

Development characteristics and formation analysis of the Liangjia Village earth fissure in the Weihe Basin, China

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Abstract Liangjia Village earth fissure, one of the 79 earth fissures along the Kouzhen–Guanshan fault located in the northern Weihe Basin, causes severe damage to buildings and farmlands. Since the late 1950s, 40 earth fissures have occurred in a similar east–west (EW) direction parallel to the Kouzhen–Guanshan fault, and a further 39 earth fissures have occurred with north–west, east–north, or north–east orientations intersecting the fault. In this study, a case study of Liangjia Village earth fissure was conducted to investigate the mechanisms of fissure generation in detail. Geotechnical and geophysical methods including measurements, trenching, drilling, and seismic exploration were used to reveal the basic characteristics, geological background, and origin model of the Liangjia Village earth fissure. This earth fissure, with a total length of 800 m in 2014, runs EW parallel to the Kouzhen–Guanshan fault, and it has damaged buildings and farmlands by forming sinkholes, gullies, subsidence, and a scarp. The trenching results indicated that this fissure underwent multi-phase activity. Analysis of geological drilling and shallow seismic profiling results showed that the fissure also possessed characteristics of a syn-sedimentary fault. Regarding its genesis, the fissure was formed through the combined actions of three factors: an earthquake created the fissure, the Kouzhen–Guanshan fault controlled its development, and loess erosion and groundwater runoff subsequently enlarged the fissure. Regional extension first generated many buried faults along the hanging wall of the Kouzhen–Guanshan fault before seismic activity caused the buried faults to

propagate to the surface, where loess erosion and groundwater runoff promoted the formation of the current earth fissure.

Keywords earth fissure, Kouzhen–Guanshan fault, earthquake, creep slip, loess erosion

1 Introduction

Researchers have been reporting on earth fissures worldwide for several decades (Leonard, 1929; Rudolph et al., 1991; El Baruni S S., 1994; Allis, 2000; Ayalew et al., 2004; Li et al., 2004; Holzer and Galloway, 2005). This geological activity has resulted in severe economic consequences by destroying roads, pipes, buildings, and other infrastructure, and has caused serious environmental issues as well.

Earth fissures often accompany land subsidence caused by over-pumping of groundwater (Jachens and Holzer, 1982; Hu et al., 2004; Pacheco et al., 2006; Phien-vej et al., 2006; Hernandez-Marin and Burbey, 2010; Pacheco-Martínez et al., 2013; Youssef et al., 2014; Wang et al., 2019b, 2020). Typically, land subsidence is first observed as a response to groundwater pumping. The stress then propagates and accumulates along structural discontinuities, particularly active faults, and creates earth fissures on the Earth's surface. For example, Holzer (1980) and Pampeyan et al. (1988) found that over-pumping of groundwater across a preexisting fault could cause modern fault movement. With a three-dimensional granular displacement model, Burbey (2002) showed that a fault plane represented a location of significant differential vertical subsidence, and that earth fissures may be significant at or near the fault plane. Hernandez-Marin

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and Burbey (2010, 2012) further found that fault zones played an important role in earth fissure formation from groundwater over-pumping. Budhu (2011) proposed that earth fissures could easily occur at or near preexisting faults because of changes in the stress state resulting from groundwater pumping.

An increasing number of scientists agree that active faults are one of the main causes of earth fissures. Active faults not only provide advantageous planes for earth fissure formation from groundwater over-pumping, but can also create earth fissures during fault movement in creep slip or an earthquake (Sarkar, 2004; Li et al., 2000; Hernandez-Marin and Burbey, 2010, 2012; Budhu, 2011). In the United States, the 1994 Double Spring Flat earthquake created five earth fissure zones in the area surrounding the epicenter, and in Ethiopia, swarms of earth fissures were created by the Main Ethiopian Rift extension (Ramelli, 2003; Williams et al., 2004). In the North China region, active faults are an important factor in earth fissure formation (Peng et al., 2013, 2016b; Xu et al., 2015).

Earth fissures are a dominant geohazard in the Weihe Basin, with 212 earth fissures having been discovered in the basin (Lee et al., 1996; Peng et al., 2018; Liu et al., 2019). Peng et al. (2016a) proposed that earth fissures in the Weihe Basin could be divided into two types: one type constitutes the ground fissures that display obvious horizontal and vertical separations on the earth surface, whereas the other type of fissures only display obvious horizontal separations on the earth surface. The fissures in the basin are triggered by four factors: basin structure, the active fault, human activity, and loess erosion.

Earth fissures along the Kouzhen–Guanshan fault (KGF) are an important feature of the Weihe Basin. Many factors affect the development of earth fissures along the KGF, such as loess joints, hidden cavities in the loess, structural joints, active faults, surface water, and earthquakes. To ascertain the mechanisms causing earth fissures along the KGF, in this paper, the distribution of earth fissures along the KGF is first summarized, and a case study is then selected for detailed analysis of these mechanisms of fissure generation.

2 Geological background

The study area is located on the northern edge of the Weihe Basin, a typical continental Cenozoic rift tectonic basin. The geological history of the Weihe Basin consists of four stages. In Archean and Proterozoic (the first stage), the basin experienced four times of combination and three times of division, which resulted in the basement breaking and laid the foundation for the later tectonic deformation. In Paleozoic (the second stage), the basin generally sank and formed depression areas. In Mesozoic (the third stage), Indosinian movement and Yanshan movement caused the basin to be strongly uplifted and compressed. In Cenozoic

(the last stage), the uplift of the upper mantle and the horizontal extension of the crust made the fault system a shovel-type extension fault, and then the area sank to form a basin (Peng et al., 2012).

The KGF, a Holocene active normal fault, is located in the northern part of the Weihe Basin with a length of 100 km, and an overall trend of WE and S dip of 70° (Li et al., 2016; Zang et al., 2019; Jia et al., 2020; Fig. 1(a)). The average normal dip-slip activity rates of the KGF in Pliocene and Middle Pleistocene are 0.18 and 0.53 mm/a, respectively, and the current activity rate is 0.75 mm/a (Xu et al., 1988; Mi et al., 1993; Li et al., 2016). Geologically, the KGF is a normal fault, with loess plateaus and rocky mountains on its north side, and pluvial platforms, pluvial fans, and alluvial terraces on its south side (Mi et al., 1993; Fig. 1(b)). The fault stretches from Kouzhen in the west, through Luqiao and Yanliang, to Guanshan in the east, with a total length of 100 km. Prior to the Cenozoic Era, the KGF exhibited compressive thrust features that were formed in the Proterozoic. During the Cenozoic Era, as the mantle of the Weihe Basin continued uplifting, the KGF transformed into a lip-slip fault.

