area.

Keywords: Luoyunshan Piedmont fault; late Pleistocene; knickpoint series; paleo-earthquake; recurrence interval

1. Introduction

With the development of active tectonic studies (Wallace, 1970; Sieh and Jahns, 1984; Deng et al., 2004), the research on the influence of active tectonics on landform and geomorphology goes also deeply. On the other hand, the regional landforms and its related sediments provide a good time and space framework for constraining important parameters of active tectonics, such as properties, rates, strong earthquake activity records, and the latest activity times and so on. Geomorphological theory and methods have become one of the most effective and promising ways to evaluate active tectonics (Schumm et al., 1987; Merritts et al., 1994; Li et al., 1998; George and Madho, 1999; Holbrook and Schumm, 1999; Bernard, 2001). In nature, river landscapes are widely developed and whose formation, development, and evolution is significantly affected by tectonic activity; and it is one of the most striking and commonly used landscape symbols in the research of tectonic geomorphology (Maruyama and Lin, 2000; Viseras et al., 2003; He and Oguchi, 2008). In fluvial geomorphology, the adjustment of river longitudinal profile shape is not only closely related to crustal movements but also a sensitive response to the fault activities inside the basin (Burnett and Schumm, 1983; Ouchi, 1985; Snow and Slingerland,

1990). The knickpoint of river gullies is one of the noteworthy contents of fault activity identification in the intraplate basin. Many studies have been done to explore the relationship between the knickpoint of river gullies and the multiperiod activities of the fault (Yang et al., 1985; Peng, 1991; Commins et al., 2005; Yanites et al., 2010; Bi et al., 2011; Sun et al., 2012; He and Ma, 2015; Wei et al., 2015). The research shows that the relationship between the knickpoints and the fault activities is close.

Field investigation can directly identify the knickpoint (Yang et al., 1985; Miller, 1991; Peng, 1991; Bishop and Goldrick, 1992; Rosenbloom and Anderson, 1994; Wohl and Ikeda, 1998; Belmont, 2011; Sun et al., 2012). With the emergence of digital elevation model (DEM) data and the improvement of spatial analysis technology, some methods of extraction and recognition of the knickpoint based on high-resolution DEM and mathematical models have been reported in recent years (Whipple, 2001, 2004; Duvall et al., 2004; Bishop et al., 2005; Crosby and Whipple, 2006; Hayakawa and Oguchi, 2006; Bi et al., 2011; Zhang et al., 2011; He and Ma, 2015; Wei et al., 2015). It has greatly promoted the knickpoint analysis and quantitative research of the longitudinal profile characteristics of a river. However, because of the resolution of the DEM, data is still not high enough for the knickpoint study; errors in the extraction and identification of the knickpoint will occur compared with the actual situation. Therefore, more detailed field investigation is needed to complete the study of the knickpoint of river gullies.

In this study, the authors chose the Luoyunshan Piedmont fault (LPF) as the experimental area, surveyed the longitudinal profiles of 28 gullies across the LPF in the field by differential GPS with precision at the centimeter level, and identified the knickpoints induced by fault activity and excluded the nontectonic ones. By dating the sediments well preserved in the typical terraces, the authors established the temporal and spatial knickpoint series of the gullies along the

Luoyunshan Piedmont, then analyzed the paleo-earthquake sequence of the LPF since late Pleistocene. The authors compared it with the previous study on the paleo-earthquakes of the LPF revealed by trenches and established a more complete paleo-earthquake sequence of the LPF supported by geomorphologic evidence and trench profiles. Study of knickpoint series can complement and improve the traditional trenching method and provide theoretical and methodological support for the research of active tectonics.

2. Geological background

The Shanxi faulted basin zone (SFB) is an important strong earthquake activity zone in the mainland of China. The study of strong earthquake activity and active fault in the SFB plays an important role in the study of strong earthquakes in China (Deng et al., 1973; Liu and Xiao, 1982; Xu and Ma, 1992; Deng and Xu, 1995; Wan, 2011). The LPF is located in the south of the SFB, west of Linfen basin and controls the western boundary of the basin. It starts in the Xiaogu area in the north; runs through Wanshengsi, Tumen, Yuli, Weicun, and Fanjiazhuang until Xiweikou; strikes NNE in general and bends to NWW at Fanjiazhuang, with a total length of 145 km (Fig. 1).

