Geometric structure and formation mechanism of Lintong-Chang'an fault zone^{*}

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Abstract

The results from investigation of large quantity of fault outcrops and artificial earthquakes suggest that the Lintong-Chang'an fault zone mainly consists of two faults. One is the Majie-Nianwan fault that separates a branch of Wangjiabian-Houjiawan fault on the right bank of the Bahe River; the other is the Hujiagou-Shoupazhang fault that separates a branch of Zhongdicun-Tangjiazhai fault in Tongrenyuan and Shaolingyuan. As tensional dip-slip normal faults, the faults distribute with approximately parallel equal intervals in local regions and the profiles drop in a step-like form to the northwest, presenting a Y-shape combination. The result from deep seismic reflection indicates that the fault is about 5~8 km in depth, which is not only a basement fault, but also a listric normal fault in the deep stratum. The Lintong-Chang'an fault is a typical outstretching rift system under the NS-trending tension stress field. At the same time, affected by the sinistral strike slip of the Yuxia-Tieluzi fault, the fault extends like a broom from the northeast to the southwest.

Key words: Lintong-Chang'an fault; tension stress; outstretching rift system; listric normal fault

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Introduction

Located in the southeastern part of the Weihe basin, the Lintong-Chang'an fault zone serves as a boundary of the secondary tectonic units: Lishan embossment and Xi'an depression in the basin, which extends in the northeast direction in the zone of Fengyukou-West Lishan to the east of Xi'an and to the north of Qinling piedmont as a tensional normal fault. Many researches have been conducted for the fault. For example, ZHANG (1957), GUAN (1966), ZHANG and LEI (1991) and LI *et al* (1992) studied respectively the location of Lintong-Chang'an fault zone and its activities on the basis of the relief, landform and outcrops. They suggested that the fault zone consists of three faults and it was active in the Late Pleistocene and Holocene. However, their knowledge for the location and activity of the fault was limited to a certain extent, for they did not have enough data. FENG *et al* (2006) and SHI *et al* (2007) analyzed the activity of Lintong-Chang'an fault zone on the basis of the large amounts of latest results from the surface geological investigations and provided some new suggestions.

The Lintong-Chang'an fault zone is one of the key faults in the project of "Detection and Seismic Risk Assessment of Active Faults in Xi'an City" in the Tenth Five-year Plan. In order to

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determine the distribution of the faults, the studying group have conducted researches in surface geological investigation, artificial earthquake exploration, drilling and deep seismic reflection and obtained the accurate location of the Lintong-Chang'an fault zone. In this paper, the characteristics of distribution and geometric structure of the Lintong-Chang'an fault zone are introduced and its formation mechanism is analyzed.

1 Distribution and activity features of Lintong-Chang'an fault zone

1.1 Distribution of Lintong-Chang'an fault zone

On the basis of the results from the surface geological investigation and artificial earthquakes, we suggest that the Lintong-Chang'an fault zone mainly consists of two faults. One is the Majie-Nianwan fault (F_1) and the other is the Hujiagou-Shoupazhang fault (F_2). The former separates a branch of Wangjiabian-Houjiawan fault (F_{1-1}) on the right bank of the Bahe River and the latter separates a branch of Zhongdicun-Tangjiazhai fault (F_{2-1}) in Tongrenyuan and Shaolingyuan (Figure 1).

1.1.1 Majie-Nianwan fault (F_1)

The fault extends from Majie in the north, passes through Tongrenyuan, Bailuyuan, Shaolingyuan and Shenheyuan and enters into the piedmont pluvial fan of Qinling Mountain in a strike of about N20°~35°E. It stretches to N70°~80°E at Shaolingyuan and strikes to about 30° at Shenheyuan, which is a tensional normal fault with a trend of NW and a total length of 47.5 km.

The fault on Tongrenyuan with a length of 13.5 km stretches from Majie to Chezhanggou located on the right bank of Bahe river. There is Bahe sandy argillite of Pliocene epoch on its basement (JIA *et al*, 1966) and the covering loess is no more than 50 km. The surface of Tongrenyuan is broken with many large and small trenches on it. The ancient soil outcrops are quite clear. Four fault profiles of Majie, Yangpo, Xiaoya (Figure 2a) and Chezhanggou are discovered here (Table 1). One can see the ancient soil stratum of the fault offsets S_1 ~ S_5 with a separation of 1~2 m. The profiles are distinct with clear vertical strias. The results from the artificial earthquakes of J₂₇ Bahe line between Tongrenyuan and Bailuyuan (Figure 1) indicate that the fault dislocates the Paleocene stratum to the depth of 80 m (Table 2).