The height of the loess plateau on the northern side of the KGF gradually decreases from west to east (Table 1), as does the dislocation of the second-order terrace (Table 2), indicating that the intensity of any fault activity gradually decreases in this direction (Mi, 1993). Several secondary faults are on the hanging wall of the KGF with dislocation gradually decreasing from north to south. Total dislocation is as much as 20 m in the cross-section of the fault along the Yeyu River (Fig. 1(c)).

Figure 2 depicts the simplified hydro-geological structure of this area and the approximate layers derived from the hydro-geological logs of wells drilled by the Shanxi Geological Survey in this area. The figure shows that the aquifer system is composed of a succession of sediments, sand, and gravel, whereas the aquiclude is composed of a succession of sediments, loess, and silty clay. These Quaternary layers are mainly lacustrine and alluvial–diluvial.

3 Spatial distribution and damage caused by fissures

The occurrence of fissures along the KGF has accelerated since 1980, with an additional 69 earth fissures occurring between 1980 and 2014 (Table 3). A site investigation in 2014 found that there had been 79 earth fissures along the KGF, with a combined length of more than 30 km and 41 villages affected. It is important to note that all these fissures developed on the hanging wall of the KGF (Fig. 3).

Liangjia Village is located in northern Jingyang County, Shaanxi Province, approximately 50 km north-west of Xi'an City and 40 km north of Xianyang City. The Liangjia Village earth fissure was first observed in 1958 after a

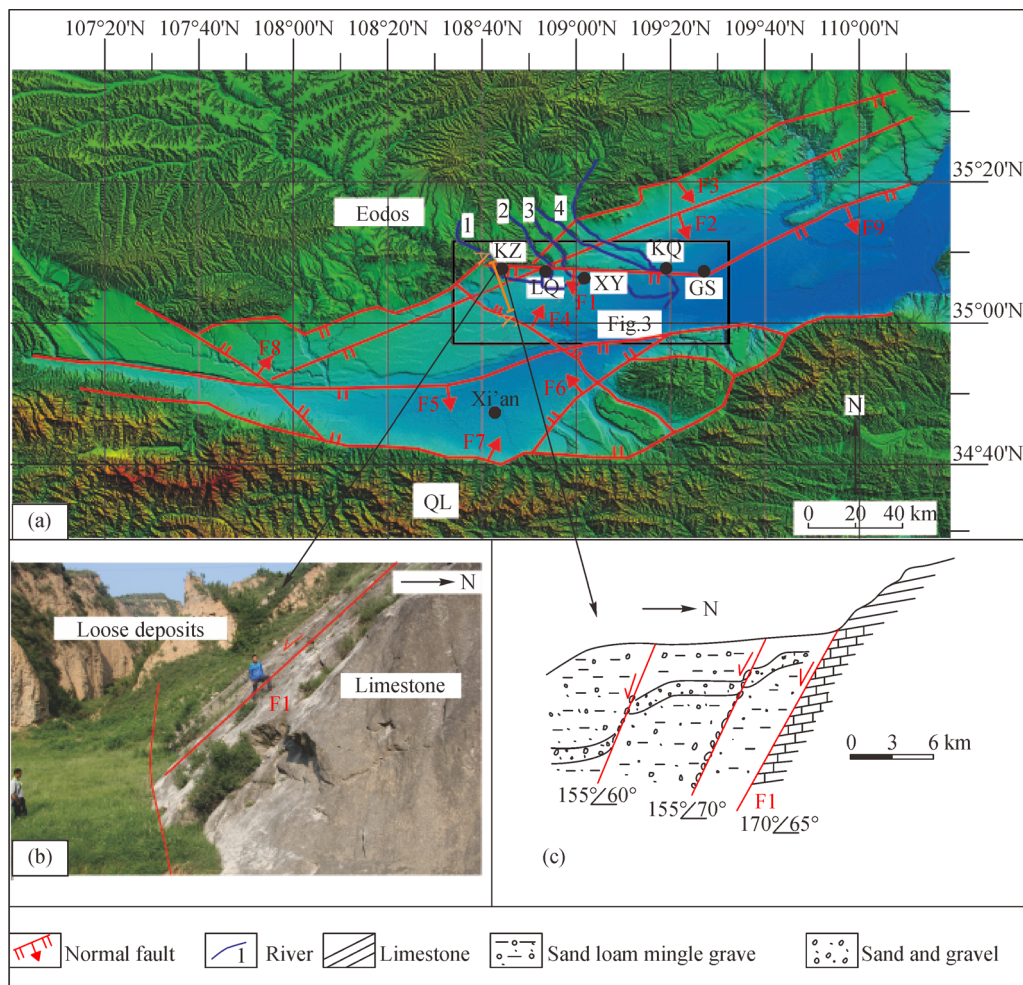


Fig. 1 Geological background of Kouzhen-Guanshan fault. (a) Location of Kouzhen-Guanshan fault in Weihe Basin, (b) photos of Kouzhen-Guanshan fault, (c) photo showing section of Kouzhen-Guanshan fault. F1: Kouzhen–Guanshan fault; F2: Liqian–Pucheng–Heyang fault; F3: Qishan–Qianxian fault; F4: Jinghe–Chanhe fault; F5: Weihe fault; F6: Lintong–Changan fault; F7: the northern QL margin fault; F8: Qishan–Qianxian fault; F9: Shuangquan–Linyi fault; WRB: Weihe Basin; QL: Qinling Mountain; KZ: Kouzhen; LQ: Luqiao; GS: Guanshan; KQ: Kangqiao; 1: Yeyu River; 2: Qingyu River; 3: Zhouyu River; 4: Shichuan River.

Table 1 Loess scarp height along Kouzhen–Guanshan fault

Position	Kouzhen	Luqiao	Xiyang	Kangqiao	Guanshan
Loess scarp height/m	150	110	70	20	5

Table 2 Dislocation of the second-order terrace along Kouzhen–Guanshan fault

River	Zhiyu	Qingyu	Zhuoyu	Shichuan
Dislocation of the second terrace/m	8	5	4	2

heavy rainfall. With a length of 160 m, the fissure was relatively short and shallow at that time. By 2014, however, the total length of the fissure had increased to 800 m, with a maximum depth of 300 cm and a maximum width of 400 cm. With an approximately east–west (EW) strike, this fissure is parallel to the KGF. Observations

during a field survey showed that this fissure has caused sinkholes (Fig. 4(b)), a scarp (Fig. 4(c)), gullies (Figs. 4(a) and 4(d)), and subsidence at the earth's surface. The sinkholes caused by the earth fissure have a maximum visible length, depth, and width of 6, 2.6 and 2.2 m, respectively.

