

Characteristics and Formation Analysis of Earth Fissure in Anren Area in Wei River Basin, China

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ABSTRACT: Since the 1950's, 212 earth fissures have been discovered in the Wei River Basin. During a field survey in 2016, an additional 48 earth fissures were discovered in Anren area, north-east of the Wei River Basin. The characteristics and formation mechanisms of these fissures were studied through field investigations, measurements, trench excavation, and drilling. On-site investigations indicated that these earth fissures were distributed along a fault-controlled geomorphic boundary. Fissures trended at 60°–80° NE and were divided into five groups. Trenches revealed multiple secondary fissures, exposing severe soil ruptures in the shallow earth surfaces. Drilling profiles revealed that earth fissures dislocated several strata, and resembled synsedimentary faults. Seismic reflection profiles revealed buried faults beneath the earth fissures. The Anren area fissures formed in the following three stages: regional extension that initially generated multiple buried faults; seismic activity rupturing multiple strata, resulting in multiple buried fractures; and finally, erosion processes that propagated the buried fractures to the surface, forming the current earth fissures.

KEY WORDS: Wei River Basin, earth fissure, buried fault, earthquake, erosion.

0 INTRODUCTION

Earth fissures are common geological hazards developed by rupturing rock or soil at the earth's surface due to natural events or human activities. They are long, near-vertical cracks, and tensile structures on shallow surfaces, with or without vertical offsets (Qiao et al., 2017; Hernandez-Marin and Burbey, 2010). They can be visible as cracks, collapsing sinkholes, gullies, or scarps on the land surface (Qiao et al., 2018; Wang et al., 2009). The difference in the vertical deformation and horizontal tension across the two sides of an earth fissure can lead to serious environmental issues and major financial losses, including damage to farmlands, roads, buildings, piping, tunnels, and other urban infrastructure (Pacheco-Martínez et al., 2013; Wu et al., 2004).

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Earth fissures have been documented at various places worldwide, especially in the southwestern United States (Holzer and Galloway, 2005; Pampeyan et al., 1988), the North China plains, the Fenwei Basin and the Yangtze delta in China (Wang et al., 2016; Ye et al., 2016), the Middle East (Mohseni et al., 2017; Youssef et al., 2014), Mexico (Brunori et al., 2015), and Ethiopia (Williams et al., 2004). The most serious earth fissure hazards in China have appeared in the Fen-Wei Basin, including the Datong Basin, Taiyuan Basin, Linfen Basin, Yuncheng Basin, and Wei River Basin, which have caused financial losses amounting to RMB 3.62 billion (Peng et al., 2020a). In total, 612 earth fissures have been found in 58 cities in the Fenwei Basin since the early 1950's; the lengths of 207 of these earth fissures exceed 1 km (Peng et al., 2017, 2007). The 14 earth fissures in Xi'an, covering an area of more than 270 km² and extending more than 170 km in length, have caused particularly serious financial losses (Peng et al., 2016a).

Earth fissures have complex formation mechanisms in which various factors play crucial roles, including land subsidence, resulting from groundwater withdrawal, developing because of differential settlements, horizontal

seepage forces, tensile stresses, horizontal deformations, rotating slabs, or shear stresses (Zhang et al., 2016; Budhu, 2011; Wang et al., 2009; Sheng et al., 2003; Burbey, 2002; El Baruni, 1994; Jachens and Holzer, 1982); underground coal mining, inducing and developing fissures by horizontal tension deformation (Xu et al., 2019a; Li et al., 2017; Liu et al., 2015); heavy rainfall, resulting in near-surface processes such as piping and hydrocompaction along the water line sources (Peng et al., 2018b; Ayalew et al., 2004); earthquakes, in which case the fissures can be seismic precursors or residual deformations after an earthquake (Peng et al., 2016b; Sarkar, 2004); buried faults, which can create fissures via large-scale tectonic activity or creeping of deep faults (Peng et al., 2018a; Lee et al., 1996; Withjack et al., 1995); and crustal extension, where regional tensile stresses can form or aggravate fissures (Xu et al., 2015; Williams et al., 2004). Researchers have generally agreed that earth fissures result from multifactor coupling (Wang et al., 2019; Xu et al., 2019b; Peng et al., 2016c), with tectonic activity, groundwater pumping, and heavy rainfall considered as the three primary factors. Additionally, extensional environments in basins can provide favorable conditions for the formation of earth fissures.

Since the 1950's, hundreds of earth fissures have formed in the Wei River Basin (Peng et al., 2016a). Many experts and scholars have studied their development characteristics and causes. The fissures are controlled by fault structures within the basin and concentrated in hanging walls along the fault zones (Wang et al., 2022; Jia et al., 2022; Peng et al., 2016b). Some fissures are caused by active faults, while other factors, including rainfall, loess collapse, and tectonics, react and expand the earth fissures (Lu et al., 2019; Wang et al., 2019; Zang et al., 2019). During a field survey in 2016, 43 new earth fissures were identified in the Anren area, northeast of the Wei River Basin. This research used a series of geological investigations to study their basic characteristics and attempts to analyze the formation mechanisms of the earth fissures.

1 GEOLOGICAL SETTING

The Wei River Basin is located in the southern Fenwei Graben System. It is bound by the Qinling (QL) fold belt in the South, the Ganqing area in the west, the Ordos Plateau in the north, and the Shanxi Graben System in the northeast (Figure 1). Under the combined action of surrounding blocks, several faults developed in the basin and divided it into numerous subblocks (Liu et al., 2020; Quan, 2005).

To study the differences in the vertical movements of the subblocks, scholars have divided the basin into three parts: the Northern slope areas, the western uplift areas, and the southern depression areas (Liu and Zhou, 2015). According to structural and sedimentary characteristics, the northern slope area can be further divided into the Qianxian slope, the Pucheng-Fuping depression, and the Hancheng heave. The southern depression area can be

further divided into the Gushi depression, the Xianyang heave, the Xi'an depression, and the Li mountains. Earth fissures in the Wei River Basin are mainly found in the Gushi depression and the Xi'an depression (Figure 1).

The present study area is located in the Northeast Wei River Basin, at the boundary of the Hancheng heave and the Gushi depression (N34°50'–35°, E110°–110°15') (Figure 2). The Shuangquan-Linyi fault and the Hancheng-Huayin fault, which are active, form the northern and eastern boundaries, respectively, of the Gushi depression. The Gushi depression is the most active neotectonic movement area in the Wei River Basin. In addition, it is the area with the highest number of earth fissures. Over the past 1 000 years, two disastrous earthquakes with $M \geq 7$ have occurred in the Gushi depression (Du, 2016). The 1501 CE Chaoyi M7.0 earthquake in the Gushi depression, along the Chaoyi fault, caused many ground collapses and changed the course of the Luo River (Han et al., 2002). The 1556 CE M8.25 earthquake in the Gushi depression, along the Huashan piedmont fault, killed 830 000 people and affected an area of 280 000 km². The Huashan piedmont fault is a Holocene active fault with a current activity rate of approximately 2.7 mm/a (Ma, 2019).

2 DESCRIPTION OF EARTH FISSURES IN THE ANREN AREA

During a field survey in 2016, 48 earth fissures were found in the Anren area. According to their developmental positions, these earth fissures were divided into five groups: FG1, FG2, FG3, FG4, and FG5. As shown in Figure 3, all these earth fissures were located within 500 m of both sides of the geomorphic boundary, and their strikes were parallel to the geomorphic boundary.