The upthrow block of the LPF is a bedrock mountain area consisting of Archean and Paleozoic formations; mid-Pleistocene Lishi loess is preserved locally. The entire downthrown block of the fault is overlain by Quaternary sediments. North of Tumen, Pliocene red clay outcrops occasionally. The Luoyunshan mountain area is part of Luliang fault uplift and has been subject to complex tectonic movements. The LPF was a thrust zone in the Yanshanian period. It was owing to the regional extension and shearing as the Pliocene that made the fault become a normal fault controlling the western border of Linfen basin. The 2000-m-thick Cenozoic deposit in the center of Linfen basin deflects to the side of the LPF, indicating the intensive activity of the fault. The

Quaternary fault activity inherits the characteristic of Pliocene activity (Wang et al., 1993).

Fig. 1. Simplified map of Shanxi faulted basin zone and geologic map of the Luoyunshan Piedmont fault (LPF).

In the 1980s ~ 1990s, some researchers indicated that Holocene activities occurred along the LPF (Su and Yan, 1985; The Research Group on 'Active Fault System around Ordos Massif' and SSB, 1988; Zheng et al., 1990; Wang et al., 1993). In recent years, the authors conducted a detailed investigation of geology and geomorphology (Sun et al., 2011, 2013; Xu et al., 2011), and 1:50,000 scale bars banded geological mapping of the LPF; and excavation of many exploratory trenches revealed paleo-earthquake events of the LPF since late Pleistocene (Table 4).

3. Methods

3.1. Method of paleo-earthquake analysis based on knickpoint series

The knickpoint (nickpoint) refers to a substantially steepened section of a stream long profile (Yang et al., 1985; Burbank and Anderson, 2001; Goudie, 2004). Down-faulted blocks can initiate

an upstream-propagating wave of incision in river reaches that cross the fault zone. A typical normal dip-slip piedmont fault develops many gullies in its footwall, and the gullies' profiles adjust sensitively with the fault's behavior (Burnett and Schumm, 1983; Ouchi, 1985). River downcutting is controlled by base levels downstream, which can in turn be affected by faulting. When base levels are affected by faulting, knickpoints are formed in the longitudinal profile and are migrating upstream. The number of knickpoints in a gully reflects the amount of faulting events; the distance between adjacent knickpoints in a gully is related to the time interval between two faulting events; and the height of knickpoints in a gully corresponds to the vertical displacement of faulting events (Yang et al., 1985; Peng, 1991; Commins et al., 2005; Yanites et al., 2010; Bi et al., 2011; Sun et al., 2012; He and Ma, 2015; Wei et al., 2015).

The authors use a simple model of knickpoint formation and recession to build the conceptual model for the geomorphic processes observed in this study (Fig. 2). Knickpoint K_1 appears when the first earthquake occurs (Fig. 2B). Knickpoint K_1 moves upstream with headward erosion on the gully (Fig. 2C). A new knickpoint K_2 appears in the gully when a second earthquake occurs (Fig. 2D). Knickpoints K_1 and K_2 move upstream with headward erosion, and a third earthquake produces the third knickpoint K_3 (Fig. 2E) and so on.

Fig. 2. Schematic map of growth and recession of knickpoints and terraces associated with faulting (Bi et al., 2011, modified). Parameters t_0 , t_1 , $t_1 + \Delta t$, t_2 , t_3 are time back from now; K_1 , K_2 , K_3 are knickpoints coming out at t_1 , t_2 ,

t_3 ; T_1 , T_2 , T_3 are terraces respectively corresponding to K_3 , K_2 , and K_1 ; L_1 , L_2 , L_3 are distance of K_1 , K_2 , K_3 away from the fault; red line is the fault.

A terrace is often developed on the gully section from the knickpoint downstream to the fault location caused by downward erosion. Each level terrace can be corresponding to a knickpoint in the upstream direction (Fig. 2). The age of the beginning of terrace formation can represent the age of the beginning of knickpoint formation and recession, i.e., the time of paleo-earthquake occurrence. Thus the authors can use the backward distance of knickpoint and the formation age of the corresponding terrace to calculate the retreat rate of the knickpoint. The number of knickpoints and the level of terraces should be equal, theoretically. In fact, the former is more than the latter, and the reason for this phenomenon is complicated. The formation of river terraces is the outcome of the combined action of climate change and tectonic uplift. The former controls the terrace formation age of the river accumulation and incision alternately, and the latter provides the driving force for the long-term incised river (Merritts et al., 1994; Maddy et al., 2001; Starkel, 2003). However, the formation of the knickpoint is not affected by climate factors. In addition, a terrace is often destroyed by long-term erosion of running water after the formation, especially if it is developed in unconsolidated sediments. The knickpoint of the gullies in the bedrock footwall is not only sensitive to the fault activity but also not easy to be destroyed. Each vertical movement of the fault can be recorded in the form of a knickpoint in the gully bed. The knickpoints distance themselves from each other at all levels and are easy to distinguish. Compared with the fault scarp on which faulting events overlap, a single event of the fault activity can be identified more easily by the investigation of the knickpoint in a gully. So it is a good method to analyze the paleo-earthquake events of the fault through the knickpoint series. The retreat rate of the first (latest) level knickpoint can be calculated through the dating of sediments preserved in the first (latest) level terrace and surveying the backward distance from the fault of the first knickpoint