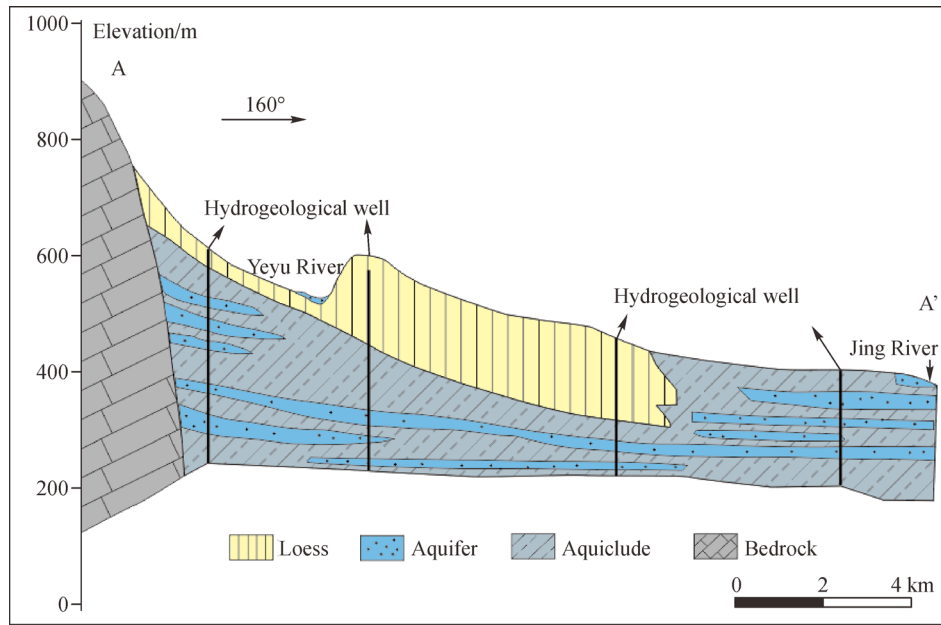


Fig. 2 Hydro-geological cross section showing simplified layers. F1: Kouzhen –Guanshan fault.

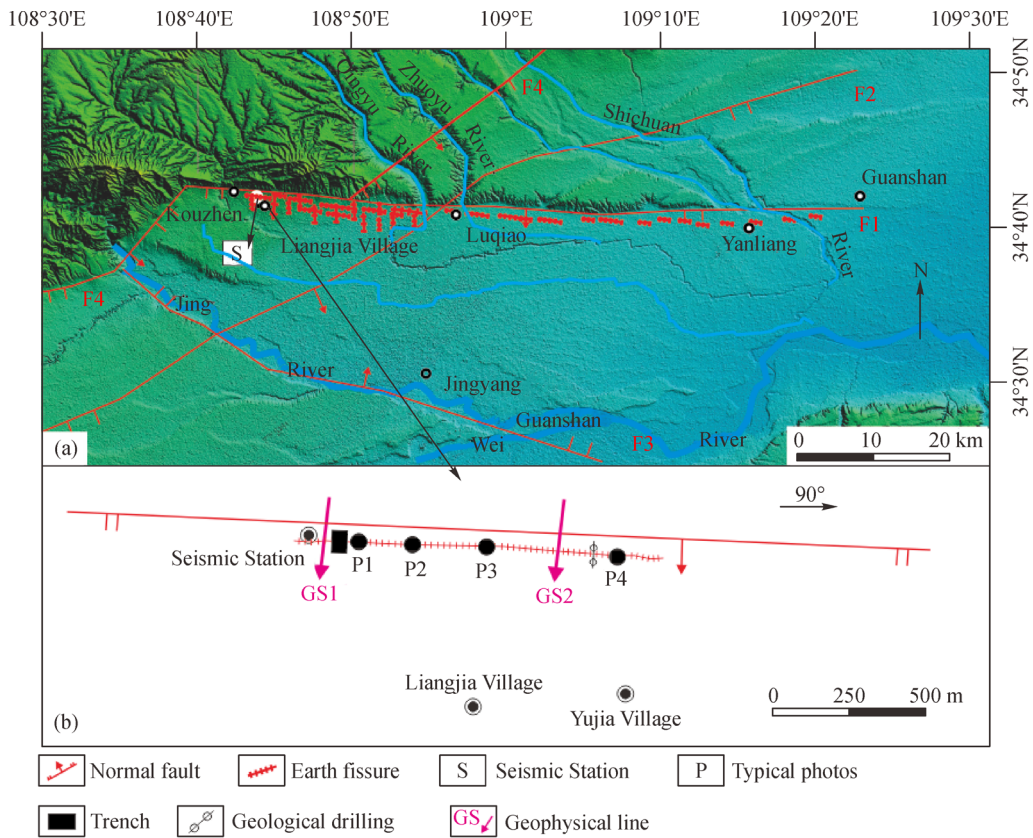
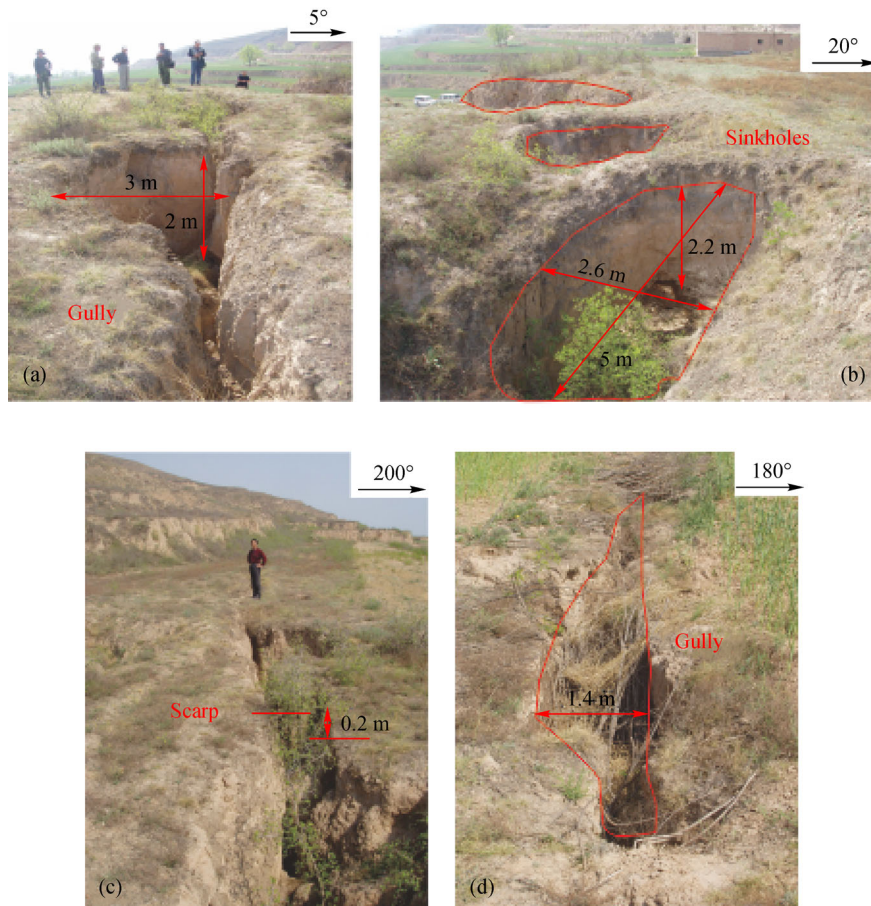