The fault on Bailuyuan stretches from Maoxicun on the left bank of Bahe river to Jingyugou on the right bank of Chanhe river in the length of about 10 km. The basement of loess is Pliocene stratum and the covering loess is about 140 m thick. Seven fault profiles are discovered in this segment (Table 1). The Jinpingtuo profile (No.7 in Figure 1) dislocates the top boundary of the S_1 ancient soil stratum to the depth of 6.0 m, which is the largest offset of S_1 that can be found at present. The Niujiaojian profile dislocates the S_1 ancient soil stratum to the depth of 5.7 m (ZHANG and LEI, 1993). The result from the artificial earthquakes of Se11 line between Bailuyuan and Shaolingyuan shows distinctively that this fault is a typical Y-shape structure (Figure 3a; Table 2).

The fault on Shaolingyuan has a length of 10 km and a strike of N60°~70°E, extending from the left bank of Chanhe river to the right bank of Zaohe river. The basement of Shaolingyuan is the "Sanmen Formation" lacustrine stratum of the Lower Pleistocene. The fault profiles of Dabaopo, Xiaobaopo and Xibeicun, *etc.* are discovered here. The fault planes are distinct with clear vertical strias. The offset separation of S_1 bottom boundary is 1.1~1.3 m for the profiles of Dabaopo and Xiaobaopo (Figure 2b), while there is not any offset on the S_1 top boundary of the profiles (Table 1). However, the fault can be seen clearly on the shallow seismic profiles Se10 and Se10-1 (Figure

3b; Table 2) at Juliancun located between Shaolingyuan and Shenheyuan. Se10-1 is an added line in the southeast direction due to the reason that Se10 has not totally controlled the principal fault.

Figure 1 Distribution of Lintong-Chang'an fault zone and positions of fault outcrops and line of artificial earthquakes

1. Location and its No. of fault outcrops; 2. Fault; 3. Normal fault; 4. Strike-slip fault; 5. Line and No. of shallow shocks; 6. Deep reflection line and number of kilometer; 7. Line No. and anomalous site of controlling shallow shocks; F_1 . Majie-Nianwan fault; F_{1-1} . Wangjiabian-Houjiawan fault; F_2 . Hujiagou-Shoupazhang fault; F_{2-1} . Zhongdicun-Tangjiazhai fault; F_3 . Huxian-Tieluzi fault

The fault on Shenheyuan goes from the left bank of Zaohe river to Nianwan on the southwest margin of Shenheyuan. It is 2.5 km long and its strike turns to $N20^\circ\sim30^\circ E$. The basement of Shenheyuan is the lacustrine stratum of the Lower Pleistocene. Two fault profiles of Nianwan and Huangpucun are discovered here and the offset separation is 1.5 m for the S_1 and S_2 top boundaries of Nianwan profile (Figure 2c; Table 1).

On Bailuyuan, Shaolingyuan and Shenheyuan, the fault basically distributes along the NE-trending loess cross scarps between the second-order and third-order loess tablelands. The cross scarps are 90~100 m, 30~50 m and 38~46 m in height, respectively.

1.1.2 Wangjiaban-Houjiawan branch fault (F_{1-2})

This is a branch fault of Majie-Nianwan fault zone, which goes from Niujiuojian in the southwest corner of Bailuyuan and enters into Shaolingyuan through Gaoqiao and Chanhe river. Then it arrives at the piedmont pluvial fan of Qinling Mountain through Shaolingyuan and Shenheyuan. It is a tensional normal fault with a length of about 35 km, a strike of $70^\circ N\sim80^\circ E$, a dip of northwest and a inclination of 60° , distributing along the NE-trending cross scarps between the first-order and second-order loess tablelands. The geomorphic cross scarp formed on Shaolin-

gyuan is quite clear with a height of 40~60 m and the cross scarp on Shenheyuan is about 20 m high. Fault profiles with an offset separation of 1~2.5 m are discovered at Gaoqiao on the right bank of Chanhe river, Wangjiabian on the left bank, Weiqudongcun on Shaolingyaun, and Shuimocun on Shenheyuan. However, horizontal stria is only discovered on the section of Shuimocun up to now. The result from Se3 seismic line at Xiabeiliang located on the piedmont pluvial fan of Qinling Mountain shows that the offset separation is about 15 m (Table 2).