corresponding to the first level terrace, i.e., $V(K_3)=L_3/t_3$ (Fig. 2). The knickpoint propagation rate on each gully is assumed to be constant and equal to the retreat rate of the first level knickpoint. Then, the ages of all knickpoints, i.e., the time of faulting, in each gully can be obtained based on their distance from the fault, resulting in the paleo-earthquake sequence of the fault. It provides the possibility for the verification, supplement, and improvement of the regional paleo-earthquake sequence.

3.2. Dating materials and methods

To determine the age of the terrace sequence, the authors use numerical dating and the relative age of the overlying loess. Note that the age of a fluvial terrace here is the age when the terrace tread was abandoned by the active stream. The overbank sand of the lower terraces (T_1 and T_2) and the overlying loess were dated by thermoluminescence (TL) and optically stimulated luminescence (OSL). The samples were collected using steel tubes (length ~ 20 cm, diameter ~ 5 cm). The tubes were sealed immediately using aluminum foil and tape to retain moisture and avoid daylight exposure. The authors collected four OSL samples and two TL samples (Tables 1, 2). The OSL samples were assayed by Junxiang Zhao, and the TL samples were tested by Huanzhen Wang, the Key Laboratory of Crustal Dynamics, Institute of Crustal Dynamics, China Earthquake Administration. Under weak red light, fine quartz grains (4–11 μm) were separated, and the purity was tested by infrared-stimulated luminescence (IRSL) scanning until the IRSL/OSL ratio was <10%. The equivalent dose was determined using fine-grained quartz (4–11 μm) on a Daybreak 2200 automated reader with the single aliquot regenerative-dose protocol initially developed by Zhou and Shackleton (2001). Following the experimental procedures of Lu et al. (2007) and Wang et al. (2010), uranium and thorium contents were determined with

Daybreak 583 thick source alpha-counter. The potassium content was measured with a flame photometer.

Table 1

OSL dating results

Sample no.	Laboratory ID ^a	Dose rate (Gy/ka)	Equivalent dose (Gy)	Age (ka)	Terrace level
OSL-3	15-OSL-75	4.28	46.33±1.69	10.84±1.15	T2
OSL-4	15-OSL-76	5.02	23.22±1.61	4.62±0.56	T1
OSL-11	15-OSL-82	5.26	54.31±1.88	10.97±1.16	T2
OSL-12	15-OSL-83	4.37	35.87±1.73	8.20±0.91	T2

^a OSL samples were analyzed in the Key Laboratory of Crustal Dynamics, Institute of Crustal Dynamics, CEA.

Table 2

TL dating results

Sample no.	Laboratory ID ^a	Dose rate (Gy/ka)	Equivalent dose (Gy)	Age (ka)	Terrace level
STL-19	998284	2.17	10.0	4.61±0.39	T1
STL-20	998285	2.44	24.0	9.84±0.84	T2

^a TL samples were analyzed in the Key Laboratory of Crustal Dynamics, Institute of Crustal Dynamics, CEA.

The authors have excavated many paleo-earthquake trenches during the 1:50,000 active fault mapping of the LPF and collected some radiocarbon (¹⁴C), OSL, and TL samples. The radiocarbon (¹⁴C) samples were analyzed at Beta Analytic Inc., USA. The OSL and TL samples were tested by Junxiang Zhao and Huanzhen Wang at CEA, respectively.

4. Results

In this study, from north to south, the authors surveyed longitudinal profiles of 28 gullies across the LPF in the field by the differential GPS with precision of centimeters and identified 6 level knickpoint series with a total of 133 bedrock knickpoints induced by fault activity and excluded the nontectonic ones by regional comparison (Figs. 3, 4, 5, Table 3). The bedrock of G1-G18 and G26-G28 is Paleozoic limestone; the bedrock of G19-G25 is Archean gneiss. The size of the 28 gullies is similar, and the upstream length of them is about 1.5-2.0 km.

Among the 133 knickpoints, 36 are 1.0-2.0 m high, accounting for 27% of the total number

of knickpoints; 73 are 2.1-3.0 m high, accounting for 55% of the total; and 24 are higher than 3.0 m, accounting for 18% of the total (Fig. 6). Thus it shows that the height of most knickpoints is 2.1-3.0 m.