FG1 was composed of six earth fissures located at the edge of the secondary depression on the second terrace of the Wei River (T_{w2}). With the length of each earth fissure in the range 0.1–1 km, the cumulative length of these six fissures was approximately 2.5 km. The largest horizontal displacement of these fissures was approximately 1.2 cm, and the vertical offset was inconspicuous. They destroyed a large number of buildings (Figure 3a). The trend of these earth fissures was in the range of NE60°–NE75°.

FG2 was composed of eight earth fissures developed along the internal scarps of T_{w2} . With the length of each earth fissure in the range 0.1–1.8 km, the cumulative length of these eight fissures was approximately 4.6 km. All these fissures displayed prominent horizontal separation only at the earth's surface. The largest horizontal displacement of these fissures was approximately 1.2 cm; however, after rainstorms or irrigation, the width significantly increased and formed a large number of sinks (Figure 3b). The trend of these earth fissures was in the range NE70°–NE75°.

FG3 was composed of 13 earth fissures located at the edge of the boundary between T_{w2} and the third ter-

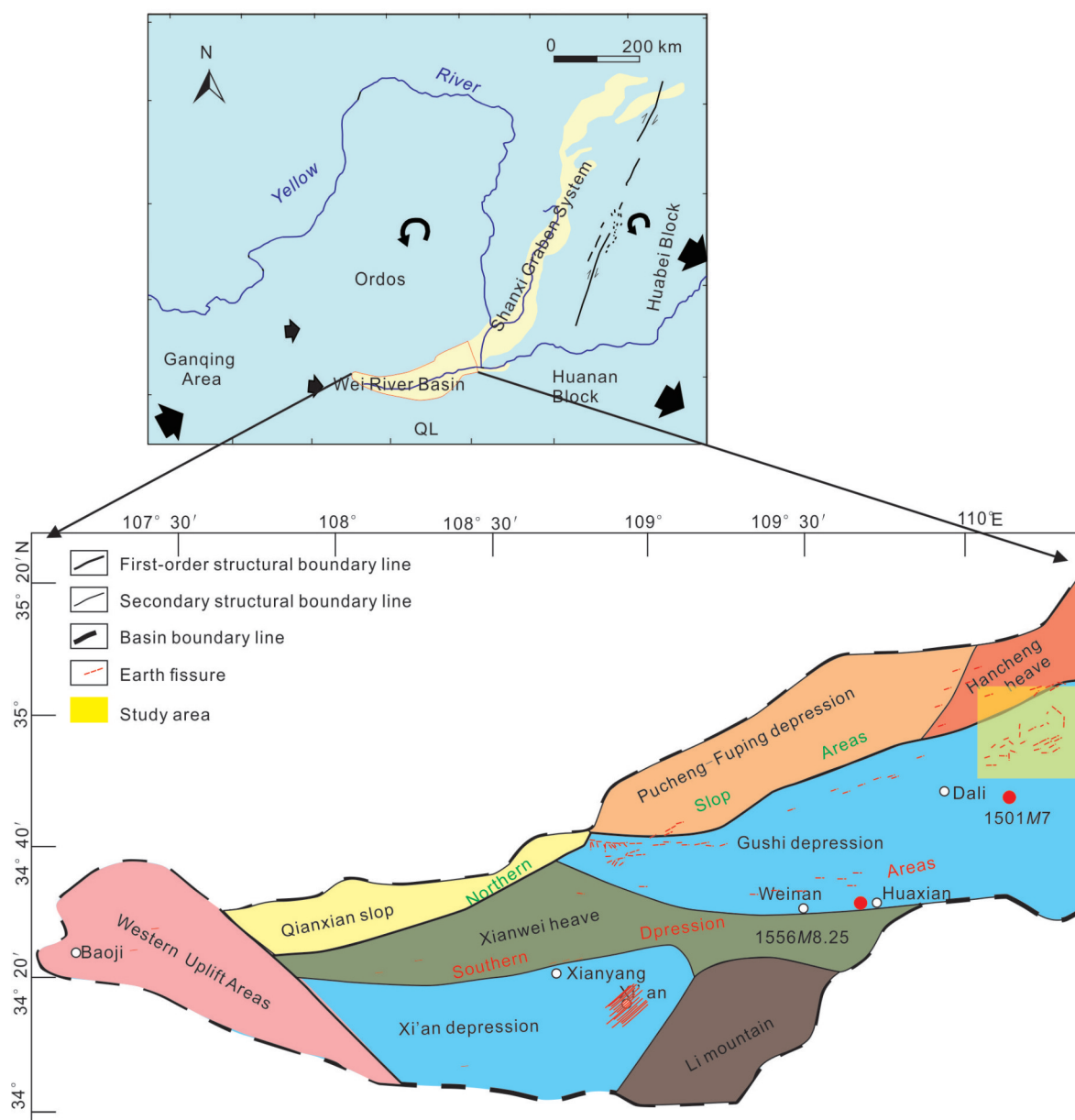


Figure 1. Regional setting of Wei River Basin and the location of study area.

race of Wei River (T_{w3}). With the length of each earth fissure in the range 0.1–2.4 km, the cumulative length of these nine fissures was 6.4 km. The longest earth fissure displayed both horizontal and vertical displacement; however, other earth fissures displayed only horizontal displacement. The largest vertical displacement was 1 cm, while the largest horizontal displacement was 1.2 cm. The width significantly increased and formed a large number of sinks after rainstorms or irrigation (Figure 3c). The orientation of these earth fissures was in the range NE 45°–NE 85°.

FG4 was composed of 13 earth fissures located at the edge of the boundary between T_{w3} and the secondary loess tableland. With the length of each earth fissure in the range 0.1–2.1 km, the cumulative length of these 13 earth fissures was 6.9 km. The longest earth fissure ex-

hibited both horizontal and vertical displacement; however, other earth fissures exhibited only horizontal displacement. The largest vertical displacement was 2 cm, and the largest horizontal displacement was 1.2 cm (Figure 3d). The trend of these earth fissures was in the range of NE 65°–NE 85°.

FG5 was composed of eight earth fissures located at the edge of the boundary between the primary and secondary loess tableland areas. In addition, they were all developed on the hanging wall of the Shuangquan-Linyi fault. With the length of each earth fissure in the range 0.1–0.8 km, the cumulative length was 7.0 km. Some earth fissures displayed both horizontal and vertical displacement; however, other earth fissures displayed only horizontal displacement. The largest vertical displacement was 5 cm, and the largest horizontal displacement

