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Investigation of Terraces along the Luoyunshan Piedmont Fault Zone and Its Tectonic Implications[1]

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Located at the west of the Linfen basin, the Luoyunshan piedmont fault zone controls the western boundary of the basin. According to the measurements of the terraces in eight gullies along the Luoyunshan fault zone, five levels of terraces, namely T_1 ~ T_5 have developed in these gullies. The heights of terraces T_1, T_2, T_3, T_4 and T_5 are about 3m, 8 ~ 10m, about 20m, about 30m and 40 ~ 50m, respectively. The dating data of the terraces and investigation of the faulted landforms show that the Luoyunshan fault zone has experienced much activity since the Late Quaternary. The uplift rate of the terraces was 0.41mm/a since the Middle-Late Pleistocene, and 0.75mm/a since the Holocene. The increasing trend of uplift rate of the terraces along the Luoyunshan fault zone from the Middle-Late Pleistocene to Holocene indicates the tendency of gradual tectonic uplift of the fault zone since the late Quaternary. This is in good agreement with the increasing trend of subsidence rate of the Linfen basin from the Late Pleistocene to Holocene.

Key words: Luoyunshan piedmont fault zone; Terrace; Late Quaternary; Uplift rate; Tectonic implication

INTRODUCTION

A river terrace is defined as a landform where the floor of the original river valley (flood plain or river bed) exceeds the general flood level due to the river's down-cutting erosion and is distributed stepwise on the bank slope of the river valley (Yang Jingchun, 1985). In areas with intense Quaternary tectonic movement, the distribution pattern of multi-level river terraces is a manifestation of these tectonic activities (Merritts et al., 1994; Starkel L., 2003). So, river terraces and their related deposits are often used widely as an important means to study the active tectonics along the normal faults (Han Mukang et al., 1980; Li Ke et al., 1994), the thrust

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faults (Chen Jie et al., 1998; Zheng Wentao et al., 2000), and the strike-slip faults (Liu Xiaofeng et al., 2003; Wang Feng et al., 2004; Zhang Peizhen et al., 2008; Wang Yong et al., 2009). The Luoyunshan piedmont fault zone is the western boundary fault of the Linfen basin of Shanxi Province, where strong earthquakes were frequent in history, e. g. the 1303 M8. 0 Hongdong earthquake and the 1695 $M7\frac{1}{2}$ Linfen earthquake (Wang Tingmei et al., 1993b), and the 649 $M7\frac{1}{2}$ Linfen earthquake (Ding Guoyu, 1998). Piecemeal results were reported in the 1980s and 1990s on the Holocene activity of this fault zone (Su Zongzheng et al., 1985; The Research Group of "Active Fault System around Ordos Massif", State Seismological Bureau, 1988; Zheng Binghua et al., 1990; Wang Tingmei et al., 1993a), but there have been few systematic investigations of the offset landforms. In this study, field investigations were made on the major river terraces and mountain-front offset landforms across the Luoyunshan piedmont fault zone, and the tectonic uplift of the fault zone since late Quaternary was discussed. The results provide geomorphologic evidence of the latest activity of the fault zone for earthquake preparedness and disaster reduction in this region.

1 AN OVERVIEW OF THE GEOLOGY AND GEOMORPHOLOGY OF LUOYUNSHAN PIEDMONT FAULT ZONE

Luoyunshan piedmont fault zone is located west of the Linfen basin and controls the western boundary of the basin. It starts at Wanshengsi area in the north, running through Tumen, Yuli, Weicun, Fanjiazhuang to Xiweikou, striking NNE in general and bending to NWW at Fanjiazhuang, with a total length of 145km (Fig. 1). The Luoyunshan piedmont fault zone is not a single fault, but a complex fault structure consisting of a series of faults. The fault zone is divided geometrically into five segments, i. e. north of Tumen segment, Tumen-Yuli segment, Yuli-Weicun segment, Weicun-Fanjiazhuang segment, and Fanjiazhuang-Xiweikou segment (Zheng Binghua et al., 1990).