The most recent (level 1) knickpoints have retreated upstream with a mean distance of 176 m from the LPF; the next most recent set of knickpoints (level 2) retreated upstream with a mean distance of 344 m; and the level 3, level 4, level 5, and level 6 knickpoints retreated, respectively, upstream with the mean distance of 514, 653, 839, and 1045 m (Table 3).

Fig. 3. Distribution of the 28 gullies surveyed along the Luoyunshan Piedmont fault.

Fig. 4. Longitudinal profiles of the 28 gullies with knickpoints, and the positions and heights of the knickpoint

scarps. Dashed lines indicate the location of the LPF; a black triangle indicates the location of the knickpoints;

numbers indicate the height of the knickpoint.

Fig. 5. Photos of knickpoints located in upstream channels that cross the LPF. Observed knickpoints in (A), (B), (C), (D), (E) and (F) are from profiles G2, G4, G19, G9, G17, and G24, respectively.

Fig. 6. Distribution of the height of the knickpoints of the gullies along the Luoyunshan Piedmont fault.

Table 3Statistics of distance between the knickpoint and the fault, and the height of the knickpoint scarp^a

No. of gully	KA	Level 1		Level 2		Level 3		Level 4		Level 5		Level 6	
		D(m)	H(m)	D(m)	H(m)	D(m)	H(m)	D(m)	H(m)	D(m)	H(m)	D(m)	H(m)
G1	3	60	7.0	111	5.5	488	3.0						
G2	2	91	3.0	218	3.0								
G3	5	57	2.8	118	1.1	168	1.9	468	1.5	846	1.5		
G4	6	85	2.1	250	2.9	336	2.1	370	2.5	415	2.8	482	2.8
G5	6	36	2.2	62	4.8	87	2.8	199	1.0	728	2.2	1362	2.3
G6	4	68	4.5	282	4.6	360	2.2	425	2.1				
G7	5	111	2.8	223	1.2	513	1.5	549	2.5	652	2.2		
G8	5	93	1.1	183	2.2	283	1.7	328	2.0	544	2.5		
G9	6	115	6.5	399	6.5	619	2.3	637	3.5	788	1.2	1129	1.5
G10	5	153	2.1	282	1.8	364	2.6	646	1.0	783	1.3		
G11	6	156	2.7	263	2.3	400	2.5	584	2.4	940	2.5	1314	3.5
G12	6	53	3.0	429	1.5	481	3.0	542	2.4	772	3.2	1202	2.3
G13	4	113	3.3	187	1.6	220	1.6	250	2.1				
G14	4	183	2.1	270	2.1	497	4.0	569	4.0				
G15	5	171	2.5	426	2.6	459	2.4	685	2.5	946	2.6		
G16	3	249	3.0	406	2.1	460	3.5						
G17	5	101	2.3	442	3.0	979	2.3	1014	3.5	1191	6.0		
G18	4	454	2.3	504	1.2	606	1.6	667	2.5				
G19	5	258	2.3	384	2.4	493	1.9	627	6.5	822	1.3		
G20	5	226	1.8	305	2.1	527	2.2	745	2.2	1058	1.8		
G21	6	148	2.2	343	3.5	423	2.5	522	2.2	691	2.2	782	2.2
G22	4	294	2.5	398	3.0	627	3.5	832	3.5				
G23	6	460	1.8	510	1.0	626	1.0	654	2.5	1010	2.7	1194	6.2
G24	4	449	1.6	831	1.8	1165	2.6	1213	1.5				
G25	5	479	2.5	786	1.4	923	2.3	1164	1.7	1331	6.5		
G26	4	58	1.2	428	2.3	640	3.0	1306	2.5				
G27	4	137	3.9	494	3.0	707	3.0	764	2.5				
G28	6	87	3.0	111	1.7	429	1.5	575	1.5	752	3.2	895	3.0
Mean		176	2.8	344	2.6	514	2.4	653	2.5	839	2.7	1045	3.0

^a KA: knickpoint amount; D: distance between the knickpoint and the fault; H: height of the knickpoint scarp.

Table 4

Paleo-earthquakes of the Luoyunshan Piedmont fault from about 28,000 years ago^a

No.	Knickpoint paleo-earthquake (y)			VDKP (m)	Trench paleo-earthquake (y) ^b				VDTP (m)	Comprehensive paleo-earthquake (y)				VDCP (m)
	Age	LTLE	RIMV		Age	Median age	LTLE	RIMV		Age	Median age	LTLE	RIMV	
①	4620			2.8	4500-5000	4750			2.2-2.9	4620-4750	4685			2.7
②	9028	4408		2.6	8140-10000	9070	4320		2.2-3.0	9028-9070	9049	4364		2.6
③	13490	4462		2.4						13490	13490	4441		2.4
④	17139	3649		2.5	16400-18480	17440	8370		2.4-3.0	17139-17440	17290	3800		2.6
⑤	22020	4881		2.7	22700-24700	23700	6260		2.0-4.0	22020-23700	22860	5570		2.9
⑥	27427	5407	4561	3.0	27670-27930	27800	4100	5762	3.0	27427-27800	27613	4753	4585	3.0

^a LTLE: Lapse time from last event; RIMV: recurrence interval mid value; VDKP: vertical displacement of knickpoint paleo-earthquake; VDTP: vertical displacement of trench

paleo-earthquake; VDCP: vertical displacement of comprehensive paleo-earthquake.