Figure 2 Map of fault profiles of Lintong-Chang'an fault zone

(a) Xiaoya profile; (b) Xiaobaopo profile; (c) Nianwan profile; (d) Shuimocun profile; (e) Huangqutou profile; (f) Zhongdicun profile. 1. Malan loess; 2. Lishi loess; 3. Ancient soil; 4. Sampling location; 5. Calcareous concretion; 6. Fault crushed belt; 7. Fault; L₁S. First incompetent ancient soil stratum of Late Pleistocene; L_{1.2}. Second-layer loess of Late Pleistocene; S_{1.1}. Upper part of first ancient soil stratum of Late Pleistocene; S_{1.2}. Lower part of first ancient soil stratum of Late Pleistocene; L_{2.1}. Upper part of first-layer loess of Middle Pleistocene; L_{2.2}. Lower part of first-layer loess of Middle Pleistocene; S_{2.1}. Upper part of first ancient soil stratum of Middle Pleistocene; S_{2.2}. Lower part of first ancient soil stratum of Middle Pleistocene; L₃. Second-layer loess of Middle Pleistocene; (116.78±9.0) ka PB Result of age testing

1.1.3 Hujiagou-Shoupazhang fault (F_2)

Extending from Xiaoyugou of Tongrenyuan, the fault passes through Tongrenyuan, Bailuyuan, Shaolingyuan and the foreriver terrace of pluvial fan from the north to the south. It has a branch in the Tongrenyuan fault and coincides with the principal fault zone at Shenyusigou.

The fault on Tongrenyuan is 13.5 km long and its strike is basically parallel to the Majie-Nianwan fault zone in Tongrenyuan. The fault profiles of Xiaogou, Hujiagou and Wangkezhai are discovered (Table 1) and the S_1 top boundary was dislocated for 0.8~1.5 m.

The fault on Bailuyuan extends from the left bank of Bahe river to the right bank of Chanhe river with a length of 10 km. It distributes along the NE-trending cross scarp between the first-order and second-order loess tablelands and the cross scarp is as high as 90~120 m. The fault passes through Tangjiagou and Shenyusigou and the fault profiles of Qiaogou, Xiaojiazhai, Shenyusigou and Zhongdian are discovered here (Table 1). The offset of S_1 is 2.0~6.0 m and the dislocated latest stratum is the L_1S incompetent ancient soil (about 0.6 m) with an age of about 32 000 a. The fault can be seen clearly in the shallow seismic profile of Zhongdiancun (Figure 3; Table 2).

The fault on Shaolingyuan goes from Yuedengge on the left bank of Chanhe river and passes through Huangqutou to Shoupazhang with a length of 10 km. It distributes along the NE-trending cross scarp between the first-order loess tableland and the Liangwa landform and the cross scarp is as high as 40~50 m. Very good fault profiles are discovered at Yuedengge and Huangqutou on Shaolingyuan. However, there is no first-order loess tableland on Shenheyuan and the geomorphic unit is river terrace. The results from Se9 seismic line at Qingliangsi, Se8 seismic line at Shoupazhang of Zaohe river terrace, and Se4 seismic line at Duhuicun of Jiaohe river terrace (Table 2) have all demonstrated the existence of this fault.

1.1.4 Zhongdicun-Tangjiazhai fault (F_{2-1})

The fault stretches from Tongrenyuan to Bailuyuan and coincides with Hujiagou-Shoupazhang fault zone (F_2) in the vicinity of Shenyusi. Its strike turns for about 90° along the geomorphic cross scarp near Tangjiazhai. The major fault profiles discovered here are Yangjiazhai, Renjiacun, Zhongdicun (Figure 2f) and Rendongcun (Table 1) and the fault have dislocated the S_1 top boundary for 0.3~2 m.

1.2 Latest activity of Lintong-Chang'an fault zone

Since the Late Pleistocene, the offset separations of Lintong-Chang'an fault zone are about 0.2~6.0 m, most of them are 0.8~1.5 m and the average value is 1.1 m. The average offset of the branch faults are: $F_1=1.94$ m; $F_{1-1}=0.73$ m; $F_2=17$ m; $F_{2-1}=0.82$ m. The activity of F_2 fault is more intensive than that of F_1 , which is characterized by westward transition, *i.e.*, to the direction of basin. Moreover, different faults of loess tablelands have different offsets. From Tongrenyuan to Shenheyuan, the average offsets of the first ancient soil stratum (S_1) of the Late Pleistocene dislocated by different geomorphic units are: Tongrenyuan 1.09 m; Bailuyuan 2.76 m; Shaolingyuan 1.70 m; Shenheyuan 0.93 m. The data of Shenheyuan are not very reliable since its profiles used in the statistics are less. Up to now, the offset evidence of Late Pleistocene has not been found on the piedmont pluvial fan of Qinling Mountain. The statistic results indicate that the spatial fault activity is stronger on Bailuyuan, while it is rather weak on Shaolingyuan. The latest stratum dislocated on the fault zone is L_1S (No. 26 in Figure 1, Qiaogou profile) with an age of 32 000 years. If we consider the age of the S_1 bottom boundary as 100 000 years, the activity rate in the early period of the Late Pleistocene of each branch fault and the fault of loess tableland will be rather low with an average value of $1 \times 10^{-2} \sim 1 \times 10^{-3}$.