The upthrown block of the Luoyunshan piedmont fault is a bedrock mountain area consisting of Archaeozoic and Paleozoic formations. Mid Pleistocene Lishi loess is preserved locally, and the initial planation surface of early the Tertiary in the mountain area has disintegrated due to faulting and erosion. All downthrown block of the fault is overlain by Quaternary sediments. On the north of Tumen, Pliocene red clay outcrops occasionally. The Luoyunshan mountain area is part of the Luliang fault uplift and has been subject to complex tectonic movements. The piedmont faults were thrust and overthrust in the Yanshanian period. Due to the regional extension and shearing since Pliocene, the fault become a normal fault controlling the western border of the Linfen basin. The 2000m-thick Cenozoic depocenter of the Linfen basin deflects to the side of the Luoyunshan piedmont fault zone, indicating the intensive activity of the fault. The Quaternary fault activity inherits the characteristics of Pliocene activity (Wang Tingmei et al., 1993a).

2 INVESTIGATION OF TERRACES

The river terraces of 8 gullies along the Luotunshan piedmont fault zone were investigated, from northeast to southwest, they are Xiandonggou, Xifangyu, Yuligou, Langquangou, Sanguanyu, Mapiyu, Huanghuayu, and Foyukougou (Fig. 1). The lengths of these 8 gullies and the terraces investigated are listed in Table 1.

2. 1 Characteristics of Cross Section of the Terraces

Table 2 shows the cross section data of terracesof the 8 gullies along Luoyunshan piedmont fault zone. Details are as follows:

(1) Xiandonggou

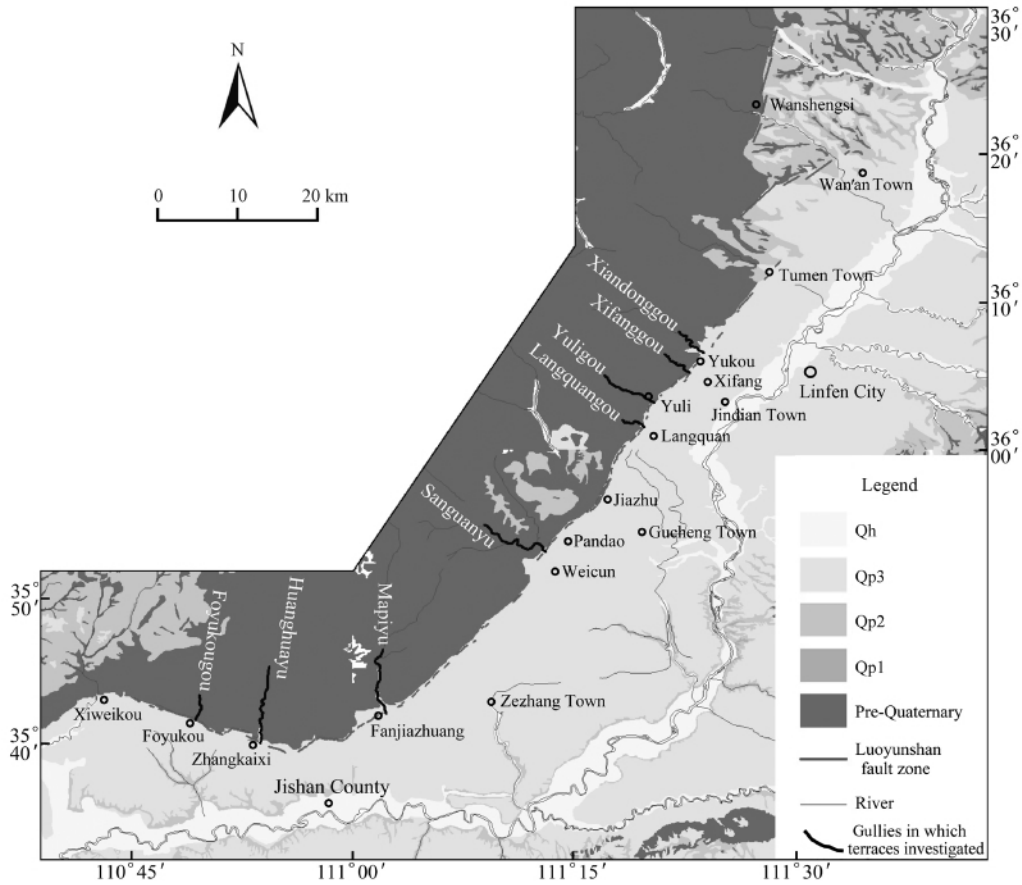


Fig. 1
Geological map of Luoyunshan piedmont fault zone and planar distribution of gullies in which terraces investigated are located