^b Trench paleo-earthquake can be seen in Xu et al. (2011) and “The report of the 1:50000 Active Fault Mapping of Luoyunshan Piedmont Fault” (in Chinese).

5. Discussion

The retreat rate of the first level knickpoint can be calculated through dating the sediments preserved in the first level terrace and through surveying the backward distance from the fault of the first knickpoint corresponding to the first level terrace. The formation time of the first level terrace is 4.62 ky BP (Table 1), so the formation time of the first level knickpoint is 4.62 ky BP. The retreat rate of the first level knickpoint is calculated through its formation time and its distance from the fault. The knickpoint propagation rate is assumed to be constant and equal to the retreat rate of the first level knickpoint on each gully. Then the age of all knickpoints in each gully (i.e., the time of faulting) is obtained based on their distance from the fault, resulting in a paleo-earthquake sequence of the fault. The authors compared it with the previous study on the paleo-earthquake of the LPF revealed by trenches (Table 4). The results show that 6 paleo-earthquake events of the LPF from about 28,000 years ago can be obtained from the 6-level knickpoint series. The LPF has the characteristics of similar recurrence intervals and quasi-periodic recurrence. Events ①, ②, ④, ⑤, and ⑥ occurred in similar time periods as the events from the previous trenching study. In addition, the knickpoint series also revealed one more paleoseismic event ③ than the trenching method. The time interval of 8370 years from event ② to event ④ of the trenching method is larger than the recurring interval mid-value of 5762 years in Table 2. In view of the periodic recurrence of characteristic earthquakes of the LPF, the occurrence of event ③ is more reasonable. So the recurring interval mid-value of the paleo-earthquake events of the trenching method is changed from 5762 to 4610 years, which is almost identical to the median 4561 years of the knickpoint series method. So the paleo-earthquake events of the LPF from about 28,000 years ago become more complete and accurate.

As shown in Table 4, the paleo-earthquake events from knickpoint and trench methods are in good agreement in terms of the vertical displacement and time of faulting. It shows studying the paleo-earthquake events of the fault by knickpoint series is feasible. At last, the authors established a more complete paleo-earthquake sequence of the LPF supported by geomorphologic evidence in the footwall and trench profiles evidence (Table 4). It can complement and improve the traditional trenching method and provide theoretical and methodological support for the research of active tectonics.

Among the 133 knickpoints of 28 gullies, the number of knickpoints with a height of 2.1-3.0 m accounts for 55% of the total, and the height of knickpoint reflects the vertical displacement of the fault activity (Yang et al., 1985; Peng, 1991; Commins et al., 2005; Yanites et al., 2010; Bi et al., 2011; Sun et al., 2012; He and Ma, 2015; Wei et al., 2015). Vertical displacement of knickpoint paleo-earthquake (VDKP) and vertical displacement of trench paleo-earthquake (VDTP) are in good agreement (Table 4). The vertical displacement of the comprehensive paleo-earthquake events of the LPF is 2.4-3.0 m (Table 4), according to the empirical equations between co-seismic displacement and earthquake magnitude; the magnitude of these events is M_s 7.0-7.5.

In reality, the retreat rate of a knickpoint would be affected by many factors and cannot be kept constant. The retreat rate of knickpoints is a function of upstream drainage area (Whipple, 2001, 2004; Bishop et al., 2005; Crosby and Whipple, 2006), and the authors selected gullies with similar drainage area and similar length to study, avoiding the influence of different drainage areas to knickpoint retreat rate. The size of the 28 gullies is similar, and the upstream length of them is about 1.5-2.0 km. The retreat rates of knickpoints also depend on types and layering structure of the bedrock. The bedrock of G1-G18 and G26-G28 is Paleozoic limestone; the bedrock of G19-G25 is Archean gneiss. So the authors can exclude bedrock's influence to knickpoint retreat

rates because of similar bedrock in each gully. Some deviations between the calculated results according to the constant rate and the actual situation will occur. However, from the assumption of constant knickpoint propagation rate and according to the distance from the fault of the second level knickpoint, the formation time of the second level knickpoint is 9028 YBP, which is very close to the formation time of the second level terrace (Tables 1, 2) and the median age (9070 YBP) of the second paleo-earthquake event revealed by the trenching method (Table 4). In spite of the likely error in knickpoint age using a stable retreat rate, the earthquake record derived from the knickpoint series seems reasonable when compared with the traditional trenching paleoseismic studies. Therefore, studying the paleo-earthquake events of the fault by knickpoint series is a good method.

