



# Development characteristics and mechanisms of the Taigu–Qixian earth fissure group in the Taiyuan basin, China

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## Abstract

Since the 1980s, increasing human activity and continuing over-exploitation of groundwater resources have caused the earth fissures in the rift basin in Shanxi, China, to enter an active phase. Buildings along these earth fissures have been seriously damaged. Four massive earth fissures that developed in the Taigu and Qixian areas of the eastern Taiyuan basin endanger the operational safety of the high-speed railway that passes through this region. Using field observations, measurements, and exploration, we determined that the four earth fissures are parallel to each other, have a northeast trend, and are separated by approximately equal distances. The rupture zones of these earth fissures are generally 10–50 m wide and are formed by the main fissures and secondary fissures. The width of the zone affected by the earth fissures is 20–50 m based on deformation and the damage done to buildings. These fissures formed on the Earth's surface; their hanging walls are lower than their foot walls, forming normal faults; and the ground surface around the fissures exhibits ridges and depressions. The fissures are connected to deep hidden faults. The fault displacement increases with increasing depth, which is characteristic of syn-sedimentary faults. These earth fissures are characterized by vertical displacement, and their average annual activity rate is 1–3 cm. We believe that the formation of this large-scale fissure group may be related to the tectonic structure of the hidden faults in the basin and may also be affected by the continuous regional extensional stress of the basin. The current increased level of activity could be caused by the over-exploitation of groundwater in the area.

**Keywords** Earth fissures · Active faults · Groundwater · Formation mechanism

## Introduction

Earth fissures are ruptures that develop in the earth's surface and in basins in Quaternary strata. Their formation and development are controlled and restricted by several complex factors. Since the twentieth century, the over-exploitation of natural resources by humans combined with new tectonic activity has resulted in the continuous deterioration of the global geologic environment. Many countries around the world have experienced disasters related to earth fissures caused by different factors, such as in the

southwestern United States (Holzer 1984), the Middle East (Baruni 1994; Bankher and Al-Harhi 1999), Ethiopia (Asfaw 1998; Ayalew et al. 2004; Williams et al. 2004), and Mexico (Rojas et al. 2002). The earth fissure disasters in the Fenwei basin (Jiang et al. 1997; Peng et al. 2007), the North China Plain (Wang et al. 2001; Wu and Chen 2003), and the Suzhou–Wuxi–Changzhou area (Liu et al. 2004) in China have also caused severe damage. These earth fissures have caused severe damage to railways, highways, airports, buildings, and underground pipelines. With respect to the causes of earth fissures, there are three different views, i.e., the single factor “constructive cause” (Leonard 1929; Savage and Hastie 1966; Holdahl 1986; Liu 1986; Wang 1989; Li 1994; Kreitler 2006) and “groundwater exploitation cause” views (Fletcher et al. 1954; Bouwer 1977; Narasimhan 1979; Yi 1984), and the current “comprehensive cause” view (Holzer 1980; Holzer et al. 1979; Pampeyan et al. 1988; Peng et al. 2007, 2016a, b).

In the 1970s, fractures of different sizes appeared successively in the Datong, Taiyuan, Linfen, Yuncheng, and