Photo 1 The offset landform near the mountain exit of Xiandonggou gully (view to SW)

Photo 2 The offset landform on the southwest bank of Xiandonggou (view to NE)

Five levels of terraces, namely terrace T_1 ~ T_5 developed in Xiangonggou gully. All are base terraces, with yellow clayey silt and gravel layers in the upper part and Ordovician limestone in the lower part. The altitude of T_1 ~ T_5 terraces above the gully is 2 ~ 5.9m, 8 ~ 15m, 17 ~ 18m, 29 ~ 30m and 48 ~ 50m, respectively (Fig. 2a).

(2) Xifanggou

Five levels of terraces, $T_1 \sim T_5$, developed in Xifanggou. Terrace T_1 and T_2 are erosion terraces, with bedrock being the Ordovician limestone and thin-layered proluvial-talus rubbles preserved occasionally on the terrace surface. Terrace $T_3 \sim T_5$ are base terraces, with yellow clayey silt and gravel layer in the upper part and Ordovician limestone in the lower part. The altitudes above gully of terraces $T_1 \sim T_5$ are 2.7 ~ 3.3m, 8 ~ 9m, 17 ~ 22.5m, 28.5 ~ 34m and 44 ~ 50m, respectively (Fig. 2b).

Table 1 The lengths of the 8 gullies and the terraces investigated

No. of gully	Name of gully	Upstream direction	Upstream length (km)	Terrace length investigated (km)
1	Xiandonggou	NW50°	4.1	1.6
2	Xifanggou	NW50°	2.6	1.6
3	Yuligou	NW60°	5.0	4.6
4	Langquangou	NW50°	1.8	1.6
5	Sanguanyu	NW75°	5.5	4.6
6	Mapiyu	N	9.6	5.8
7	Huanghuayu	NE5°	9.6	7.1
8	Foyukougou	NE5°	5.3	2.1

(3) Yuligou

Five levels of terraces, $T_1 \sim T_5$, are developed in Yuligou, all are base terraces, with yellow clayey silt and gravel layer in the upper part and Ordovician limestone in the lower part. The altitudes above gully of terraces $T_1 \sim T_5$ are 3 ~ 3.8m, 7.2 ~ 8m, 20 ~ 24m, 27 ~ 27.5m and 40 ~ 50m, respectively (Fig. 2c).

(4) Langquangou

Four levels of terraces, namely T_1, T_2, T_3 and T_5, developed in Langquangou. All are base terraces, with yellow clayey silt and gravel layer in the upper part and Ordovician limestone in the lower part. The altitudes above gully of terraces T_1, T_2, T_3 and T_5 are 3 ~ 3.5m, 7.2 ~ 10m, 20 ~ 21m and 45 ~ 49m, respectively.

(5) Sanguanyu

Four levels of terraces, namely $T_2 \sim T_5$, developed in Sanguanyu. All are base terraces, with yellow clayey silt and gravel layer in the upper part and Ordovician limestone in the lower part. The altitude above gully of terraces $T_2 \sim T_5$ are 8 ~ 11m, 19m, 26 ~ 30m and 45 ~ 50m, respectively.

(6) Mapiyu

Five levels of terraces, $T_1 \sim T_5$, developed in Mapiyu. All are base terraces, with yellow clayey silt and gravel layer in the upper part and Archaean migmatitic granite in the lower part. The altitudes above gully of terraces $T_1 \sim T_5$ are 2.8 ~ 3m, 8 ~ 10m, 17 ~ 24m, 30m and 40 ~ 50m, respectively (Fig. 2d).