Fig. 3 Map showing earth fissures along Kouzhen–Guanshan fault. (a) Distribution of earth fissures along Kouzhen–Guanshan fault, (b) Liangjia Village earth fissure and exploration work layout; F1: Kouzhen–Guanshan fault; F2: Liquan–Pucheng–Heyang fault; F3: Jinghe–Chanhe fault; F4: Qixian–Qianxian fault.

Table 3 Number of earth fissures occurring in different decades

Year	1950–1969	1970–1979	1980–1989	1990–1999	2000–2014
Number of fissures	2	8	19	22	28
Percentage/%	2.5	10.1	24.1	27.8	35.5

**Fig. 4** Damage related to Liangjia ground fissures. (a)&(d) Gullies, (b) sinkholes, (c) scarp.

4 Structural characteristics of fissure

4.1 Trench excavation

A trench was excavated to establish the shallow profile structure of the Liangjia Village earth fissure. The trench was laid out in northern Liangjia Village, with a length, width, and depth of 20, 14, and 13.2 m, respectively (Fig. 3). The trench excavation revealed the shallow ruptured features of the Liangjia Village earth fissure. As shown in Fig. 5, the trenching profile of the east segment uncovered 2 main fissures that extended to the earth's surface, and 31 secondary fissures on both sides of the main fissure near the surface. The rupture width was about 16 m. The near-surface parts of the two main fissures were vertical and extended downward, slanting to the south. The shape of the profiles was wide on top (313 cm) and narrow

at the bottom (2 cm).

The trench also revealed Quaternary Holocene diluvium and Pleistocene aeolian sediments, eluvium, and diluvium (Fig. 5). The strata, from the top downward, consist of silt, palaeosol (S_0), Malan loess (L_1), silty clay, sandy gravel, palaeosol (S_1), and Lishi loess (L_2). As shown in the profile of the trench (Fig. 5), the S_1 palaeosol was dislocated, with silty clay and sandy gravel filling in the offset. The vertical offset of the S_1 palaeosol layer was 97.3 cm, and the horizontal displacement was approximately 430 cm. Thus, we speculate that this area experienced taphrogenic activity between 0.01 MaBP (the formation age of the bottom strata S_0) and 0.029 MaBP (the formation age of the top strata S_1). The taphrogenic activity resulted in many ancient earth fissures in the S_1 palaeosol and L_2 Lishi loess layers. Moreover, the trenching showed that two main earth fissures dislocated the strata, with the stratigraphic throws

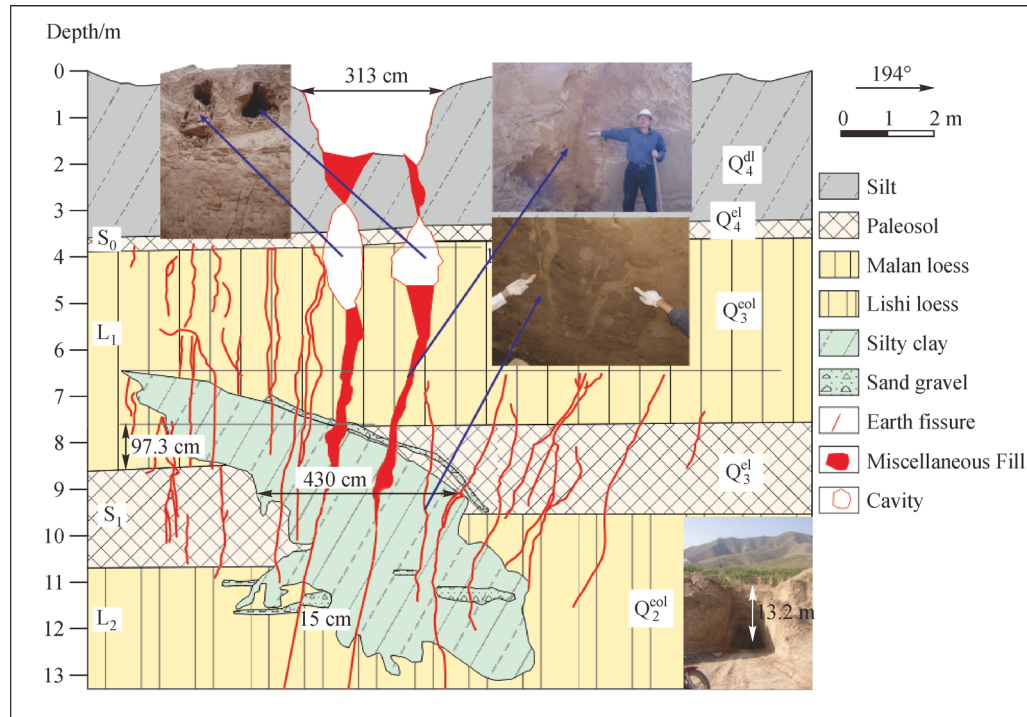


Fig. 5 Trenching profile of Liangjia Village earth fissure.

varying and gradually increasing with depth. For example, the vertical offset was 10 cm in S_0 and 15 cm in the sandy gravel. We expect that larger stratigraphic throws will be found in deeper strata.

From the larger vertical dislocation of 97.3 cm in S_1 , we deduce that the taphrogenic activity corresponds to a larger-scale earthquake in the Late Pleistocene (Q_3), whereas the small vertical dislocations of 10 cm in S_0 and 15 cm in the sandy gravel layer suggest a relatively small-scale earthquake in the Holocene (Q_4). Thus, modern earth fissures can be traced back to the Late Pleistocene or even earlier.