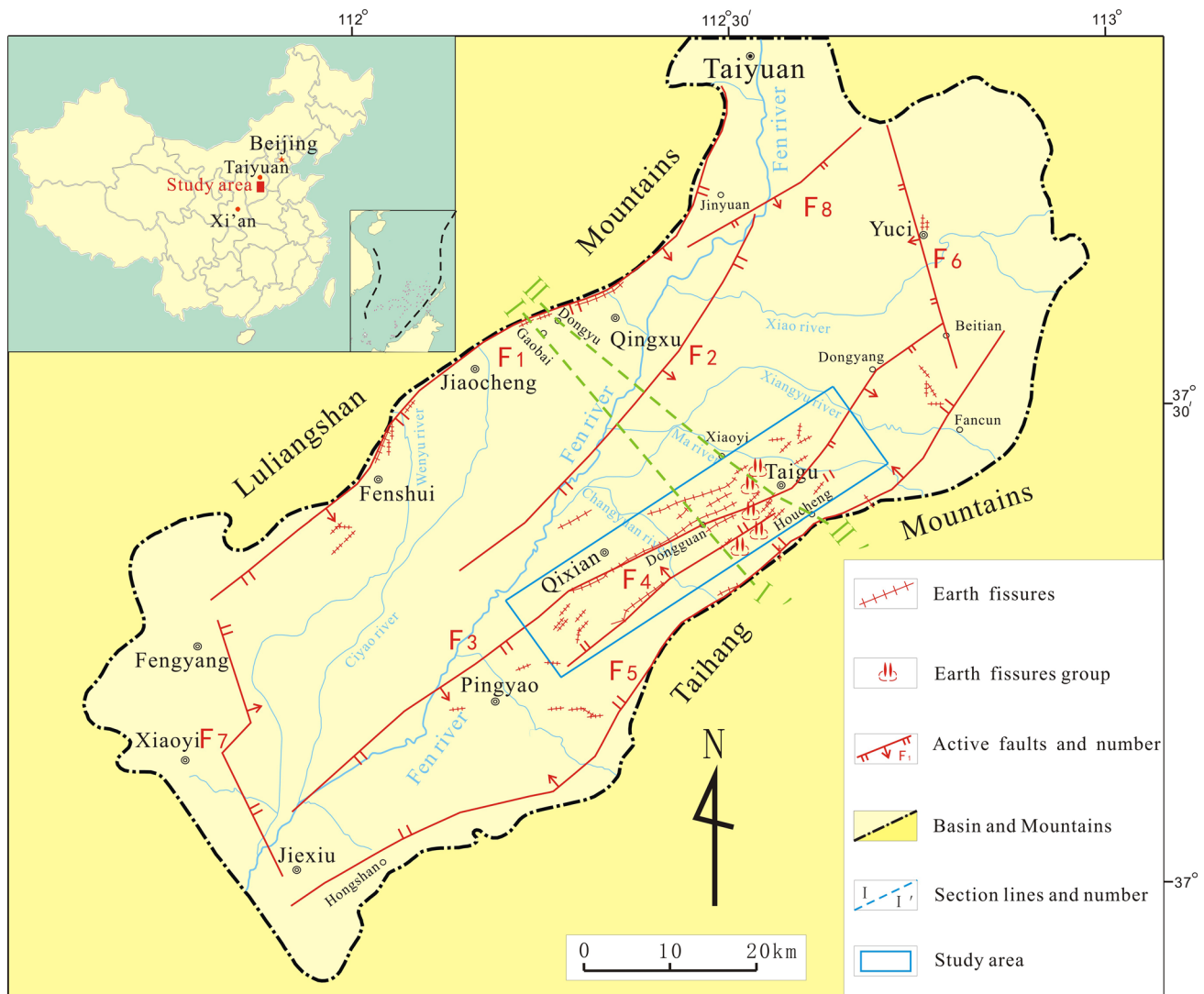
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Weihe basins in the Fenwei fault depression. According to field investigations and analyses, there are a total of 107 fractures in the Taiyuan basin (see Fig. 1). In particular, in the Taigu–Qixian area in the southeastern part of the Taiyuan basin, 51 fractures of different sizes appeared en masse, accounting for 47.7% of the total number of earth fissures in the basin. They mainly have northeast trends, and they are several hundreds of meters to several kilometers in length, with the longest being more than 20 km long. Since the 1980s, fissure activity in the Taigu–Qixian area has intensified, resulting in massive property damage and economic loss. Obviously, the single-factor “constructive cause” and “groundwater exploitation cause” views cannot explain the earth fissures in the Shanxi fault zone. Therefore, many scholars have conducted comprehensive studies on the earth fissures in the Shanxi rift basin. Jiang et al.