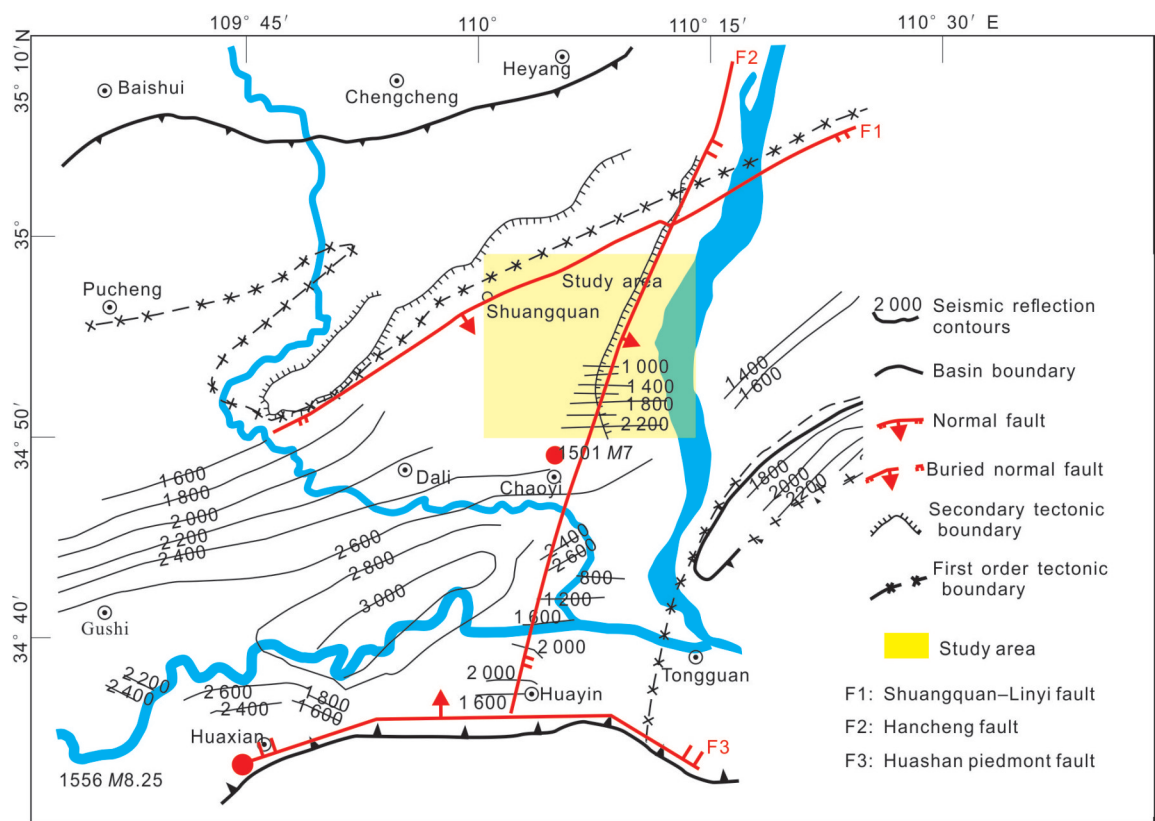


Figure 2. Geological setting of the study area.

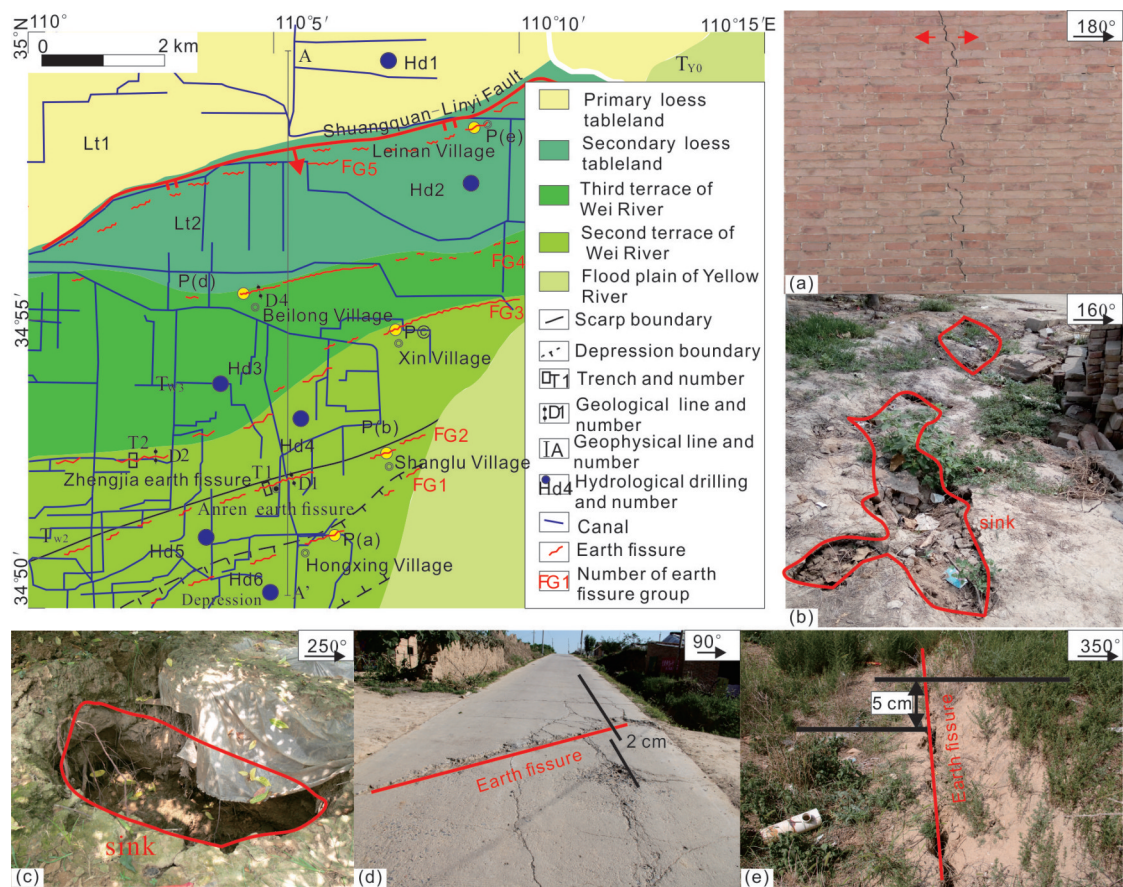


Figure 3. Distribution, picture of earth fissures, and layout of the exploration work in the study area. (a) earth fissure damage in a building in Hongxing Village; (b) earth fissure in Shanglu Village; (c) earth fissure in Xin village; (d) earth fissure in Beilong Village; (e) earth fissure in Leinan Village.

was 1.2 cm (Figure 3e). The trend of these fissures was in the range NE70°–NE85°.

Based on the results of the field surveys, the Anren earth fissure (one earth fissure within FG2) and the Zhengjia earth fissure (one earth fissure within FG3) were selected as the two cases for this study. The Anren earth fissure is developed on the south side of the internal scarps of T_{w2} . The strike of this fissure is NE 75°, and the length is 1.8 km, which is the longest of FG2. Zhengjia earth fissure is located at the boundary between T_{w2} and T_{w3} . The strike of this fissure is NE 85°, and the length is 2.1 km, which is the longest of FG3. In addition, these two earth fissures cause the most damage to infrastructure and farmland.

3 PROFILE CHARACTERISTICS

3.1 Trenching Exploration

The fissure activities induce the production of permanent deformation and rupture by the shallow strata. The excavation of trenches allows for the visual observation of the rupture characteristics in the earth fissures. Two trenches (T1 and T2) were perpendicular to the Anren earth fissure and the Zhengjia earth fissure, respectively (Figure 3).

Trench 1 was located in the courtyard of a closed factory in the north of Anren town and was 20 m long, 10 m wide, and 8 m deep (Figure 4a). Three strata were revealed in the descending order as Malan loess, clay, and

silty clay. However, only Malan loess was developed north of the main earth fissure (Figure 4). More than 18 earth fissures were disclosed in the trench with a 16 m rupture width. The main fissure was approximately vertical, exhibiting 5 cm width and 0 cm vertical displacement on the surface. However, the vertical displacement and the width increased to more than 240 and 104 cm, respectively, at the bottom of the Malan loess (at depth 5 m). Six secondary fissures were developed north of the main fissure, among which two fissures (f2 and f4) dislocated the clay layer. Their dislocations were 30 and 35 cm, respectively. In addition, the widths of the four earth fissures (f2, f3, f4, and f5) exceeded 10 cm. More than 12 fissures were developed south of the main fissure. The width of all these fissures were less than 1 cm, and their failure surface was rough (Figure 4b). Moreover, the fresh fissures filled the old fissures, indicating that the earth fissure activities in this area had multiple stages (Figure 4c). After the heavy rainfall, the moisture content of soil around the earth fissures and the stratum at the same depth was 23.6% and 13.6%, respectively (Figure 4d), which confirmed that the earth fissure was a seepage channel.