(7) Huanghuayu

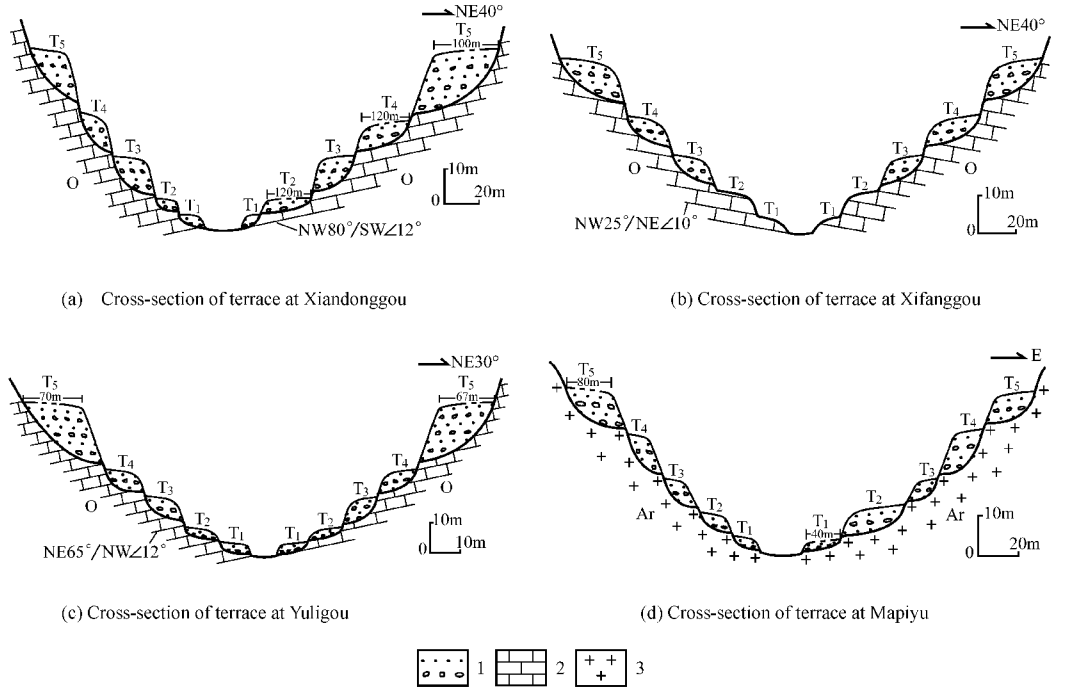
Five levels of terraces, $T_1 \sim T_5$, are developed in Huanghuayu. All are base terraces, with yellow clayey silt and gravel layers in the upper part and Archaean migmatitic granite in the lower part. The altitudes above gully of terraces $T_1 \sim T_5$ are 2.5 ~ 5m, 7 ~ 10m, 17 ~ 20m, 30m and 44 ~ 48m, respectively.

Table 2 Cross section data of terraces of the 8 gullies along Luoyunshan piedmont fault zone