6. Conclusions

Using various technical means available to restore the complete and reliable history of the fault tectonic activity since late Pleistocene is the premise and foundation to establish the model of the fault activity, assess seismogenic capacity, and predict the future behavior of the fault. The latest research results show that the integrity of the paleo-earthquake sequence revealed by the traditional trenching method needs further examination, supplement, and completion because it is limited by the location, depth, and scale of the trench excavation. The authors surveyed the longitudinal profiles of 28 gullies across the LPF in the field by differential GPS and dating of sediments well preserved in the typical terraces and obtained a 6-level knickpoint series of the gullies. The authors excluded the nontectonic knickpoints by regional comparison and analyzed the relationship between tectonic knickpoints and the number, time, and vertical displacement of the fault activities, then extracted the paleo-earthquake information of the LPF since late

Pleistocene recorded by the knickpoint series. The results show that 6 paleo-earthquake events of the LPF from about 28,000 years ago are obtained through the 6-level knickpoint series of the gullies along the Luoyunshan Piedmont. The LPF has the characteristics of similar recurrence intervals and quasi-periodic recurrence.

The authors compared the result with previous studies on the paleo-earthquake of the LPF revealed by trenches and found that the paleo-earthquake events from knickpoint and trench methods are in good agreement in terms of the time of occurrence and vertical displacement of the fault. It shows studying the paleo-earthquake events of the fault by knickpoint series is feasible.

At last, the authors established a more complete paleo-earthquake sequence of the LPF supported by geomorphologic and sedimentary evidence, i.e., six paleo-earthquake events happened on the LPF from about 28,000 years ago and the LPF has the characteristic of quasi-periodic recurrence and the average recurrence interval is 4585 years. The vertical displacement of the paleo-earthquake events is 2.4-3.0 m, empirical equations between co-seismic displacement and earthquake magnitude indicate that the magnitude of these events is M_s 7.0-7.5.

This study aims to complement and improve the traditional trenching method, provide theoretical and methodological support for the research of active tectonics, and contribute important information for the seismic hazard assessment of the densely populated Linfen area.

Acknowledgements

This work was supported by a research grant from the Institute of Crustal Dynamics, China Earthquake Administration (grant No. ZDJ2013-17) and the National Science Foundation of China (grant No. 41402184). The authors sincerely thank two anonymous reviewers for their constructive and helpful reviews, Junxiang Zhao and Huanzhen Wang respectively for the OSL

and TL dating analysis, and Zhongxian Huang for improving the writing. We also thank Richard A. Marston, our editor, for his time and effort dedicated to improving our manuscript in format and English.

References

- Belmont, P., 2011. Floodplain width adjustments in response to rapid base level fall and knickpoint migration. *Geomorphology* 128 (1-2), 92-102.
- Bernard, D., 2001. Geomorphic response to growing fault-related folds: example from the foothills of central Taiwan. *Geod. Acta.* 14 (5), 265-287.
- Bi, L., He, H., Xu, Y., Wei, Z., Shi, F., 2011. The extraction of knickpoint series based on the high resolution DEM data and the identification of paleo-earthquake series—A case study of the Huoshan Mts. Piedmont Fault. *Seismol. Geol.* 33 (4), 963-977 (in Chinese).
- Bishop, P., Goldrick, G., 1992. Morphology, processes and evolution of two waterfalls near Cowra, New South Wales. *Aust. Geogr.* 23 (2), 116-121.
- Bishop, P., Hoey, T., Jansen, J. Artza, I., 2005. Knickpoint recession rate and catchment area: the case of uplifted rivers in Eastern Scotland. *Earth Surf. Process. Landf.* 30 (6), 767-778.
- Burbank, D., Anderson, R., 2001. *Tectonic geomorphology*. Blackwell Scientific, Oxford, 274 pp.
- Burnett, A., Schumm, S., 1983. Alluvial-river response to neotectonic deformation in Louisiana and Mississippi. *Science* 222, 49-50.
- Commins, D., Gupta, S., Cartwright, J., 2005. Deformed streams reveal growth and linkage of a normal fault array in the Canyonlands graben, Utah. *Geology* 33 (8), 645-648.
- Crosby, B., Whipple, K., 2006. Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand. *Geomorphology* 82 (1-2), 16-38.
- Deng, Q., Xu, X., 1995. Segmentation Study of Active Faults in the Shanxi Fault-Depression Basin Belt. In: Institute of Geology State Seismological Bureau (Ed.), *Research on Recent Crustal Movement* (6). Seismological Press, Beijing, pp. 225-242 (in Chinese).