Trench 2 was located in a farmland in the eastern Zhengjia Village and was 20 m long, 12 m wide, and 11 m deep (Figure 5a). Three strata were revealed on both sides of the main earth fissure in a descending order as Malan loess, clay, and silty clay (Figure 5). More than 14

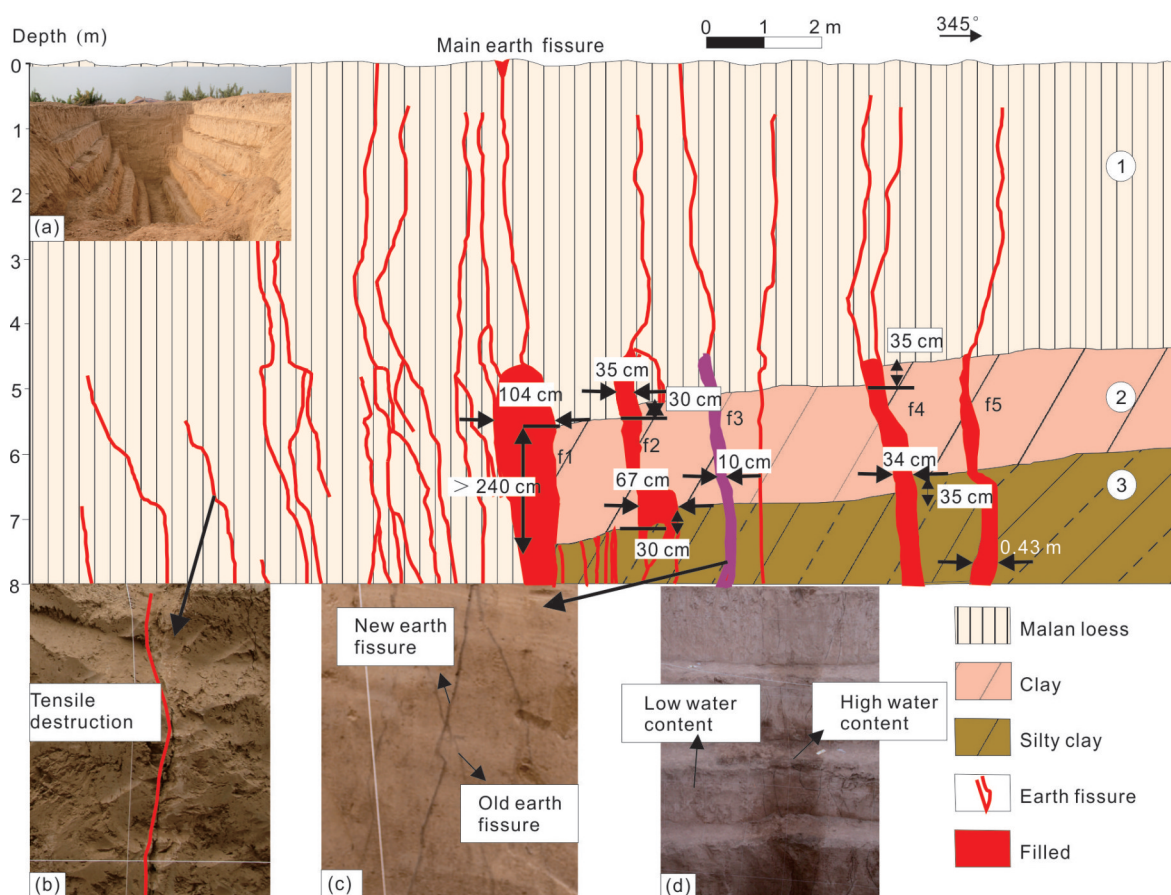


Figure 4. Profile of trench 1 across FG2. f1–f5, secondary fissures.

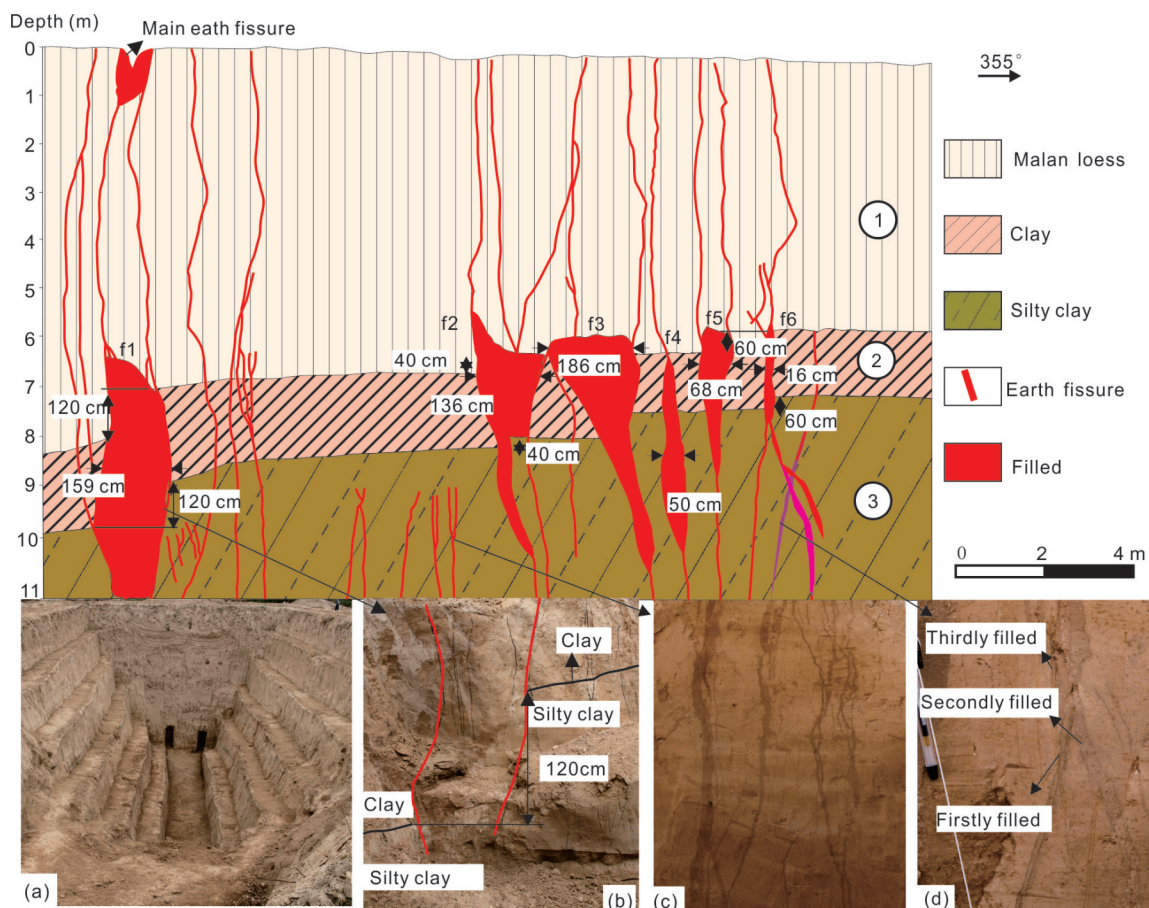


Figure 5. Profile of trench 2 across FG3. f1–f6, secondary fissures.

earth fissures were revealed in the trench with 18 m rupture width. The main fissure was approximately vertical, exhibiting 0 cm vertical displacement and 15 cm width on the surface. However, the vertical displacement and the width increased to 120 and 159 cm, respectively, at the bottom Malan loess (depth 8 m), as shown in Figure 5b. All the secondary fissures were developed north of the main fissure, among which two fissures (f2 and f6) dislocated the clay layer by 40 and 60 cm, respectively. In addition, the widths of the five earth fissures (f2, f3, f4, f5, and f6) exceeded 10 cm. The failure surface of these fissures was rough and had water flow traces (Figure 5c). Moreover, the fresh fissures had cut the old fissures, indicating that the earth fissure activities in this area had multiple stages (Figure 5d).