(1997) concluded that the fractures in the Shanxi rift basins were formed by enhanced tectonic activity and believed that the overuse of groundwater played an important role in the development of earth fissures. Li et al. (1998, 2000) concluded that fissures in the soil formed due to basement fault activity and ancient earthquake vibrations in the Shanxi rift basin, which evolved into earth fissures due to groundwater erosion. Wu et al. (2001, 2003) analyzed the tectonic dynamics of the formation of earth fissures in the Shanxi rift basin, their formation mechanism, and the relationship between groundwater exploitation and the formation of earth fissures. Wang et al. (2005) analyzed the relationship between the Qixian earth fissures and tectonics, faults, hydrogeology, and lithology. Although the above-mentioned scholars analyzed the comprehensive causes of earth fissures in the Shanxi rift fault zone from a macroscopic point of view, there is



**Fig. 1** The distribution of earth fissures and the main active faults in the Taiyuan basin: F<sub>1</sub>, Jiaocheng fault; F<sub>2</sub>, Longjiaying fault; F<sub>3</sub>, Qixian fault; F<sub>4</sub>, Pingyao–Taigu fault; F<sub>5</sub>, Hongshan–Fancun fault; F<sub>6</sub>, Yuci–Beitian fault; F<sub>7</sub>, Sanquan fault; F<sub>8</sub>, Tianzhuang fault

still no clear explanation as to why large-scale earth fissures occurred en masse in the Taigu–Qixian area. The following questions need to be answered: what is the relationship between these earth fissures and the regional tectonic stress field and hidden faults? What role does groundwater play in the formation and development of earth fissures?

This paper attempts to study the planar distribution characteristics, profile characteristics, and activity characteristics of the Taigu–Qixian earth fissures through various forms of exploration to reveal the relationship between these fissures and the fracture structures, regional tectonic stress field, and groundwater exploitation. We will also discuss the mechanism by which the large group of earth fissures in Taigu–Qixian county formed.

## Geological background

The Taiyuan basin is a large rift basin in the Cenozoic rift basin zone of the land platform in Shanxi, and it is located between the platform and the Fenwei fault zone. The geomorphology of the Taiyuan basin is controlled by active faults. It is an oblique, long basin with an NE–SW trend. It is 105 km in length, 40 km width, and has an area of approximately 4000 km<sup>2</sup>. The basin is surrounded by hills and mountains. The eastern mountains are the Taihang mountains, and the western mountains are part of the Luliangshan mountains (Fig. 1).

### Active faults

The Taiyuan basin is active with respect to fault development, which not only controls the shape of the basin, but also controls the historic development of the basin (Fig. 1). The fracture zone of the Taiyuan basin is mainly composed of the Jiaocheng fracture ( $F_1$ ), the Hongshan–Fancun fracture ( $F_5$ ), the Yuci–Beitian fracture ( $F_6$ ), the Sanquan fracture ( $F_7$ ), and the Tianzhuang fracture ( $F_8$ ). Among these, the Jiaocheng fracture is the main fault on the western boundary of the Taiyuan basin. It generally trends NE: extending north from the mountains on the western edge of Taiyuan city, south through Jinyuan, Qingxu, Jiaocheng, and Wenshui, and terminates in Fenyang. It is a high-angle normal fault with a total length of approximately 130 km and an SE dip (Xie et al. 2008). The Hongshan–Fancun fault is the main fault on the eastern boundary of the Taiyuan basin. It is a high-angle normal fault with an NE (45°) trend, an NW dip, and it is approximately 100 km in length (Xie et al. 2004). The Yuci–Beitian fault is located on the northern boundary of the basin, has an NNW trend, an SWW dip, and is approximately 34 km in length (Chen et al. 2003). The Sanquan fault is the southwestern boundary fault of the Taiyuan basin. It has an NNW trend and an ENE dip (Wang

et al. 1996). The hidden faults in the Taiyuan basin include the Longjiaying fault ( $F_2$ ), the Qixian fault ( $F_3$ ), the Pingyao–Taigu fault ( $F_4$ ), and the Tianzhuang fault ( $F_8$ ). The Longjiaying fault is located in the middle of the Taiyuan basin. It is a hidden positive fault with an overall trend of 30°, an SE dip of 47°–75°, and has a total length of approximately 60 km. The Qixian fault is a hidden positive fault with an overall trend of 45°, an SE dip of 50°–60°, and is approximately 96 km in length. The Pingyao–Taigu fault has an overall trend of NE, an NW dip, and is approximately 40 km in length. The Tianzhuang fault is a hidden normal fault with an overall trend of NE, a southward dip, and a total length of approximately 35 km (Han et al. 2008). It can be seen from Fig. 1 that the Taigu–Qixian earth fissures are mainly distributed along the sides of two hidden faults: the Qixian fault and the Pingyao–Taigu fault, both of which occur in the hanging wall of the Hongshan–Fancun fault on the eastern boundary of the Taiyuan basin.