- Deng, Q., Wang, K., Wang, Y., Tang H., Wu, Y., Ding, M., 1973. On the tendency of seismicity and their geological set up of the seismic belt of Shanxi Graben. *Sci. Geol. Sin.* (1), 37-47 (in Chinese).
- Deng, Q., Chen, L., Ran, Y., 2004. Quantitative studies and applications of active tectonics. *Earth Sci. Front.* 11 (4), 383-392 (in Chinese).
- Duvall, A., Kirby, E., Burbank, D., 2004. Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California. *J. Geophys. Res.* 109 (F3), doi: 10.1029/2003JF000086.
- George, P., Madho, P., 1999. Geomorphic signatures of active tectonics in the Trans-Yamuna segment of the western Doon valley, northwest Himalaya, India. *Int. J. Appl. Earth Obs.* 1 (1), 54-63.
- Goudie, A., 2004. *Encyclopedia of Geomorphology*. Taylor Francis Group, Routledge Ltd, London, New York, 1156 pp.
- Hayakawa, Y., Oguchi, T., 2006. DEM-based identification of fluvial knickzones and its application to Japanese mountain rivers. *Geomorphology* 78 (1-2), 90-106.
- He, H., Oguchi, T., 2008. Late Quaternary activity of the Zemuhe and Xiaojiang faults in southwest China from geomorphological mapping. *Geomorphology* 96 (1-2), 62-85.
- He, Z., Ma, B., 2015. Holocene paleoearthquakes of the Daqingshan fault detected from knickpoint identification and alluvial soil profile. *J. Asian Earth Sci.* 98, 261-271.
- Holbrook, J., Schumm, S., 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. *Tectonophysics* 305 (1-3), 287-306.
- Li, Y., Yang, J., Xia, Z., Mo, D., 1998. Tectonic geomorphology in the Shanxi Graben System, northern China. *Geomorphology* 23 (1), 77-89.
- Liu, G., Xiao, Z., 1982. Shanxi graben system and its seismotectonics. In: Commission on Tectonics of the Geological Society of China (Ed.), *Selected Papers of the Second Congress on Tectonics, Volume III: The Mid Cenozoic Tectonics*. Science Press, Beijing, pp. 66-74 (in Chinese).
- Lu, Y., Wang, X., Wintle, A.G., 2007. A new OSL chronology for dust accumulation in the last 130,000 yr for the Chinese Loess Plateau. *Quat. Res.* 67, 152-160.
- Maddy, D., Bridgland, D., Westaway, R., 2001. Uplift-driven valley incision and climate-controlled river terrace

- development in the Thames Valley, UK. *Quat. Int.* 79 (1), 23-36.
- Maruyama, T., Lin, A., 2000. Tectonic history of the Rokko active fault zone (southwest Japan) as inferred from cumulative offsets of stream channels and basement rocks. *Tectonophysics* 323 (3-4), 197-216.
- Merritts, D., Vincent, K., Wohl, E., 1994. Long river profiles, tectonism, and eustasy: A guide to interpreting fluvial terraces. *J. Geophys. Res.* 99 (B7), 14031-14050.
- Miller, J., 1991. The influence of bedrock geology on knickpoint development and channel-bed degradation along down-cutting stream in south-central Indiana. *J. Geol.* 99 (4), 591-605.
- Ouchi, S., 1985. Response of alluvial rivers to slow active tectonic movement. *Geol. Soc. Am. Bull.* 96 (4), 504-515.
- Peng, J., 1991. The activities and age of the fault at the northern foothills of the mountains Lishan. *J. Xi'an Coll. Geol.* 13 (3), 29-38 (in Chinese).
- Rosenbloom, N., Anderson, R., 1994. Hillslope and channel evolution in a marine terraced landscape, Santa Cruz, California. *J. Geophys. Res.* 99 (B7), 14013-14029.
- Schumm, S., Mosley, M., Weaver, W., 1987. *Experimental fluvial geomorphology*. Wiley-Interscience, New York, 413 pp.
- Sieh, K., Jahns, R., 1984. Holocene activity of the San Andreas Fault at Wallace Creek, California. *Geol. Soc. Am. Bull.* 95 (8), 883-896.
- Snow, R., Slingerland, R., 1990. Stream profile adjustment to crustal warping: Nonlinear results from a simple model. *J. Geol.* 98 (5), 699-708.
- Starkel, L., 2003. Climatically controlled terraces in uplifting mountain areas. *Quat. Sci. Rev.* 22 (20), 2189-2198.
- Su, Z., Yan, F., 1985. New discovery on the Holocene activity of Luoyunshan Fault. *Earthq. Res. Shanxi* (4), 6 (in Chinese).
- Sun, C., Xie, X., Xu, J., 2011. Research on terraces investigation of Luoyunshan fault zone and its tectonic implication. *Earthq. Res. China* 27 (2), 126-135 (in Chinese).
- Sun, C., Xie, X., Jiang, W., 2012. Distribution of the knickpoints in fluvial gullies in response to the events of Holocene fault activity—A case study of the Jiaocheng fault in Shanxi. *Seismol. Geol.* 34 (2), 254-268 (in Chinese).