3.2 Drilling Exploration

The characteristic profile structure of an earth fissure at a depth range 0–50 m can be revealed by drilling. As shown in Figures 6 and 7, the two drilling profile lines, D1 and D2 (from Figure 3), were individually arranged across the fissure, parallel to the trenches T1 and T2, respectively. D1 was 65 m long and composed of seven boreholes. Eleven strata were revealed north of the fissure; however, only eight strata were revealed south of the fissure. The fissure had dislocated all these strata. The dislocations of the second, fourth, sixth, and eighth

strata were 4.3, 7.7, 10.4, and 14.7 m, respectively (Figure 6a). These results indicate that the Anren earth fissure dislocated all the strata and the dislocation increased with an increase in the depth. In addition, the fissure was revealed by zk4 to be at a depth of 17.1 m. The dip angle of the fissure was 84° , and the strata were silty clay and silt on both sides of the fissure (Figure 6b).

D2 was 50 m long and was composed of seven boreholes. Eight strata were revealed north of the fissure, while only seven strata were revealed south of the fissure. All the strata were dislocated by the fissure. The dislocations of the second, fourth, and sixth stratum were 1.5, 3.6, and 7.9 m, respectively (Figure 7a). These results indicate that all the strata were dislocated by the Zhengjia earth fissure and that the dislocation increased with an increase in the depth. In addition, the fissure was revealed by zk4 to be at a depth of 15 m. The dip angle of the fissure was 83° , and it was filled with gray silty clay (Figure 7b).

4 DISCUSSION

The formation and development of earth fissures is a complicated process involving both predisposing factors (regional tectonic regime and local tectonic structures including faults) and causative factors (groundwater exploitation and loess erosion). Peng et al. (2020a) proposed that an earth fissure is the result of the synergistic effects

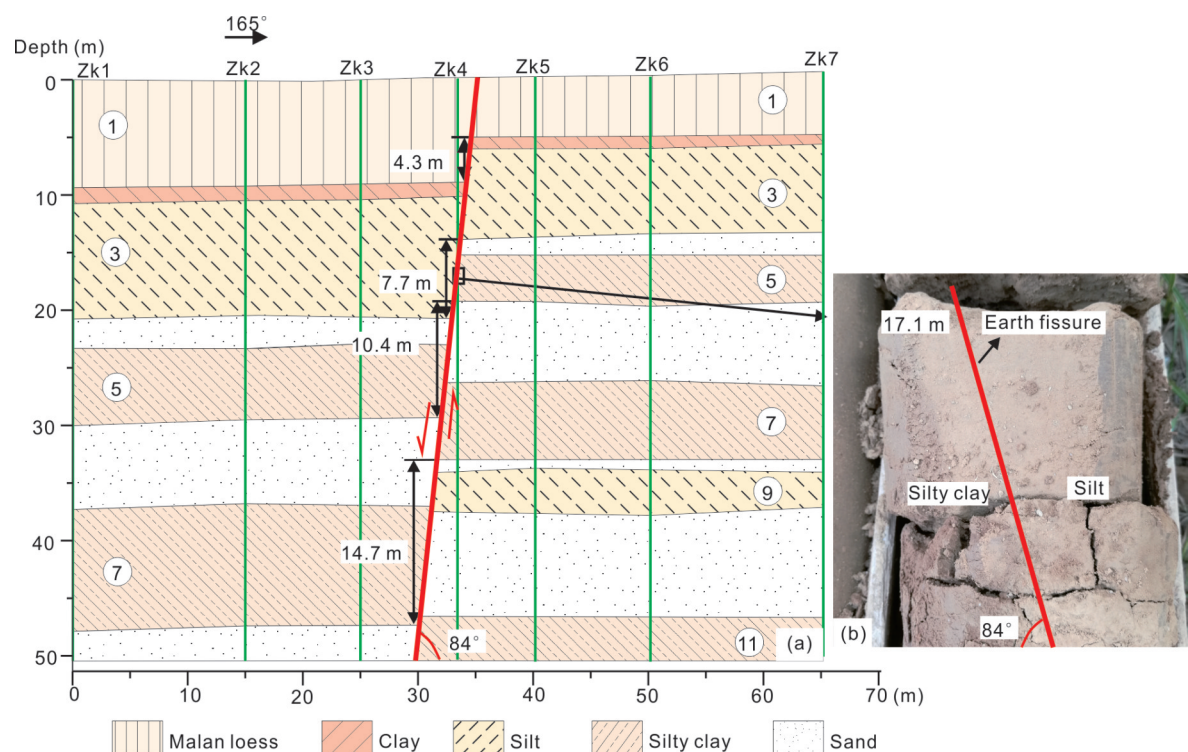


Figure 6. Profile of drilling line #1 across FG2 and soil anomalies revealed by drilling. (a) Engineering geological profile; (b) photo of soil anomalies.

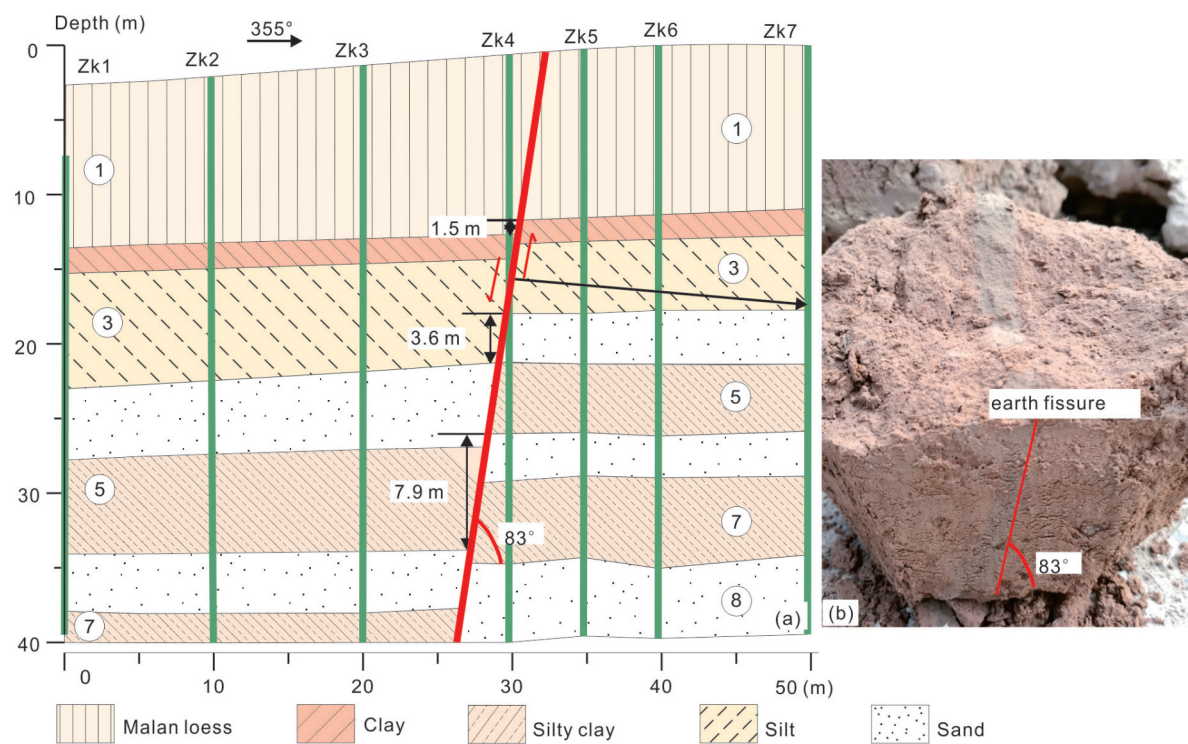


Figure 7. Profile of drilling line #2 across FG3 and soil anomalies revealed by drilling. (a) Engineering geological profile; (b) photo of soil anomalies.

of internal geological dynamic coupled with anthropomorphic stress.