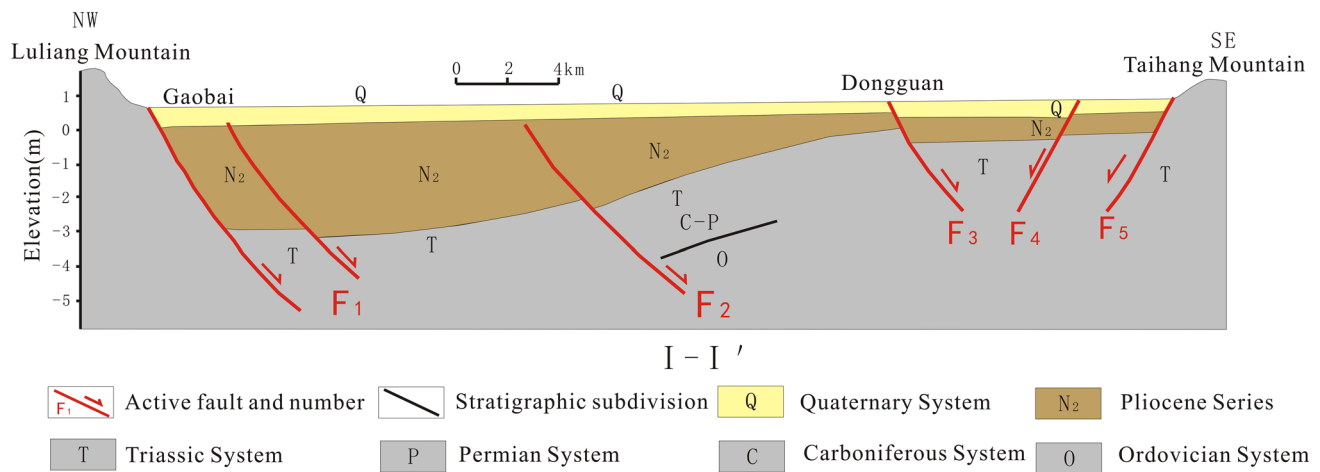
The NW–SE profile ( $I-I'$ ) across Taiyuan basin shows that the strata on both sides of the hidden faults have been significantly disrupted (Fig. 2), the hanging wall has dropped, and the separation is small in the shallow layers and larger in the deeper layers. Therefore, it is indicated that the hidden faults are synsedimentary faults or growth faults.

### Stratigraphy and lithology

Taiyuan basin is a large-scale Cenozoic rift basin filled with thick Cenozoic strata. The thickness of the Cenozoic sedimentary layer in the basin is generally 1000–2000 m, but can get as high as 3800 m (Han et al. 2008). The bottom of the basin is mostly covered by Permian and Triassic sandy shale, and the exposed and deep strata in the basin are mainly Paleozoic, Ordovician, Carboniferous, Permian, and Triassic strata.

The Cenozoic strata in the Taiyuan rift basin is mainly composed of the following: Pliocene clay and silty clay with sandy gravel layers, Quaternary and Early Pleistocene sand and sandy gravel layers with thin layers of silty sand and silty clay; Middle Pleistocene alluvial–diluvial sandy gravel, silt, and silty clay; Late Pleistocene sandy gravel layers and silt; and Holocene mixed sandy gravel, sand layers, and silt. The Quaternary strata of the Taiyuan basin are shown in Fig. 3.