Figure 3 Shallow seismic profile and geological explanation near Gaoqiao (Se11) (a) and Shallow seismic profile and geological explanation near Juliancun (Se10 and Se10-1) (b)

Figure 3 Shallow seismic profile and geological explanation near Zhongdiancun (Se12) (c)

2 Characteristics of plane and profile combinations of fault zone

2.1 Plane combination shape of fault zone

1) Broom-like shape (Figure 4a) The Lintong-Chang'an fault zone is about 2.5 km in width on Tongrenyuan in the northeast end, which scatters gradually to the southwest. The fault is 10 km wide on Shenheyuan, which bulges slightly to the northwest. It looks like a broom in plane.

2) Parallel shape (Figure 4b) Lintong-Chang'an fault zone develops in a specific geomorphic tectonic location. And in local segments of loess tablelands as Bailuyuan, Shaolingyuan and

Figure 4 Plane combination characteristics of Lintong-Chang'an fault zone

(a) Broom-like shape; (b) parallel shape; (c) elbow-like shape; (d, e) forking or convergent shape; (f) opposite dip in different segment

Figure 5 Profile combination characteristics of Lintong-Chang'an fault zone

(a) Single type; (b) step shape; (c) "Y" shape; (d, f) leisurely wave-like bending shape; (e) graben-and-horst type

Shenheyuan, several faults of this fault zone extend in a parallel shape with approximate equal separations.

3) Forking or convergent shape (Figure 4d, 4e) A fault zone divides into two or more faults. For example, the Majie-Nianwan fault separates a branch of Zhongdicun-Houjiawan at Niujiaojian.

4) Elbow-like shape (Figure 4c) The fault zone bends in an almost right angle, showing an elbow-like shape, such as the F_{2-1} Tangjiazhai fault. In addition, the Lintong-Chang'an fault has opposite dip in different segment (Figure 4f).

Table 1 Statistics of Late Quaternary fault outcrops of Lintong-Chang'an fault zone

Geo.unit	Location and No. of fault profile	Attitude	Dislocated stratum	Vertical shift/m	Major characteristics
Majie-Nianwan fault zone (F_1)	TRY Yingbeihou 1	N35°E/NW/62°	S ₁ bottom Boundary	1.0	Geomorphic cross scarp
	Yangpo 2		S ₃ , S ₄ top boundaries	2.0	Geomorphic cross scarp
	Xiaoya 3	N35°E/NW/62°	S ₂ top boundary	1.5	With polished surface and vertical stria
	Chezhanggou 4	N35°E/NW/62°	S ₁ top boundary	1.5	Geomorphic cross scarp
	Jinpingtuo 7		S ₁ bottom Boundary	6.0	Geomorphic cross scarp
	BLY Jiangjiagou 8	N45°E/NW/80°	S ₁ bottom boundary	1.1	With polished surface and vertical stria
	Niujiaojian 9	N315°E/NW/70°	S ₁ bottom boundary	5.7	Clearly dislocated stratum
	Jingyugou 10	N85°E/NW/65°	S ₄ , S ₆	1.0	
	Dabaopo 11	N72°E/NW/72°	S ₁ bottom boundary	1.0	With polished surface and vertical stria
	SLY Xiaobaopo 12	N68°E/NW/82°	S ₁ bottom boundary	1.3	
	Xibeicun 13	NE/NW	S ₁	0	With polished surface and vertical stria
	SHY Longweigou 15	N72°E/NW/70°	S ₁ top boundary	1.0	1.5 m offset on S ₂ top boundary
	Huangpucun 16	N30°E/NW/68°	S ₁ top boundary	0.8	
Wangjiabian-Houjiawan fault (F_{1-1})	BLY Gaoqiao 17	N25°E/SE/72°	S ₁ bottom boundary	1.0	Clearly dislocated stratum
	Wangjiabian 18	N55°E/SE/65°	S ₃ top boundary	2.5	
	SLY Weiquzhen 19	N70°E/NW/72°	S ₁ top boundary	0	
	SHY Shuimocun 20	N75°E/NW/66°	S ₁ bottom boundary	1.0	With horizontal stria and polished surface
Huijiagou-Shoupazhang fault (F_2)	TRY Xiaojiagou 22		S ₂ top boundary	2.0	
	Huijiagou 23	N95°E/NW/78°	S ₁ bottom boundary	1.5	Geomorphic cross scarp
	Wangkezhai 24	N55°E/NW/62°	S ₁ bottom boundary	about 0.8	Geomorphic cross scarp and dislocated S ₂ and S ₃
	Qiaogou 25	N70°E/NW/82°	S ₁ top boundary	0.8	L ₁ S is dislocated for 0.6m
	BLY Xiaojiiazhai 26	N34°E/NW/82°	S ₁ bottom boundary	3.9	With polished surface and vertical stria
	North to Shenyusigou 28	N60°E/NW/73°	S ₁ bottom boundary	6.0	With polished surface and vertical stria
	South to Shenyusigou 27	N60°E/NW/73°	S ₁ bottom boundary	2.0	S ₂ and S ₃ are dislocated
	Zhongdiancun 29		S ₂ bottom boundary	0.3	S ₁ is not dislocated
	SLY Huangqutou 31	N65°E/SE/74°	S ₁ bottom boundary	0.3	Horst-and-graben fault
Zhongdicun-Tangjiazhai (F_{2-1})	Lijiagou 32	NE/70°	S ₁ bottom boundary	0.3	Geomorphic cross scarp
	TRY Yangjiazhai 33	N40°E/SE/80°	S ₁ bottom boundary	0.5	
	Fanjiaicun 34	N20°E/NW/50°	S ₃ top boundary	1.5	
	Zhongdicun 35	N70°E/NW/63°	S ₁ top boundary	2.0	Stimulating light age is (116.4±9.0)ka
	Renjiacun 36	N20°/NW/70°	S ₂ top boundary	0.8	
	BLY North to Tangjiazhaigou 37	N95°E/N/75°	S ₁ bottom boundary	0.3~0.4, 1.4	With polished surface and vertical stria; dislocated S ₂
	South to Tangjiazhaigou 38	N342°E/W/78°	S ₁ bottom boundary	0.3~0.5	Dislocated S ₂ , S ₃ and S ₄