4.1 Fissures Controlled by Fault

Other studies have shown that active faults are important to earth fissure formation and development. For instance, many earth fissures in Fenwei Basin cluster

along active fault zones and coincide with active faults (Peng et al., 2020b; Zhu et al., 2020). Moreover, Peng et al. (2008) found that the activity of normal faults was an important mechanism for the formation of earth fissures through physical simulation experiments. The study area was located in the northeastern Wei River Basin. Under the levorotation of the Ordos Block, the eastward extru-

sion of Gansu-Qinghai Block, and the stretching effect of the South China Block in the southeast direction, Wei River Basin had NNW-SSE extension (Qu et al., 2011) (Figure 8), which provided tensile stresses for the faults. The field investigation results showed that the strike of earth fissures in the Anren area ranged from NE45° to NE85°, which was approximately perpendicular to the direction of tectonic tension stress. Therefore, the NNW-SSE tensile stress is an internal geological dynamic mechanism of earth fissure in the Anren area.

By using the shallow seismic, Qiao et al. (2020) revealed that five buried faults are developed in the Anren area, all of which dislocate the quaternary bottom strata, and they are developed on the hanging wall of the Shuangquan-Linyi fault (Figure 9). These synsedimentary faults are connected with the geomorphic boundary or the scarp boundary; therefore, these faults are major factors for geomorphic scarp formation. Filed investigation results showed that five earth fissure groups were distributed along the geomorphic boundary or the scarp boundary. Hence, these five buried faults are major factor for the Anren earth fissure formation. Combining this seismic result and the hydrogeological boreholes of different geomorphic units, the engineering geological sections of the study area were drawn, as shown in Figure 10. The results showed that five buried faults developed along the margin of geomorphic boundaries or the scarp boundary. The quaternary strata were dislocated to different extents by these buried faults. The fault displacement increased with an increasing depth. These buried faults belonged to the category of synsedimentary faults. Trench and drilling results revealed that earth fissures dislocated the shallow strata and posse the characteristics of synsedimentary faults. Therefore, five earth fissure groups in the Anren area are connected with buried

faults; the developed location and formation of these earth fissures are controlled by the buried faults.

4.2 Fissures Formed by Earthquake

Earthquakes strengthen the activity of pre-existing earth fissures and form new earth fissures (Sarkar, 2004). The study area has long been in a state of tension, which promotes the formation of buried faults and the occurrence of multiple earthquakes (Liu et al., 2022; Peng et al., 2016a). These earthquakes caused the rupture of surface soil and resulted in a large number of earth fissures. For example, the 1556 CE Huaxian M8.25 earthquake and the 1501 CE Chaoyi Earthquake in the south of the study area led to surface soil fracture and formed many surface scarps (Li et al, 2018; Du, 2016). The study area is located in Intensity 9 of the Chaoyi Earthquake and Intensity 10 of the Huaxian Earthquake (Figure 11).

On comparing Figure 3 and Figure 10, it was observed that the strikes of the Anren earth fissure groups were approximately parallel to the seismic intensity contour. In addition, trench results revealed that the strata on both sides of earth fissures were seriously fractured and developed many secondary fissures. The failure surface of these fissures was rough, indicating the characteristics of tensile failure (Figure 4 and Figure 5). Hence, the tensile stress on the surface resulting from earthquake is a crucial factor for the formation of these earth fissures.

4.3 Fissures Developed by Erosion

Seven sets of samples from trench 1 and six sets of samples from trench 2 were collected to measure the physical properties and the self-weight collapsibility coefficient of Malan loess. The self-weight collapsibility coefficient of Malan loess was calculated using Eq. (1).

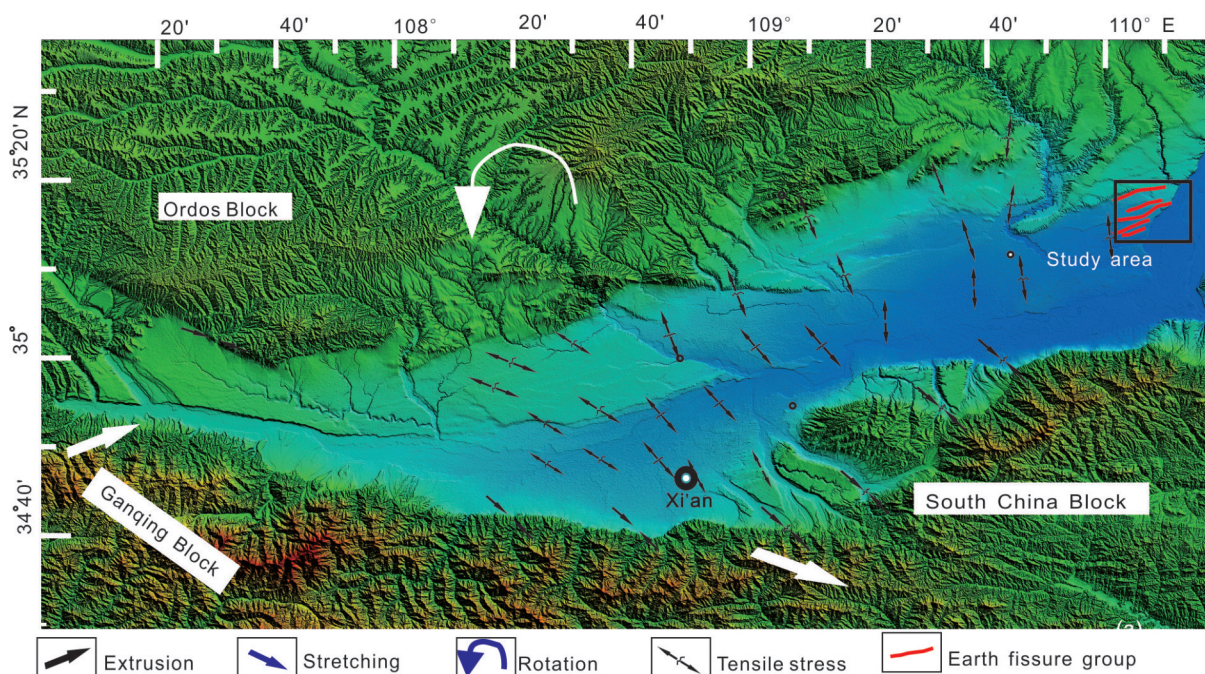


Figure 8. Crustal tectonic stress vector map of the Wei River Basin.