The maximum thickness of the Taiyuan basin Quaternary strata is more than 500 m and is located on the northwestern border of the Taiyuan basin. In general, the Taiyuan basin Quaternary strata are deeply buried and gradually become shallower from northwest to southeast. The Taigu–Qixian area is located on the southeastern side of the Taihang mountain hilly area. The thickness of the Quaternary strata in this area is less than 200 m, the northwestern region is the basin's plain area, and the thickness of the Quaternary



**Fig. 2** Geological profile (*I-I'*) in the Taiyuan basin, for the profile's position see Fig. 1.  $F_1$ , Jiaocheng Fault;  $F_2$ , Longjiaying Fault;  $F_3$ , Qixian Fault;  $F_4$ , Pingyao–Taigu Fault; and  $F_5$ , Hongshan–Fancun Fault

strata exceeds 300 m (Han et al. 2008). The depths of the Quaternary strata on the two sides of the Taigu–Qixian earth fissure group differ by approximately 100 m. The earth fissure area is just barely within the transition zone, in which the thickness of the Quaternary strata transitions from shallow to deep, and the lithology is mainly fine sand, silt, and silty clay.

### Hydrogeological conditions

The lateral recharge of groundwater in the Taiyuan basin is mainly supplied by the groundwater surrounding the Taiyuan basin. The mountain fault exerts considerable control on the morphological structure and hydrogeological conditions of the basin.

The aquifers in the Taiyuan basin can be roughly divided into four aquifer groups based on their nature, hydraulic characteristics, spatial distribution, and the burial characteristics of the water medium (see Fig. 4). Group 1 is the Quaternary Holocene unconfined aquifer group (0–50 m), group 2 is the Quaternary Late and Middle Pleistocene confined aquifer group (50–200 m); group 3 is the Quaternary Early Pleistocene lacustrine–alluvial weak aquifer group (200–400 m); and group 4 is the Neogene red soil with thin layers of sandy gravel lacustrine weak confined aquifer group. Shallow unconfined aquifers are distributed throughout the area and are located in the shallow basin areas (within 50 m). The aquifers are mainly Holocene and Late Pleistocene alluvial–diluvial sandy gravel and sand. The thickness of the aquifers ranges from 10 to 30 m. For the middle to deep confined aquifers, the aquifer medium is alluvial and lacustrine sandy pebble from the Early, Middle, and Late Pleistocene, and medium, coarse, and fine sand are present. The aquifer is mostly composed of silty clay,

forming multi-layered confined aquifers that are 50–200 m deep and 5–50 m thick (Han et al. 2008). This is the main groundwater source used for regional mining.

### Methods and information

Through field investigations, it was determined that the 51 earth fissures located in the Taigu–Qixian territory mainly trend northeast. There are four giant fissures near Dongguan town, which is located at the junction of Taigu county and Qixian county. From north to south, the fissures are the Dongguan electric substation earth fissure ( $f_1$ ), the Baigui earth fissure ( $f_2$ ), the Dongliuzhi earth fissure ( $f_3$ ), and the Guanchang earth fissure ( $f_4$ ). The section of the Daxi high-speed railway from Xi'an to Taiyuan, which was opened in July 2014 with a designed maximum speed of 250 km, intersects at a small angle with earth fissures  $f_1$  and  $f_3$  near Dongguan town, see Figs. 5 and 6.

To explain the formation mechanism of the numerous Taigu–Qixian earth fissures, we investigated the distribution of the earth fissures in Dongguan town and the surrounding areas, which have the most developed earth fissures. We selected typical exposed sections of the earth fissures and excavated four large exploratory trenches to investigate the development of these earth fissures near the surface. We conducted two drilling sections perpendicular to the earth fissures to explore any changes in the shallow strata on both sides of the earth fissures. We deployed high-precision, three-dimensional seismic exploration equipment across the four massive earth fissures to determine the relationship between the earth fissures and the hidden faults. The locations of the exploratory trenches, drilling sections,