Note: The location and number are the same for the fault profiles both in Table 1 and Figure 1. TRY: Tongrenyuan; SLY: Shaolingyuan; SHY: Shenheyuan; BLY: Bailuyuan; Geo.: Geomorphic.

Table 2 Result from shallow seismic exploration of Lintong-Chang'an fault zone^①

No.	No. of line	Name of line	No. of fault	Property	Apparent inclination	Apparent dip	Fault separation/m	Buried depth of upper break-point/m	Length of line/m
1	Se12	Zhongdian cun	F_{Se12}	Normal fault/ major fracture	NW	66°	100	≤35	2190
2	Se11	Gaoqiao	F_{Se11-1}	Normal fault/ major fracture	NW	65°	30~200	≤30	4187
			F_{Se11-2}	Normal fault/ major fracture	NW	65°	30	≤30	
			F_{Se11-3}	Normal fault/ low sequence	SE	63°	10	≤30	
			F_{Se11-4}	Normal fault/ low sequence	SE	63°	20	≤30	
			F_{Se11-5}	Normal fault/ low sequence	SE	63°	30	≤30	
			F_{Se11-6}	Normal fault/ low sequence	SE	63°	10	≤30	
3	Se10	Juliancun	F_{Se10-1}	Normal fault/ major fracture	NW	58°	100		3389
			F_{Se10-3}	Normal fault/ low sequence	SE	67°	15	≤40	
			F_{Se10-4}	Normal fault/ low sequence	SE	65°	15	≤40	
			F_{Se10-5}	Normal fault/ low sequence	SE	68°	15	≤40	
			F_{Se10-6}	Normal fault/ low sequence	SE	68°	20	≤50	
			F_{Se10-7}	Normal fault/ low sequence	SE	65°	20	≤50	
4	Se10-1	Juliancun	F_{Se10-1}	Normal fault/ major fracture	NW	69°	40	≤50	1206
			F_{Se10-2}	Normal fault/ subfracture	NW	69°	20	100	
5	Se9	Qingliangsi	F_{Se9}	Normal fault	N	66°	25	≤40	902
6	Se8	Zhangcun	F_{Se8-1}	Normal fault/ low sequence	NW	70°	15	≤50	2033
			F_{Se8-2}	Normal fault/ low sequence	NW	70°	15	≤50	
7	Se7	2nd middle school	F_{Se7}	Normal fault	NW	65°	20	≤35	870
8	Se4	Duhuicun	F_{Se4}	Normal fault	NW	68°	30	≤40	1800
9	Se3	Xiabeiliang	F_{Se3-1}	Normal fault/ major fracture	NW	70°	15	≤50	2370
			F_{Se3-2}	Normal fault/ major fracture	NW	70°	10	260	
			F_{Se3-3}	Normal fault/ low sequence	SE	65°	8	175	
10	J27	Bahe	F_{J27-1}	Normal fault/ major fracture	NW	68°	80	≤30	4890
			F_{J27-2}	Normal fault/ major fracture	NW	69°	200~400	≤30	
11	L1	Darencun to Xiwangqu	F_{L-1}	Normal fault	NW	85°	70	250	12660
			F_{L-2}	Normal fault	NW	70°	94	350	
			F_{L-3}	Normal fault	SE	75°	45	400	
			F_{L-4}	Normal fault	NW	85°	35	500	
			F_{L-5}	Normal fault	N	81°	45	330	