4.2 Geological drilling

The characteristic cross-section of the Liangjia Village earth fissure for depths of 0 to 50 m was revealed by drilling. The geological drill line consisted of six drill holes laid out in northern Yujia Village (Fig. 3). The geological cross-section revealed 15 layers, and all the layers were dislocated by the earth fissure (f1) (Fig. 6). The stratigraphic dislocation started from the first palaeosol (S_0) layer at a depth of 4 m and a vertical offset of 0.1 m, which is consistent with the results revealed by trenching. As the earth fissure extended deeper, its vertical offset periodically increased, with an offset of 1 m in the second palaeosol (S_1) layer at a depth of 12 m, an offset of 2 m in the third palaeosol (S_2) layer at a depth of 19 m, an offset of 2.5 m in the silty clay at a depth of 29 m, and an offset of 5.1 m in the silty clay at a depth of 41 m. Beyond this

depth, the geological profile revealed that another buried fault (Fb') existed in the southern 13 m of the earth fissure (f1); the stratigraphic throw started from the third palaeosol (S_2) layer at a depth of 19 m and gradually increased with depth. These results indicate that the earth fissure exhibited the syn-sedimentary characteristics of an active fault.

Based on the regional geological data and stratigraphic features revealed by drilling, we speculate that the geological layers follow a pattern. The first strata just below the surface at 4 m are silt and palaeosol (S_0), and their age is Holocene. From depths of 4 m to 14 m are Malan loess and palaeosol (S_1) layers from the Late Pleistocene. Finally, from depths of 14 m to 50 m are Lishi loess, palaeosol (S_2), silty clay, fine sand, and medium sand layers, and their age is Middle Pleistocene (Fig. 6). Thus, we can infer that the fissure is connected to the active fault and has characteristics of sustainability. Moreover, the fissure can be traced back to the Middle Pleistocene.

4.3 Seismic exploration

To reveal the structural characteristics of the fissure at Liangjia Village at deeper locations, two geophysical lines were arranged perpendicular to the earth fissure for this work (Fig. 3). The profile lines had a total length of 4430 m and essentially covered the entire earth fissure. The geophysical survey provided a maximum depth of approximately 300 m. The seismic reflection profiles (Figs. 7 and 8) revealed a structural sag between 100 m and 2200 m. Geophysical survey GS1 showed 11 buried active

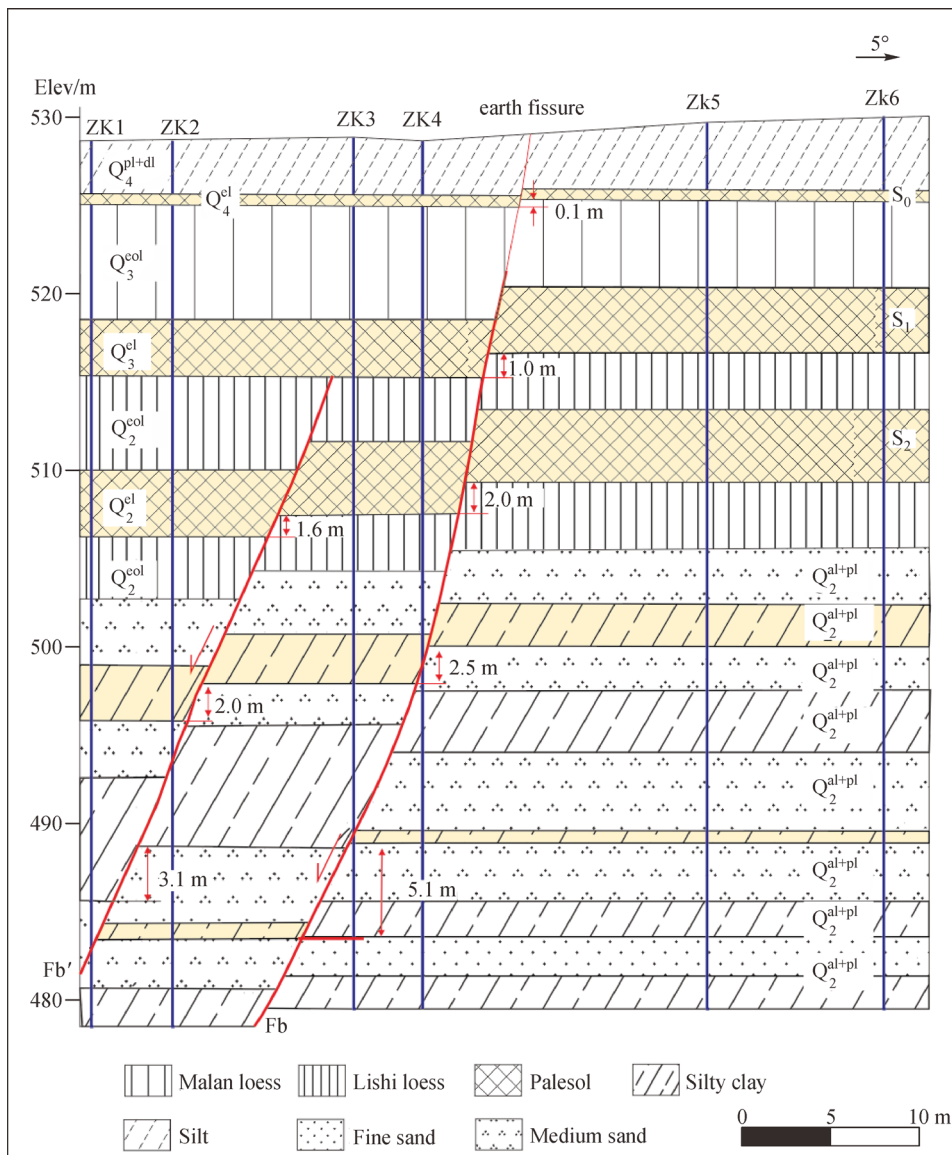


Fig. 6 Geological cross-section of earth fissure in Liangjia Village. Fb&Fb', buried faults.

faults, and geophysical survey GS2 showed 15 buried active faults. The main fault inclined southward, whereas the secondary fault inclined northward, developed on the upper wall, and formed a Y-shape with the main fault. For identification, the main faults were named as Fa, Fb, Fc, Fd, and Fe. The Liangjia Village earth fissure is an outcrop of Fb that extends toward the earth's surface. Thus, the surface appearance of the earth fissure is parallel to the KGF (F1). The seismic reflection and velocity contour section show that the earth fissure is an outcrop of a buried fault (Fb) that extends toward the surface, where the vertical offset of the main earth fissure gradually increases with depth. These results are similar to those of a syn-sedimentary fault, and are consistent with the trenching and drilling results, further demonstrating that the ground fissure grew along the underlying fault.