		T_1	T_2	T_3	T_4	T_5
Xiandonggou	Altitude above gully /m	2 ~ 5.9	8 ~ 15	17 ~ 18	29 ~ 30	48 ~ 50
	Type of terrace	Base terrace	Base terrace	Base terrace	Base terrace	Base terrace
	Terrace materials	Yellow clayey silt and gravel layer for the upper part and limestone for the lower part of terrace T_1 ~ T_5				
Xifanggou	Altitude above gully/m	2.7 ~ 3.3	8 ~ 9	17 ~ 22.5	28.5 ~ 34	44 ~ 50
	Type of terrace	Erosion terrace	Erosion terrace	Base terrace	Base terrace	Base terrace
	Terrace materials	Ordovician limestone for T_1 and T'_2s bedrock			Yellow clayey silt and gravel layer for the upper part and limestone for the lower part of terrace T_1 ~ T_5	
Yuligou	Altitude above gully/m	3 ~ 3.8	7.2 ~ 8	20 ~ 24	27 ~ 27.5	40 ~ 50
	Type of terrace	Base terrace	Base terrace	Base terrace	Base terrace	Base terrace
	Terrace materials	Yellow clayey silt and gravel layer for the upper part and limestone for the lower part of terrace T_1 ~ T_5				
Langquangou	Altitude above gully /m	3 ~ 3.5	7.2 ~ 10	20 ~ 21	—	45 ~ 49
	Type of terrace	Base terrace	Base terrace	Base terrace	—	Base terrace
	Terrace materials	Yellow clayey silt and gravel layer in the upper part and limestone in the lower part of terrace T_1 ~ T_3.			—	Yellow clayey silt and gravel layer in the upper part and limestone in the lower part
Sanguanyu	Altitude above gully/m	—	8 ~ 11	19	26 ~ 30	45 ~ 50
	Type of terrace	—	Base terrace	Base terrace	Base terrace	Base terrace
	Terrace materials	—	Yellow clayey silt and gravel layer in the upper part and limestone in the lower part of terrace T_2 ~ T_5			
Mapiyu	Altitude above gully/m	2.8 ~ 3	8 ~ 10	17 ~ 24	30	40 ~ 50
	Type of terrace	Base terrace	Base terrace	Base terrace	Base terrace	Base terrace
	Terrace materials	Yellow clayey silt and gravel layer in the upper part and migmatitic granite in the lower part of terrace T_1 ~ T_5				
Huanghuayu	Altitude above gully/m	2.8 ~ 5	7 ~ 10	17 ~ 20	30	44 ~ 48
	Type of terrace	Base terrace	Base terrace	Base terrace	Base terrace	Base terrace
	Terrace materials	Yellow clayey silt and gravel layer in the upper part and migmatitic granite in the lower part of terrace T_1 ~ T_5				
Foyukou-gou	Altitude above gully/m	3 ~ 3.5	10 ~ 10.5	19.5 ~ 20	30	—
	Type of terrace	Base terrace	Base terrace	Base terrace	Base terrace	—
	Terrace materials	Yellow clayey silt and gravel layer in the upper part and migmatitic granite in the lower part of terrace T_1 ~ T_4				—

(8) Foyukougou

Four levels of terraces, namely $T_1 \sim T_4$, developed in Foyukougou. All are base terraces, with yellow clayey silt and gravel layers in the upper part and Archaean migmatitic granite in the lower part. As a V-shape canyon-like gully with undeveloped higher level terraces, T_5 terrace is undeveloped in Foyukougou gully. The altitudes above gully of terraces $T_1 \sim T_4$ are 3 ~ 3.5m, 10 ~ 10.5m, 19.5 ~ 20m and 30m, respectively.



(a) Cross-section of terrace at Xiandonggou

(b) Cross-section of terrace at Xifanggou

(c) Cross-section of terrace at Yuligou

(d) Cross-section of terrace at Mapiyu

Fig. 2

Cross-sections of the gully terraces along Luoyunshan fault zone

1. Yellow clayey silt and gravel layer; 2. Ordovician limestone; 3. Archaean migmatitic granite

2.2 *Characteristics of Longitudinal Profiles of the Terraces*

Longitudinal profiles of terraces of the 8 gullies are drawnbased on their cross section data (Fig. 3). These terraces die away when extending to the outlets of the gullies in the downstream reaches. The synchronous deposits of the terraces are buried on the side of the Linfen basin, for the terraces developed in these gullies were all offset by the Luoyunshan piedmont faults and buried by the piedmont alluvial/fluvial deposits at the mountain exits of the gullies along their extension downstream to the mountain exit.

Except for the three gullies of Langquangou, Sanguanyu and Foyukougou, where 4 levels of terraces are developed, five levels of terraces, namely $T_1 \sim T_5$, are developed in all of the remaining 5 gullies. Comparative analysis of these 8 gullies shows the altitudes above the gully of the terraces as 3m, 8 ~ 10m, 20m, 30m and 40 ~ 50m, respectively for $T_1 \sim T_5$.

2.3 *Dating of the Terrace Deposits*

The age of a terrace usually refers to the formation time of the top surface of the terrace. The surface of a river terrace can be the surface of accumulation or the erosion surface of the river.