- Sun, C., Xie, X., Xu, J., 2013. Late Quaternary faulted landforms characteristics on the Tumen-Jiazhu village segment of the Luoyunshan piedmont fault. *Earthq. Res. China* 29 (3), 347-357 (in Chinese).
- The Research Group on 'Active Fault System around Ordos Massif', State Seismological Bureau, 1988. Active Fault System around Ordos Massif. Seismological Press, Beijing, pp. 98-102 (in Chinese).
- Viseras, C., Calvache, M., Soria, J., Juan, F., 2003. Differential features of alluvial fans controlled by tectonic or eustatic accommodation space. Examples from the Betic Cordillera, Spain. *Geomorphology* 50, 181-202.
- Wallace, R., 1970. Earthquake recurrence intervals on the San Andreas Fault. *Geol. Soc. Am. Bull.* 5, 190-205.
- Wan, T., 2011. The Tectonics of China – Data, Maps and Evolution. Higher Education Press and Springer, Beijing, Dordrecht, Heidelberg, London, New York, 501 pp.
- Wang, P., Jiang, H., Yuan, D., Liu, X., Zhang, B., 2010. Optically stimulated luminescence dating of sediments from the Yellow River terraces in Lanzhou: tectonic and climatic implications. *Quat. Geochronol.* 5, 181-186.
- Wang, T., Zheng, B., Li, X., Wang, Y., 1993. Quaternary activity characteristics of the Luoyunshan frontal fault zone. In: Ma, Z. (Ed.), *Linfen Earthquake Research and Systematic Disaster Reduction in Shanxi*. Seismological Press, Beijing, pp. 159-171 (in Chinese).
- Wei, Z., Bi, L., Xu, Y., He, H., 2015. Evaluating knickpoint recession along an active fault for paleoseismological analysis: The Huoshan Piedmont, Eastern China. *Geomorphology* 235, 63-76.
- Whipple, K., 2001. Fluvial landscape response time: How plausible is steady-state denudation? *Am. J. Sci.* 301 (4-5), 313-325.
- Whipple, K., 2004. Bedrock rivers and the geomorphology of active orogens. *Annu. Rev. Earth Planet. Sci.* 32: 151-185.
- Wohl, E., Ikeda, H., 1998. Patterns of bedrock channel erosion on the Boso Peninsula, Japan. *J. Geol.* 106 (3), 331-346.
- Xu, J., Xie, X., Sun, C., 2011. The Holocene active evidence on the Longci-Yukou segment of Luoyunshan frontal fault zone, Shanxi. *Seismol. Geol.* 33 (4), 855-864 (in Chinese).
- Xu, X., Ma, X., 1992. Neotectonic activity along the Shanxi rift system, China. *Tectonophysics* 219, 305-325.
- Yang, J., Guo, Z., Cao, J., 1985. Investigation on the Holocene activities of the Helan Mountain piedmont Fault by use of geomorphological method. *Seismol. Geol.* 7 (4), 23-31 (in Chinese).

- Yanites, B., Tucker, G., Mueller, K., Chen, Y., 2010. How rivers react to large earthquakes: Evidence from central Taiwan. *Geology* 38 (7), 639-642.
- Zhang, H., Zhang, P., Fan, Q., 2011. Initiation and recession of the fluvial knickpoints: A case study from the Yalu River-Wangtian'evolcanic region, northeastern China. *Sci. China Earth Sci.* 54, 1746–1753, doi:10.1007/s11430-011-4254-6.
- Zheng B., WANG T., LI X., 1990. Investigation and study on the Luoyunshan piedmont fault zone. In: Chen Z. (Ed.), *China Earthquake Yearbook*. Seismological Press, Beijing, pp. 416-423 (in Chinese).
- Zhou, L., Shackleton, N., 2001. Photon-stimulated luminescence of quartz from loess and effects of sensitivity change on palaeodose determination. *Quat. Sci. Rev.* 20, 853–857.

Graphical Abstract