5 Discussion

Three issues must be examined to identify the underlying mechanisms that have shaped the Liangjia Village earth fissure: 1) the relationship between the earth fissure and the KGF, 2) the periodicity and sustainability of the Liangjia Village earth fissure, and 3) the cause of the 2 m earth fissure width on the western end of the KGF. These topics are discussed in detail below.

5.1 Seismic origin of earth fissures

The Weihe Basin, where the study area is located, exhibits characteristics of the upper mantle uplift, the middle crustal horizontal flow, and the upper crustal extension. The present tectonic stress of the basin is mainly represented by

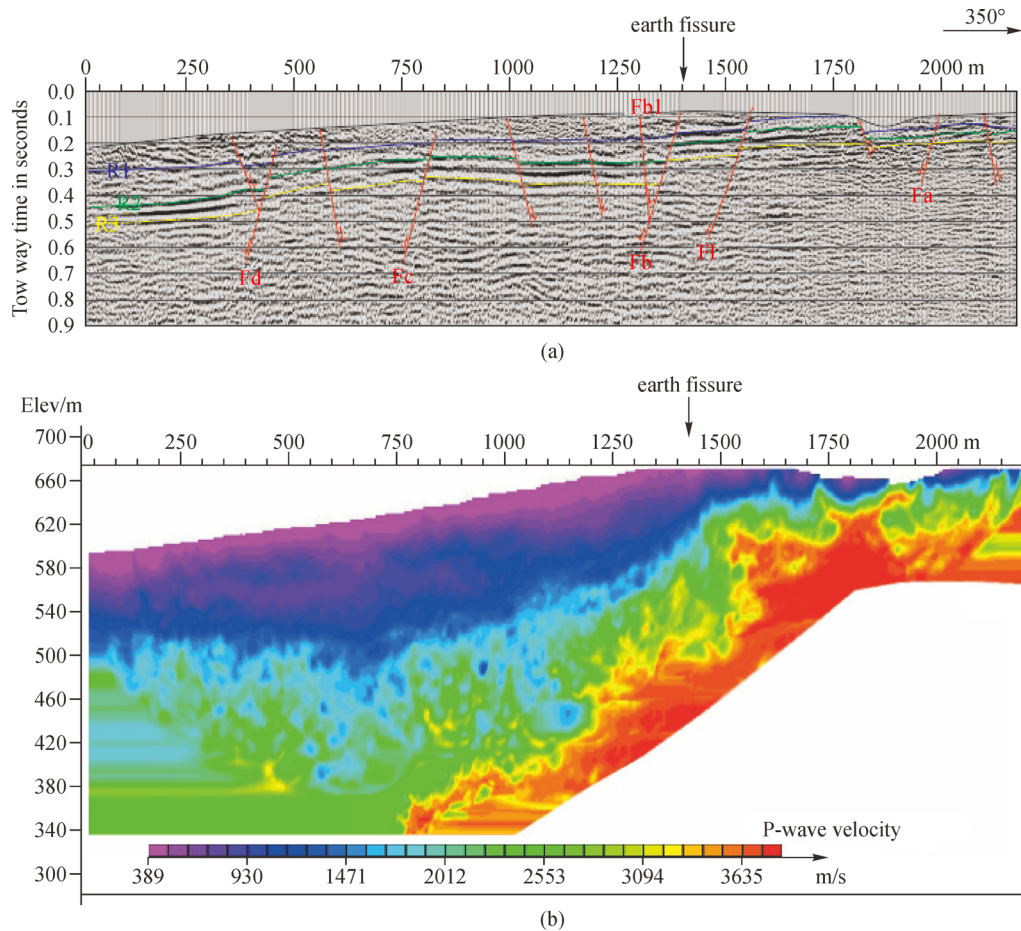


Fig. 7 Results of geophysical survey GS1 across Liangjia Village earth fissure. (a) Seismic reflection profile, (b) p-wave velocity distribution for the uppermost 300 m of the reflection profile; F1: Kouzhen–Guanshan fault; Fa–Fd: buried faults; R1–R3: CT velocity stratification interfaces.

the NW-SE tensile stress, which is an internal dynamic mechanism of the fault activities in the Weihe Basin (Figs. 9 and 10(a); Peng et al., 2018). Therefore, the Basin has been one of the most earthquake-prone areas in China. Since 1177 BC, the basin has experienced 243 earthquakes, including 26 earthquakes with magnitudes greater than 5. Mi et al. (1993) found that the period of seismicity in the Weihe Basin was approximately 800 years. The KGF is one of the seismic faults in the Weihe Basin, and a seismograph was set up on the hanging wall of the KGF in 1958. No earthquakes occurred from 1958 to 1970, whereas nine earthquakes were recorded from 1970 to 1976, showing that earthquakes were becoming much more active. Since 1983, the seismograph has recorded more than 400 small earthquakes, indicating that KGF activity is strengthening. As shown in Table 3, most of the earth fissures along the KGF have appeared since 1980, which is consistent with the modern seismic activity of the KGF. Additionally, the trenching results indicate that the earth fissure appeared in the Holocene (Q_4) and Late Pleistocene (Q_3) and was caused by earthquakes in the Weihe Basin.

In fact, earthquakes not only strengthen the activity of pre-existing earth fissures, but can also extend buried active faults (Sarkar, 2004). Given these results, a possible mode for the formation of the Liangjia Village earth fissure becomes clear. The tectonic structure in the Weihe Basin inherited the features that uplifted the upper mantle and intruded into the crust since the Late Cretaceous. These activities led to the stretching and thinning of the middle crust, creating tensile stress in the upper crust (Fig. 10(b)). The KGF and several other secondary buried active faults were formed under the influence of this tensile stress. After an earthquake occurred in the KGF, the seismic waves passed through the secondary buried fault, giving rise to a fault that extended to the earth surface, thus creating the earth fissure. The buried active fault Fb extended to the surface and created the Liangjia Village earth fissure. Other buried faults also extended to the surface and created other earth fissures.