^① Xi'an Research Institute of General Institute of Coal Science. 2007. Report on shallow artificial earthquakes survey for the project of active fault detection and seismic risk evaluation in Xi'an city.

2.2 Profile combination shape of the fault zone

1) Single type (Figure 5a) There is only one fault in a profile. This phenomenon appears the most in the Lintong-Chang'an fault zone.

2) Step shape (Figure 5b) A step-shape landform is constituted on the profile of the Lintong-Chang'an fault zone, which drops gradually from the southeast to the northwest with a tilted front side and an inclined back side.

3) "Y" shape (Figure 5c) The characteristics of Y-shape faults combination is shown very clearly on the shallow seismic profiles of Se11 (Figure 3a), Se10 (Figure 3b) and Se3 (Table 2).

The major fault zone tilts to the northwest, while the secondary faults tilt to the southeast. The major fault zone and the secondary faults have the same strike, but the opposite inclination.

The Y-shape structure develops not only on a certain fault of the Lintong-Chang'an fault zone, but also on the faults of different orders and different scales. For example, the entire Lintong-Chang'an fault zone develops a series of (about 14) low-sequence reversal normal faults, *i.e.*, the Xi'an ground fissures on the upper side, *i.e.*, the Xi'an depression, which forms a Y-shape structure together with the Lintong-Chang'an fault zone. It is called the basin-and-range landform (ZHANG, 1990).

4) Graben-and-horst type (Figure 5e) The Huangqutou profile (Figure 2e, No.31 in Figure 1) exhibits a small-scale graben-and-horst structure. In addition, some profiles show a leisurely wave-like bending shape (Figure 5d and 5f).

2.3 Relation between fault and cross scarp

It is apparent from the above analysis that the Lintong-Chang'an fault zone basically develops along the geomorphic cross scarps. As far as the scarp height and fault separation are concerned, the difference between the two seems very large. For example the Xiaobaopo profile, the fault separation is 1.2 m for the bottom boundary of the first ancient soil stratum of the Late Pleistocene, while the corresponding cross scarp is as high as about 40 m. Is there any relation between the two? The results from prospecting indicate that the upper and lower geomorphic planes of the cross scarp near Xiaobaopo is actually the same plane. Their loess sediments are both 110 m thick and beneath them, there is "Sanmen Formation" lake stratum. The result from prospecting in the river valley between the loess tablelands shows that the upper separation of the "Sanmen Formation" lake stratum as the basement is about several to more than ten meters^①. That is to say that the accumulated separation of the fault in the basement loess tableland is not as high as the loess cross scarp and this scarp was not totally formed by the fault. In addition, some evidences^② indicate that the cross scarp was formed on the existed fault location by the erosion in the time period when the "Sanmen Formation" retreated. The geomorphic scarp has resulted from the joint action of fault activity and erosion, while the height of the cross scarp is mainly due to erosion.

Figure 6 Form line of cross scarp near Xiaobaopo

^① Research Institute of Engineering Geological Survey of Shannxi Province. 2007. Report on borehole composite profile for the project of active fault detection and seismic risk evaluation in Xi'an city.

^② SHI Ya-qin. 2007. Genesis analysis on the cross scarp where Lintong-Chang'an fault zone is located, to be published.

3 Deep-seated structure of Lintong-Chang'an fault zone^①

The deep seismic reflection line is located between Chang'an district in the southwestern part and Liquan county in the northwestern part of Xi'an city. With a total length of 69 km, the line has a direction of NW-SE. Its SE end point (Pile No.0 m) is near Shachangcun, Taiyigong township, Chang'an district; its NW end point is close to Fuguanzhai, Junma township, Liquan county. A length of about 25 km of its southeast end has covered the width range of the Lintong-Chang'an fault zone (Figure 1). The tested result of the local region in the southeast end of the deep seismic reflection line is shown in Figure 7.