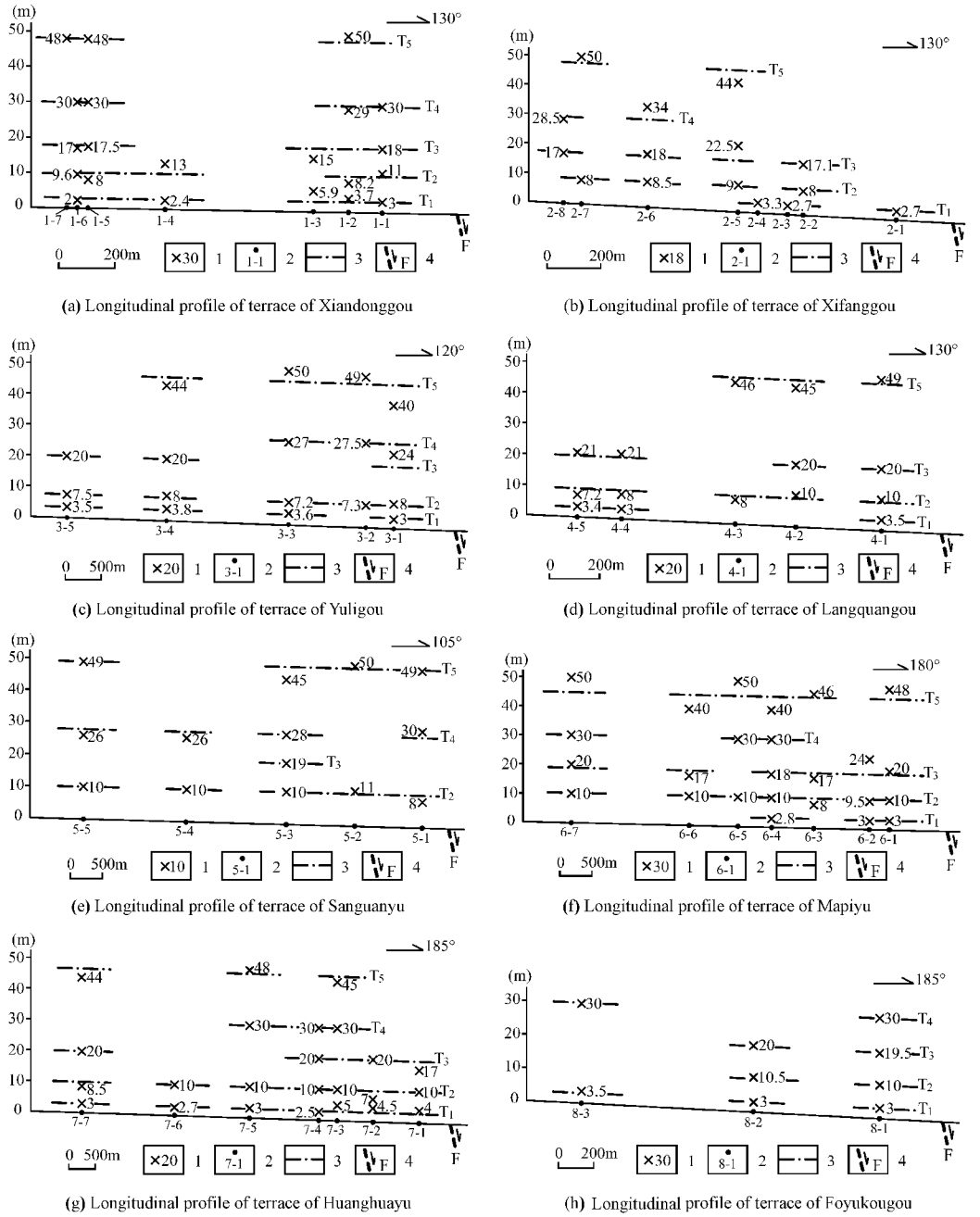


Fig. 3

Longitudinal profiles of the gully terraces along Luoyunshan fault zone

1. Terrace surface and altitude; 2. Observation site; 3. Lineation of terrace surfaces; 4. Luoyunshan piedmont fault zone

Limited by sample and dating conditions, it is difficult to determine the actual age of a terrace surface. Generally, we use the age of deposits on the terrace surface to approximate the formation time of the terrace, that is, the time when the river was abandoned and began to incise.

The deposits on the lower level terraces of two gullies alongthe Luoyunshan fault zone were dated using thermoluminescence dating (TL) method, and the results are shown in Table 3.