5.2 Controls of active fault

Other studies have shown that active faults are important to

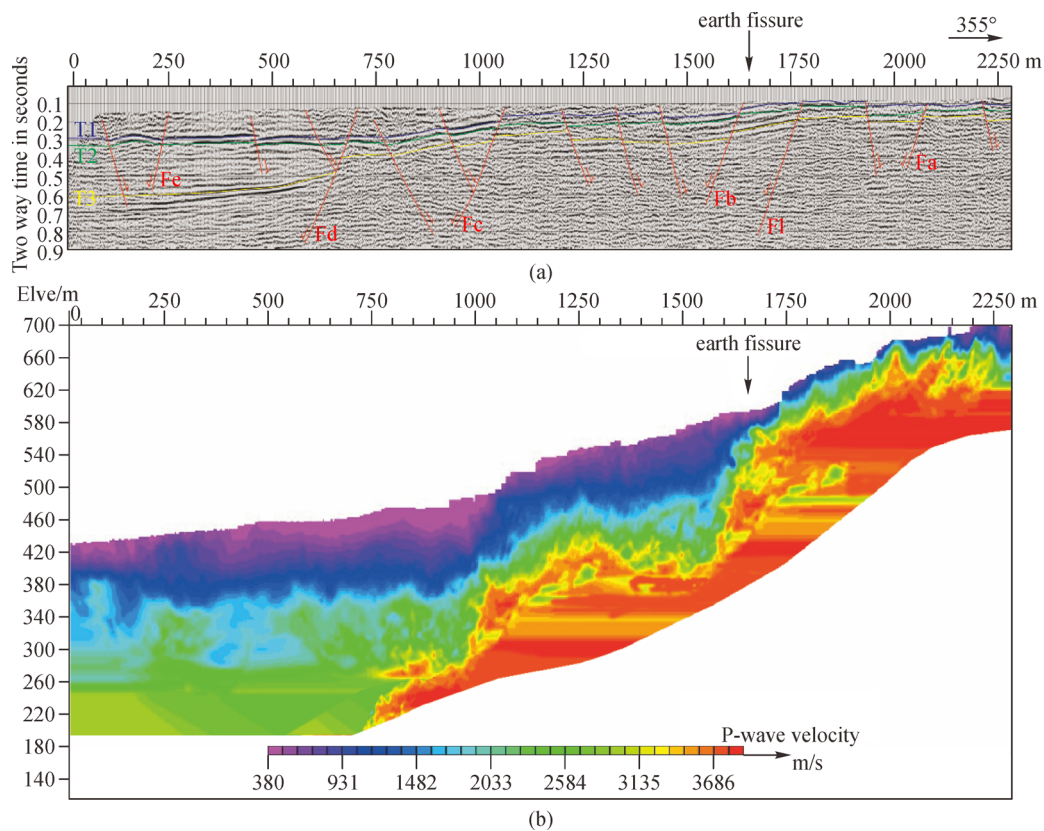


Fig. 8 Results of geophysical survey GS2 across Liangjia Village earth fissure. (a) Seismic reflection profile, (b) p-wave velocity distribution for the uppermost 300 m of the reflection profile; F1: Kouzhen–Guanshan fault; Fa–Fe: buried faults; T1–T3: CT velocity stratification interfaces.

earth fissure development. For example, many earth fissures in the Shanxi Graben System in Northern China coincide with active faults and act as the surface expression of fault movements (Li et al., 2000). Moreover, Bonini et al. (2015) used analog models to illustrate that master fault activity can create earth fissures with different relationships between a pre-existing discontinuity and a master fault. Comparison of the geological profiles revealed by the trenching, drilling, and geophysical surveys conducted in this work reveals that the profiles of the earth fissure and the active fault are highly associated. The Liangjia Village earth fissure is consistent with the inclination of the buried fault (both incline southward), indicating that the fissure inherited its basic characteristics from fault activity. The results from the geophysical surveys show that many buried active faults developed on the upper wall of the KGF. Using the dislocation of the terrace along the KGF, Mi et al. (1993) calculated that the active rate of the KGF was 0.17–0.67 mm/a after the late Pleistocene. Based on geodetic levelling data, Mi et al. (1993) further calculated that the active rate at that time was 0.75 mm/a. These results indicate that the formation of the Liangjia Village earth fissure was significantly affected by activity along the KGF.

The geophysical results from this work revealed that many buried faults exist on both sides of the KGF. The Liangjia Village fissure developed on the upper wall of the KGF and is connected with the buried active fault Fb. The trenching and geological cross-section profiles both showed that the vertical offset of the Liangjia Village earth fissure gradually increased with depth, demonstrating the characteristics of a syn-sedimentary fault. The geological cross-section also indicated that the vertical offset of Fb was 100 cm in the second palaeosol (S_1) layer and 10 cm in the first palaeosol (S_0) layer. In addition, another buried active fault was detected under the third palaeosol (S_2) layer. Thus, we speculate that these buried faults are all secondary faults of the KGF and older than the Holocene, and that they are connected to the KGF at depth. That is, the activity of these buried faults is controlled by the KGF. Therefore, development of the Liangjia Village earth fissure is controlled by the buried active fault Fb, and its development is dependent on the KGF.

5.3 Effects of loess erosion and groundwater runoff

Trenching results revealed that the strata, from the top downwards, were silt, palaeosol (S_0), Malan loess (L_1), silty clay, sandy gravel, palaeosol (S_1), and Lishi loess