Figure 7 Characteristics of deep structures in the Lintong-Chang'an fault zone
 F_1 Majie-Nianwan fault; F_3 Wangjiabian-Houjiawan branch fault; F_4 Hujiagou-Shoupazhang fault; F_2 Huxian-Tieluzi fault; F_5 Qinling north-margin fault; T_Q reflection wave group of bottom boundary of Quaternary system; T_{N_1} , T_{N_2} reflection wave group of bottom boundary of Miocene system; T_{N_2} reflection wave group of bottom boundary of Pliocene; T_E reflection wave group of bottom boundary of Paleogene system; T_g reflection wave group of crystalline basement F_6 , F_7 Two faults discovered lately

On the basis of the cophase-axis offset or strong-weak variation features, the data can be explained that there are five faults in the width range of the Lintong-Chang'an fault zone in Figure 7, i.e. F_1 , F_2 , F_3 , F_4 and F_5 . They are located respectively at the pile Nos. 10.2 km, 14.2 km, 16.0 km and 17.5 km, while the surface location of F_5 is not recorded. The five faults are all normal ones.

The result suggests that F_1 in Figure 7 is the Yuxia-Tieluzi fault, which is corresponding to the regional fault distribution. With a strike of EW, the fault is called Zhouzhi-Yuxia fault in the Weihe basin, while it is called Tieluzi fault in the Qinling mountainous area. The fault is characterized by distinct left-lateral strike-slip motion with a displacement of about 750 m since the Middle Pleistocene (YANG *et al*, 2005). F_2 at the location of 14.2 km in Figure 7 should be the Majie-Nianwan fault of the Lintong-Chang'an fault zone, which has a certain error as compared

^① Geophysical Exploration Center of China Earthquake Administration. 2005. Report on deep earthquake survey for the project of active fault detection and seismic risk evaluation in Xi'an city.

with its surface location. F_3 and F_4 in Figure 7 indicate respectively Wangjiabian-Houjiawan branch fault and Hujiagou-Shoupazhang fault, which correspond well to their surface locations. F_5 in Figure 7 is the Qinling north-margin fault. The Lintong-Chang'an fault zone has dislocated the reflection layers of T_N , T_E and T_g . F_3 and F_4 faults are apposed to F_2 fault at the depth of about 5 km; F_2 fault is apposed to F_1 fault at the depth of about 8 km; and F_1 fault extends in a listric shape to the depth of 8.5~9 km and is apposed to F_5 there.

It is apparent from deep seismic reflection profile that the Lintong-Chang'an fault zone has a depth of about 5~8 km. It is a basement fault, but a listric fault in the deep stratum, which belongs to a typical outstretching tectonic system.

4 Formation mechanism of Lintong-Chang'an fault zone

The Lintong-Chang'an fault zone serves as a boundary between the Xi'an depression in the Weihe basin and Lishan embossment, and its formation mechanism should be closely related to the generation of Weihe graben basin (Figure 8). The Weihe basin is a Cenozoic graben basin. Before the Paleocene, affected by the movement of Yanshan Mountain, this area uplifted intensively and suffered from degradation. From Eocene to Oligocene, the uplift of the deep mantle speeded up the crustal stretching and tensional thinning in this area (DENG and YOU, 1985; Studying Group of *Ordos Peripheral Active Fault System* of State Seismological Bureau, 1988). Then the axial rock of the preceding uplift ruptured (MA *et al*, 1983) and longitudinal tensional fracture occurred. At first, the outstretching rift began to occur on the EW-trending Weihe fault and small-range Eocene and Oligocene deposits appeared. After the Late Tertiary Himalaya movement, the uplifted Qinghai-Xizang Plateau intensified the NE-trending compression to the Ordos block. At the same time, the westward compression of the Pacific Ocean (DENG and YOU, 1985), under the press from the EW direction, generated a proximate NS-trending tension local stress field in this area. And under the action of the NNW-SSE tension stress field (GAO, 1979; Earthquake Administration of Shannxi Province, 1996), the Weihe basin further enlarged. The faults controlling the development of the basin, *i.e.* the Weihe fault, Yuxia-Tieluzi fault and Qinling north-margin fault, migrated from the north to the south, and the blocks among the faults rotated along the listric normal fault plane. Then an outstretching fault system, with a step-shaped normal

Figure 8 Distribution map of faults and stress field in the Weihe basin

1. Fault and No.; 2. Direction of local stress field; 3. Bedrock; F_1 . Piedmont fault of Qinling mountain; F_2 . Piedmont fault of Huashan mountain; F_3 . Yuxia-Tieluzi fault; F_4 . Piedmont fault of Lishan mountain; F_5 . Weihe fault; F_9 . Piedmont fault of Beishan mountain; F_{10} . Qishan-Mazhao fault; F_{11} . Lintong-Chang'an fault zone

fault dropping gradually from the south to the north, the south-margin fault as the major fault and the northmargin fault as the opposite secondary fault, had been generated. The Yuxia-Tieluzi fault along the basin margin is characterized by left-lateral strike slip.