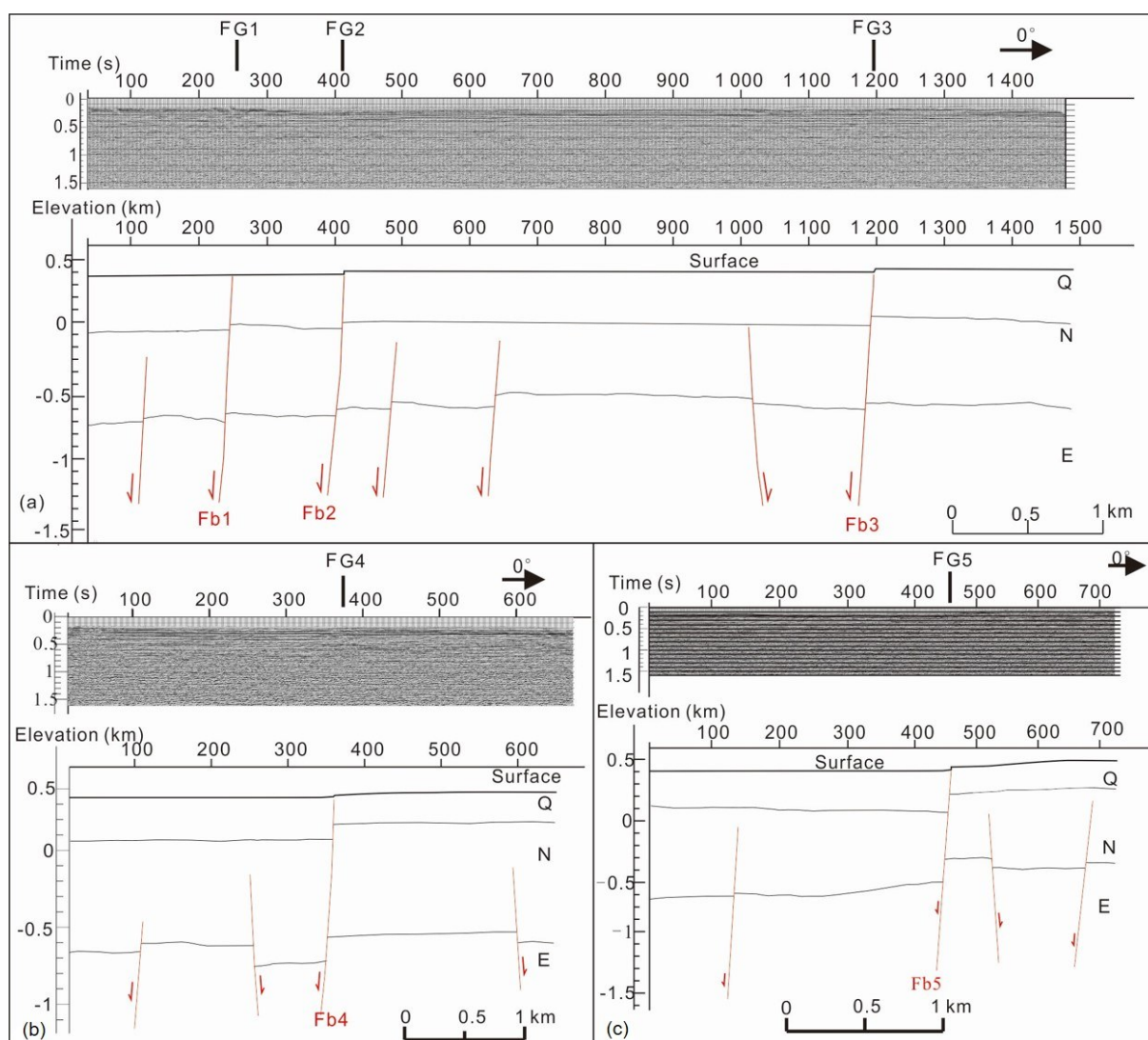


Figure 9. Seismic profiles of Anren earth fissures (revised from Qiao et al., 2020).

$$\delta_{zs} = \frac{h_z - h_z'}{h_0} \quad (1)$$

where δ_{zs} is the self-weight collapsibility coefficient of the loess, h_z is the stabilized sample height after the sample was loaded to its self-weight, h_z' is the stabilized sample height when it was saturated after the sample was loaded to its self-weight, and h_0 is the original sample height.

The test results are presented in Table 1 and Table 2. According to the Code for Building Construction in Collapsible Loess Regions, Malan loess distributed in earth fissure area is considered self-weight collapse loess and is easily eroded. In addition, two samples of filler in earth fissures from trench 1 and trench 2 were collected to measure the organic matter content. The results showed that the organic matter content of fissure filler in trench 1 and trench 2 were 11.3% and 12.5%, respectively. Therefore, the dark colored filler in the fissure contained organic matter.

During the field investigations, it was found that the width of the earth fissures increased and then generated

gully lines or sinkholes on the surface after anomalous heavy rainfalls or irrigation (Figures 3b and 3c). The canals in the study area are vertically and horizontally distributed (Figure 3). Since 2000, to ensure agricultural production, the annual flood irrigation has exceeded 650 m³/mu. The filler in the fissure featured water flow traces (Figure 5c), which further demonstrated the hidden fissures are the dominant seepage channel. After anomalous heavy rainfalls or irrigation, the surface water flows downwards through the dominant seepage channel (hidden fissures), thus eroding the Malan loess at surface and then expanding earth fissures. Hence, the erosion process resulting from overland flow is also an important factor for the development of earth fissures.

5 CONCLUSIONS AND RECOMMENDATIONS

Based on the above analysis, it can be concluded that there three main factors including in fault, earthquake and erosion, cause these 48 earth fissures formation and development. The tectonic structure in the Wei River Basin inherited the materials that up-welled from

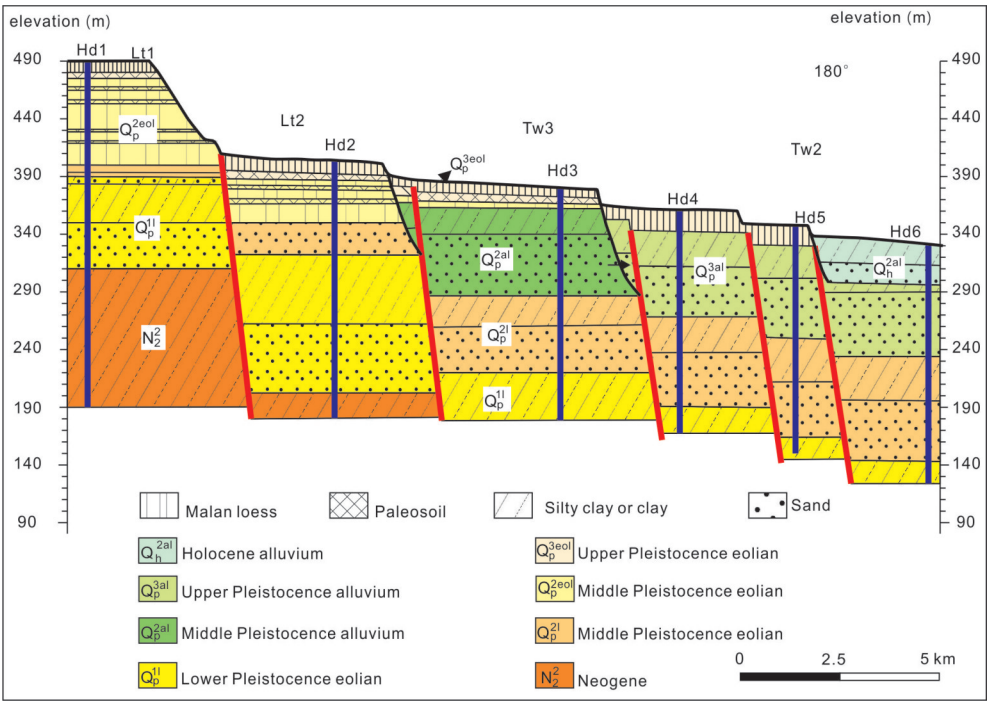


Figure 10. Geological cross section of earth fissures in Anren.