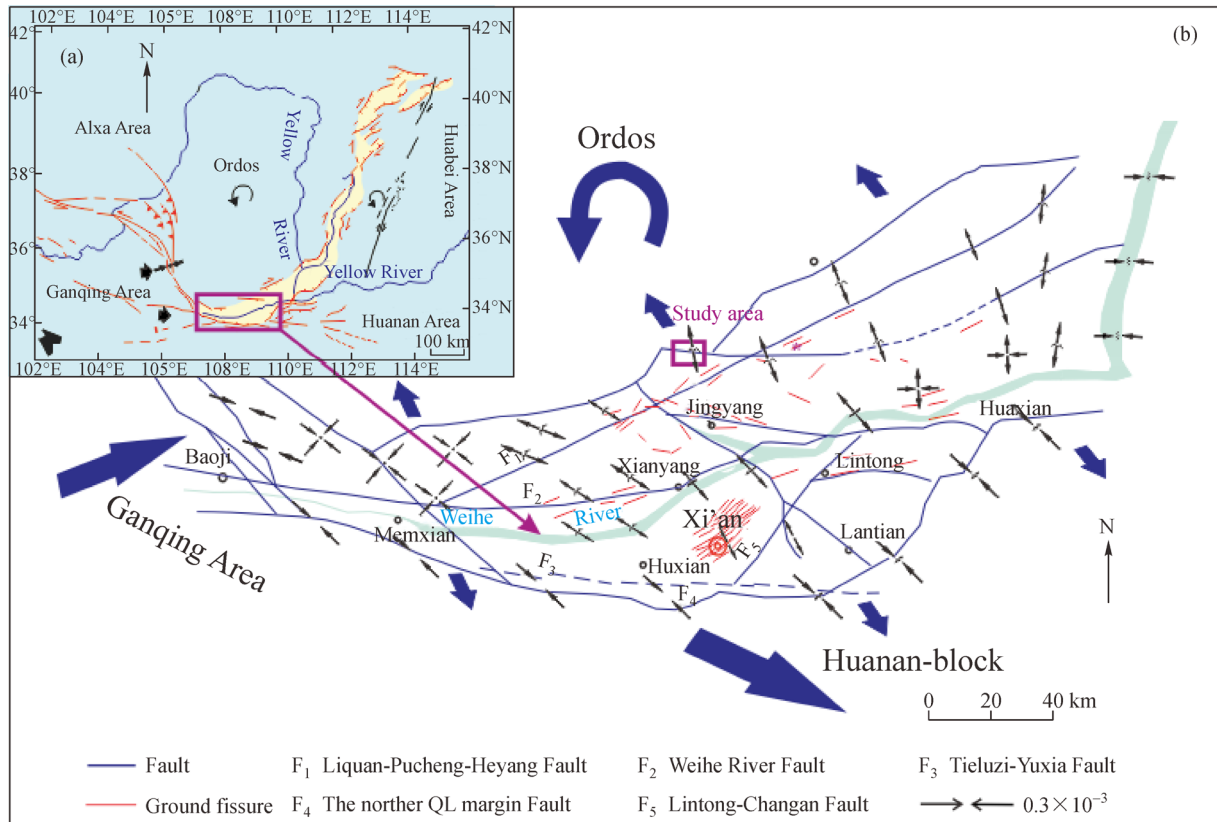


Fig. 9 Relationship between regional stress and fault activities in the Weihe Basin (Peng et al., 2018).

(L_2). It is well understood that loess is widely distributed on the hanging wall of the KGF. Loess has many special characteristics, such as fine particle size, macropores, and a weak tensile strength prone to collapse (Li et al., 2000; Sun et al., 2009). Field investigations found that many sinkholes and gullies have developed along the Liangjia Village earth fissure. Furthermore, overland flows are able to stand for extended periods on the hanging wall of the KGF after anomalous heavy rainfalls, and the preexisting earth fissure provides a preferred pathway for infiltration. The trenching results showed that some cavities have developed in the Liangjia Village earth fissure (Fig. 5). Analysis of these results suggests that the scouring of surface water and erosion caused by infiltration have caused earth fissures in the area to expand into gullies or sinkholes (Fig. 10(c)).

Moreover, because of differences in elevation, the groundwater surface gradually slopes away from the mountains toward the basins. Thus, it is inferred that the groundwater flows from the mountains to the Jing River. The exploitation of groundwater may promote groundwater runoff. This process can generate a seepage force in the underlying aquifer systems and produce either vertical differential compaction or cumulative horizontal deformation that can enlarge the earth fissures. In particular, surface water infiltration from existing earth fissures after a heavy

rainfall will strengthen groundwater runoff. In conclusion, loess erosion and groundwater runoff are major factors contributing to the expansion of earth fissures in this region.

6 Conclusions

Earth fissures are a severe geo-hazard in the Weihe Basin of China. Based on field investigations along the KGF and geotechnical and geophysical surveys of the Liangjia Village earth fissure, the following conclusions can be drawn:

- 1) The Liangjia Village earth fissure developed on the hanging wall of the Kouzhen–Guanshan fault in 1958 after a heavy rainfall, with a length of 160 m and an EW strike.
- 2) The Liangjia Village earth fissure is connected to a buried syn-sedimentary fault, which suggests that the activity of the ground fissure is sustainable.
- 3) An active fault, earthquakes, and loess erosion are the three factors that have contributed to the formation of the Liangjia Village earth fissure. An earthquake created the fissure, the active fault has controlled the fissure's development, and loess erosion continues to enlarge the modern fissure.

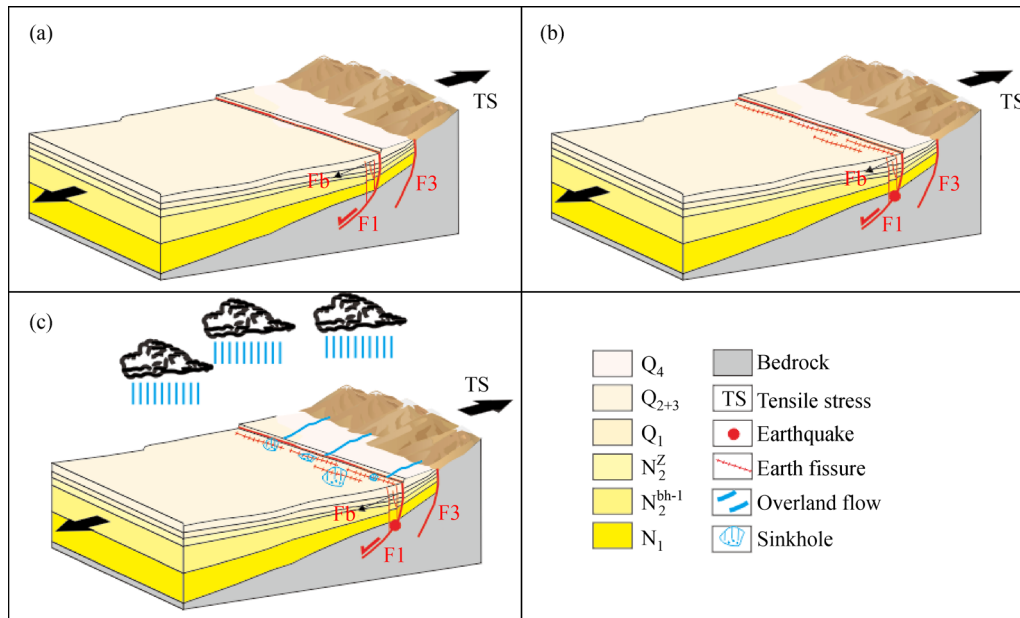


Fig. 10 Processes of Liangjia Village earth fissure (revised from Peng et al., 2016b). F1: Kouzhen–Guanshan fault; F3: Qishan–Qianxian fault; Fb: buried fault.

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