Table 3 The formation time and uplift rate of the terraces of Xiandonggou and Langquangou gullies

Terrace		T_1	T_2	T_3
Xiandonggou	Terrace age/ka	4.95 ± 0.42	10.42 ± 0.88	
	Altitude/m	3.7	8.2	
	Uplift rate mm/a	0.75	0.79	
Langquangou	Terrace age/ka	4.61 ± 0.39	9.84 ± 0.84	49.14 ± 4.18
	Altitude/m	3	7.5	20
	Uplift rate mm/a	0.65	0.76	0.41

3 THE OFFSET LANDFORMS ALONG THE LUOYUNSHAN PIEDMONT FAULT ZONE

The offset landforms along the Luoyunshan piedmont fault zone are represented mainly by mountain-front bedrocks and linear scarps located at the posterior edges of the pluvial fans. Fault planes are sometimes visible.

3.1 The Offset Landforms Corresponding to Terrace T_1

Direct contact of the posterior edges of pluvial fans with limestone was observed at the north bank of Xifanggou gully outlet in Hebei village, Jingdian town, Linfen city. The fault between the pluvial fan and limestone is apparent on the gully floor. In the gully, the upper part is overlain by deluvial deposits. Inferred from the 2.5m-high continuous fault scarp on the surface at the southwest of the gully and the fault has offset the entire posterior edge of the pluvial fan and reached to the ground surface (Fig. 4).

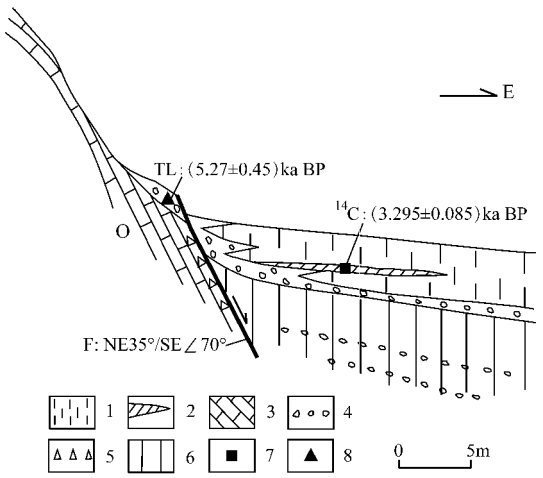


Fig. 4

Geological section of the northeast bank at the gully outlet of Xifanggou (after Wang Tingmei et al., 1993a)

1. Secondary loess; 2. Dark-gray loam; 3. Limestone; 4. Gravel; 5. Fault and gouge; 6. Loess; 7. ^{14}C sample site; 8. TL sample site

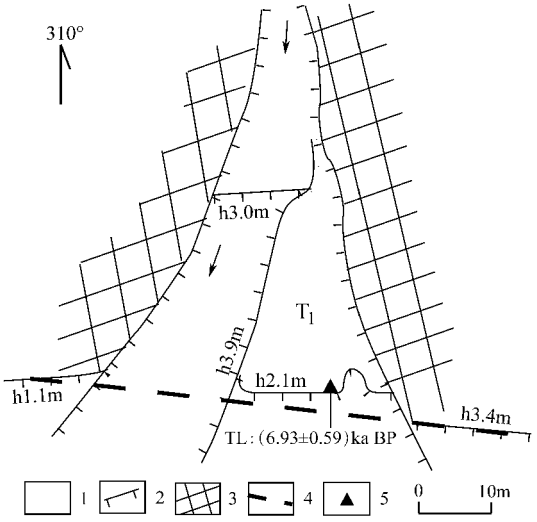


Fig. 5

Plan of offset landform at west of Jiazhu village

1. Holocene unconsolidated deposits; 2. Scarp; 3. Limestone; 4. Inferred fault; 5. TL sample site

A NE-trending 2.1m-high continuous scarp composed of limestone rubble and yellow clayed silt is developed on the pluvial fan at the outlet of a NW-directed gully on the west of Jiazhucun village, Gucheng town, Xiangfen city (Fig. 5). The TL age of this scarp is (6.93 ± 0.59) ka BP.

3.2 The Offset Landforms Corresponding to Terrace T_2

The fault is located on the State Road 309 at Longsi village of Jingdian town. An 8.5m high scarp consisting of limestone rubble and yellow clayey silt is developed on the posterior edge of the pluvial fan (Fig. 6). By comparison with the strata of the two sides of Xifanggou gully in the north nearby, the stratum of the top surface of this pluvial fan should be mid to late Holocene. This indicates that the fault had multiple activities in the mid to late Holocene, for an 8.5m high scarp would not be generated by a single earthquake.