In Eocene, the Lintong-Chang'an fault zone began to subside intensively and receive deposits. In the vicinity of Maoxicun, Bahe river, the offset separation of the Late Eocene-early Oligocene of Paleogene epoch was about 1 000 m (FENG *et al*, 2006). In Miocene and Pliocene, the two sides of the faults were still characterized by subsidence, while the magnitude was distinctively small. In the early Pleistocene, the fault displayed an intensive differential movement, and the west side of the fault had a thick Upper Pleistocene deposit. From the Middle and Late Pleistocene to the recent, this area was in an uprising state (GUAN, 1966). Since the early Oligocene, due to the continuous tilting uplift of the Lishan Mountain of overriding in the north and underthrusting in the south, the whole relief surface has tilted from the northeast to the southwest. At the same time, the continuous uplift of the west piedmont of the Huashan mountain on the east side has made the Lishan area tilted northwestwards and formed the elongated deposit area in the SE-NW direction. The terrain in this area lowers successively from the northeast to the southwest and from the southeast to the northwest. In the generating and extending processes of the basin, the Lintong-Chang'an fault zone, under the action of the proximate SN-trending tension stress field, also tilted and extended continuously and formed the outstretching fault zone from the southeast to the northwest. With the uplift of the Lishan embossment, the lake water of the Pliocene and early Pleistocene epochs retreated gradually and the lake water had an erosive erosion action at the former fault location. By the repeated processes of crustal uplift, fault activity, lake-water erosion, the cross scarp with both fault activity and erosive action has formed. After the lake water retreated, the loess deposited on the cross scarp that is characterized by erosion. The amount of each fault activity after the loess deposit would be accumulated on the cross scarp. The Lintong-Chang'an fault zone is subject to the proximate SN-trending tension stress, at the same time, it is also affected by the proximate EW-trending shear stress. The Shuimocun profile shows that the fault is under the action of the horizontal shear stress. And the Yuxia-Tieluzi fault displays a kind of horizontal left-lateral torsion. The Lintong-Chang'an fault zone lies on the north side of the Yuxia-Tieluzi fault. Its southwestern segment bulges northwestward under effect of the Yuxia-Tieluzi fault and the total fault zone forms a NE-striking plane broom shape from the northeast to the southwest.

5 Conclusions

1) The results from the field ground geological investigation and artificial earthquakes suggest that the Lintong-Chang'an fault zone mainly consists of two faults. One is the Majie-Nianwan fault that separates a branch of Wangjiabian-Houjiawan fault on the right bank of the Bahe River. The other is the Hujiagou-Shoupazhang fault that separates a branch of Zhongdicun-Tangjiazhai fault in Tongrenyuan and Shaolingyuan. The faults display as tension dip-slip normal ones.

2) The Lintong-Chang'an fault zone scatter from the northeast to the southwest in plane, showing a broom-like shape. In local segments, the major fault zone and the branch faults extend with approximately parallel intervals. In profiles, the faults drop in step forms from the northeast to the southwest and the blocks between the faults are characterized by tilted rotation. The faults generally exhibit a feature of "Y"-shape combination, no matter a single fault or the total Lintong-Chang'an fault zone. We can also see the horst-and-graben combination from the profile. The

result from deep seismic reflection indicates that the Lintong-Chang'an fault zone is a listric normal fault in the deep stratum, while in shallow depth; it basically corresponds with the surface faults. The characteristics of geometric structure of the Lintong-Chang'an fault zone indicate that it is a typical outstretching fault system, reflecting a uniform tension tectonic stress field.

3) There is a close relationship between the formations of the Lintong-Chang'an fault zone and the Weihe basin. Due to the tilting in the north and subsiding in the south of the Lishan mountain in the Pliocene in the north end and the uplift of the Huashan mountain on the east side, a landform that drops gradually from the northeast to the southwest and from the southeast to the northwest has generated in the range of the Lintong-Chang'an fault zone. In the generating and extending processes of the Weihe basin, the Lintong-Chang'an fault zone, under the action of the proximate SN-trending tension stress field, tilted and extended continuously and formed the outstretching fault zone of a dropping step-like shape from the southeast to the northwest. With the crustal uplift of Pliocene and early Pleistocene epochs, the lake water retreated gradually and eroded the former fault location. As a result, the cross scarps with both fault activity and erosive action have formed. At the same time, affected by the left-lateral strike-slip movement of the proximate EW-trending Yuxia-Tieluzi fault, the Lintong-Chang'an fault zone exhibits a plane broom-shape distribution from the northeast to the southwest.

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