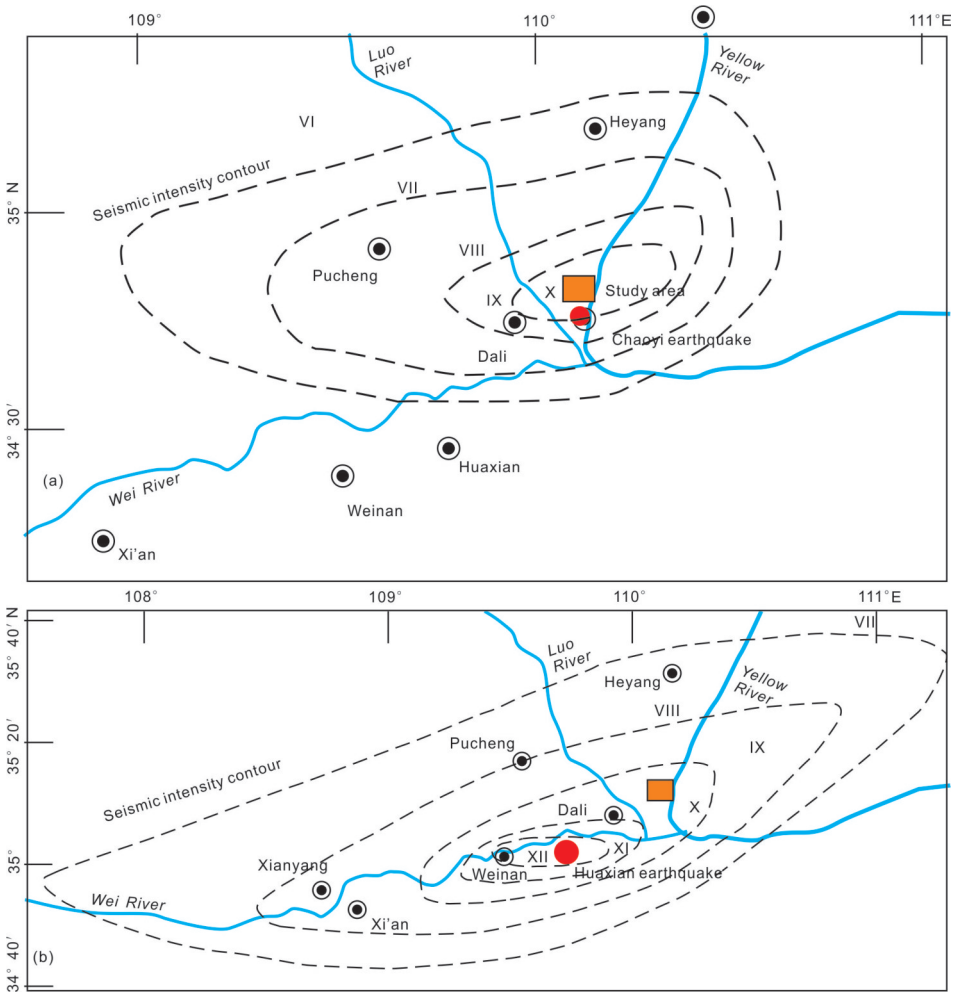


Figure 11. Seismic intensity contour of earthquakes. (a) Seismic intensity contour of 1501 Chaoyi Earthquake; (b) seismic intensity contour of 1556 Huaxian Earthquake.

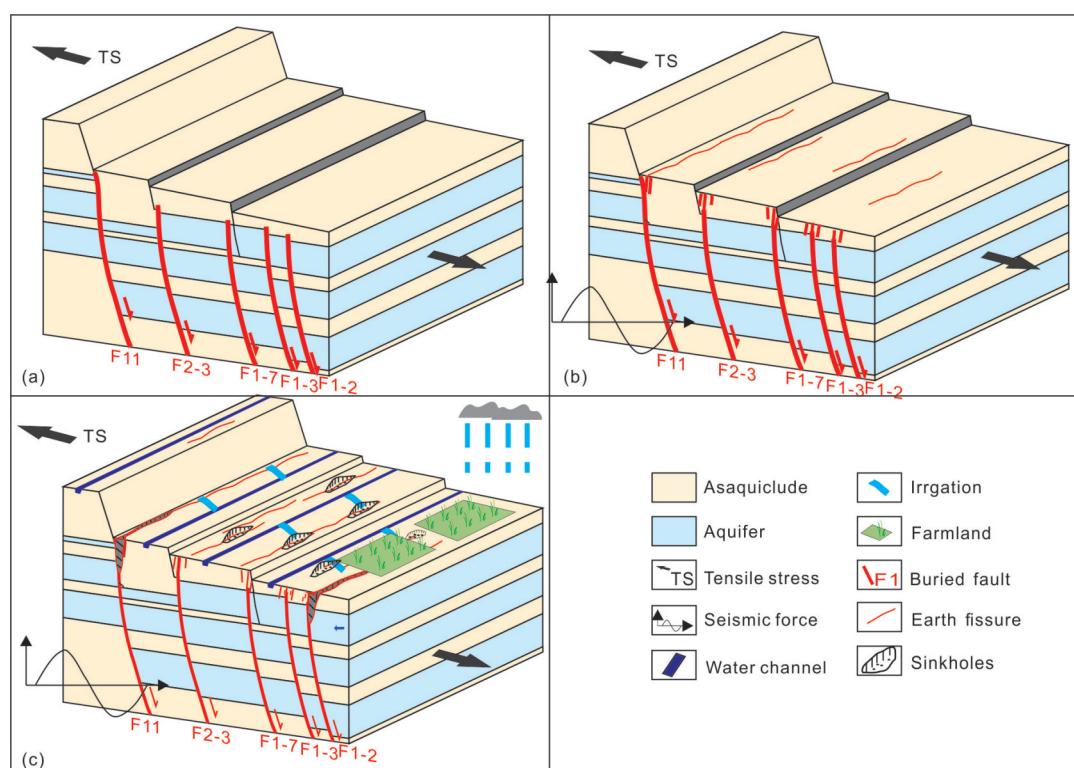


Figure 12. Earth fissure formation process in the Anren area.

Table 1 Physical and self-weight collapsibility coefficient of Malan loess in trench 1

Depth (m)	Water content (%)	Dry density (g/cm ³)	Void ratio	δ_{zs}
1	13.7	1.35	1.007	0.025
2	10.3	1.26	1.145	0.033
3	11.1	1.24	1.188	0.043
4	13.6	1.22	1.218	0.030
5	12.7	1.28	1.118	0.040
6	13.5	1.30	1.092	0.024
7	13.8	1.26	1.151	0.022

the upper mantle and intruded into the crust bottom since the Cretaceous Period. These activities led to many buried faults, and they are the “prototypes” of earth fissures (Figure 12a). The historical earthquakes induced the buried faults to expand upward and rupture the upper stratum, thereby promoting the formation of earth fissures in the approximately buried faults (Figure 12b). The erosion process resulting from heavy rainfall and irrigation aggravated the expansion of ground fissures in the superficial layers (Figure 12c).

These results show that the seepage force resulting from the erosion process expands the fissures and generates the current earth fissures. Hence, we recommend taking some measures, such as waterproofing or reducing overland runoff, to prevent or mitigate the problems of earth fissures. Modern irrigation methods, e.g., micro-irrigation and trickle irrigation, are used to replace the traditional irrigation methods in the area of earth fissures.

Table 2 Physical and self-weight collapsibility coefficient of Malan loess in trench 2

Depth (m)	Water content (%)	Dry density (g/cm ³)	Void ratio	δ_{zs}
1	11.2	1.38	0.957	0.043
2	7.7	1.38	0.959	0.030
3	9.6	1.37	0.980	0.037
4	13.1	1.34	1.016	0.021
5	10.0	1.35	1.001	0.027
6	13.7	1.35	1.014	0.022

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Conflict of Interest

The authors declare that they have no conflict of interest.

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