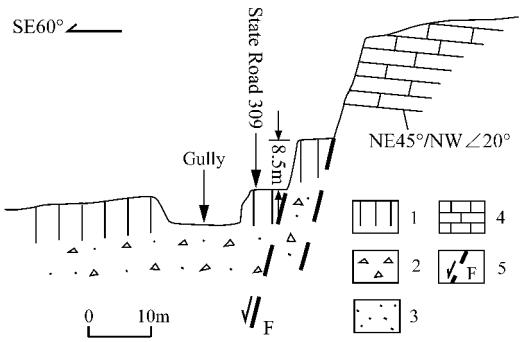


Fig. 6

Geological section on 309 highway at Longsi village

1. Yellow clayey silt containing small amount of rubble; 2. Limestone rubble; 3. Clayey silt; 4. Limestone; 5. Inferred fault

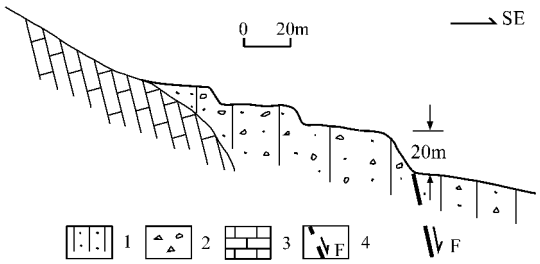


Fig. 7

Fault profile at the outlet of a NW-directed gully at west of Xuecun village

1. Clayey silt; 2. Limestone rubble; 3. Limestone; 4. Inferred fault

T_2 terrace, which is relatively continuous and has an altitude of 11m above gully, can be observed near the mountain exit of Xiandonggou gully on the northeast of Yukou village of Jingdian town. A 7m-high scarp trending NE is developed at the mountain exit of the gully (indicated by the arrow in Photo 1). Further toward the southwest along the scarp, there is a 7m-high scarp consisting of limestone rubble and yellow clayey silt at the posterior edge of the bedrock piedmont pluvial fan (indicated by the arrow in Photo 2).

3.3 The Offset Landforms Corresponding to Terrace T_3

A 20m-high NE45°-trending continuous scarp is developed at the posterior edge of the pluvial fan near the outlet of a NW-directed piedmont gully at the west of Xuecun village, Langquan town, Linfen city (Fig. 7). The northwest side of the fault is limestone, and the farmland on the southeast side is deserted.

4 CONCLUSION AND DISCUSSION

(1) Investigations of the terraces in the 8 gullies have revealed that there are five levels of terraces, namely $T_1 \sim T_5$ developed along the Luoyunshan piedmont fault zone. The altitude of T_1 is 3m above gully, and that of T_2 is 8 ~ 10m, T_3 is 20m, T_4 is 30m, and T_5 is 40 ~ 50m.

(2) The formation time for T_1, T_2 and T_3 is (4.5 ~ 5) ka BP, 10ka BP and 50ka BP, respectively.

(3) Dating data of the terraces and survey of the offset landforms show that there have been multiple activities on the Luoyunshan piedmont fault zone since late Quaternary. The uplift rate of the gully terraces was 0.41mm/a since the mid and late period of late Pleistocene and 0.75mm/a since Holocene. There is an increasing trend in the uplift rate of the terraces along the Luoyunshan piedmont fault zone from the mid-late period of late Pleistocene to Holocene, which indicates the tendency of gradual tectonic uplift since late Quaternary.

According to a study on borehole logs made by Deng Qidong et al. (1993), the subsidence rate of the Linfen basin is 0.74mm/a in late period of the late Pleistocene and 1.86mm/a in the Holocene. It is clear that the subsidence rate of the Linfen basin also has an increasing tendency from the late period of late Pleistocene to Holocene, indicating the enhanced neotectonic movement in the Linfen basin since late Quaternary. This is in good consistency with the constant tectonic uplift of the Luoyunshan piedmont fault zone since late Quaternary, a fault zone that controls the western boundary of the Linfen basin.

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