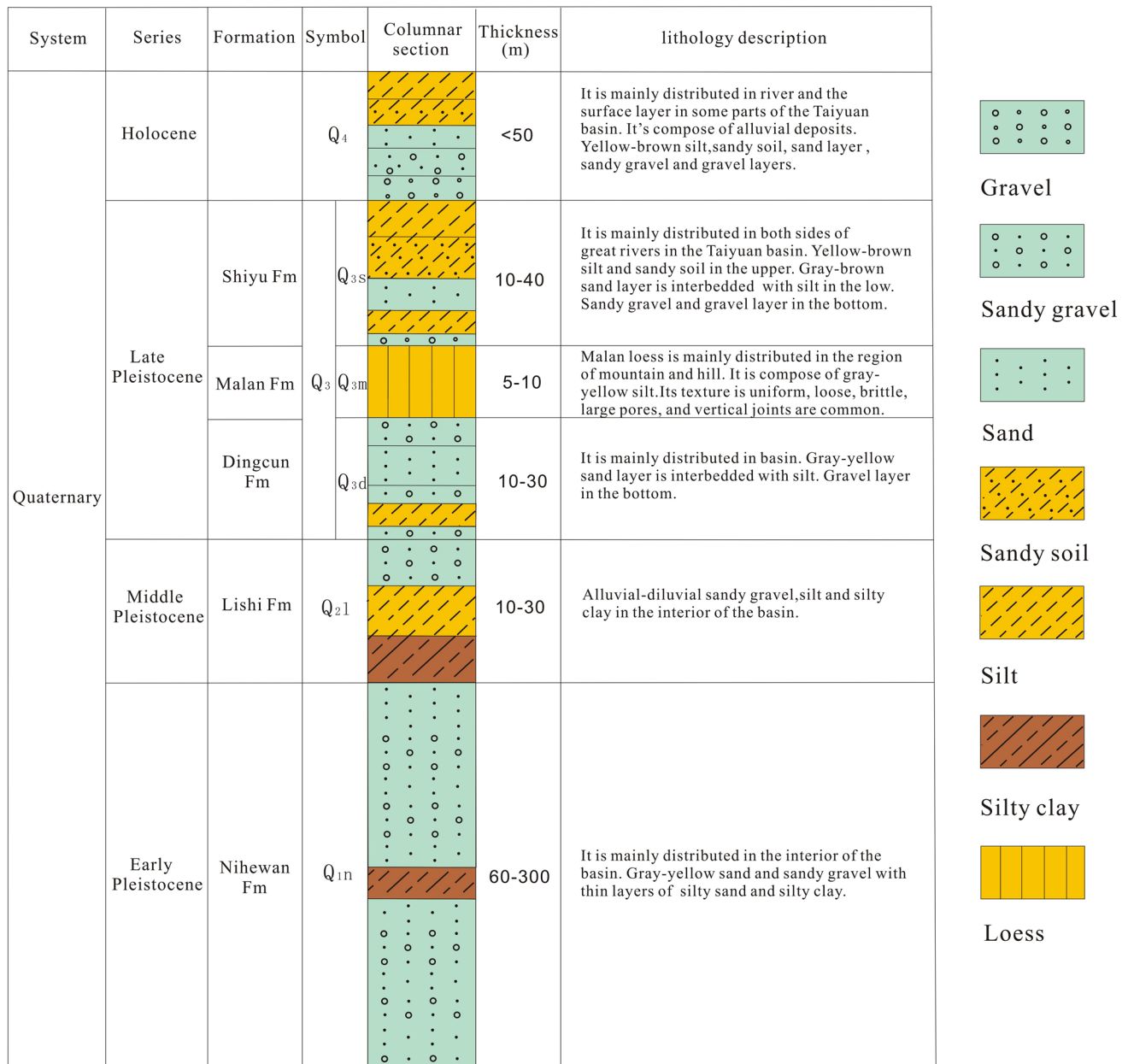


Fig. 3 Quaternary columnar section of the Taiyuan basin

and seismic exploration near Dongguan town are shown in Fig. 6.

## Results

### Dongguan substation earth fissure f<sub>1</sub>

The Dongguan substation fissure (f<sub>1</sub>) first appeared in 1978. This earth fissure extends from Wujiapu village in Taigu county south–southwest through Zhangjiapu in Qixian, the Dongguan substation, Zhangnan, Qiaojiapu, and

other locations. Its overall trend is NE (73°), with an SE dip; the southern wall has moved downward, and the fissure is approximately 10.2 km in length (Figs. 5, 6). In recent years, the f<sub>1</sub> earth fissure’s segmentation activity has been significant. The activity near the Dongguan substation in the middle section of the earth fissure is strong, while the activity in the western and eastern sections is weak or hidden. The earth fissures near the Dongguan substation mainly exhibit horizontal displacement and vertical differential settling. The maximum width of the horizontal displacements reaches 1 m (see Fig. 7a), while the vertical differential settling shows a relative decrease in the

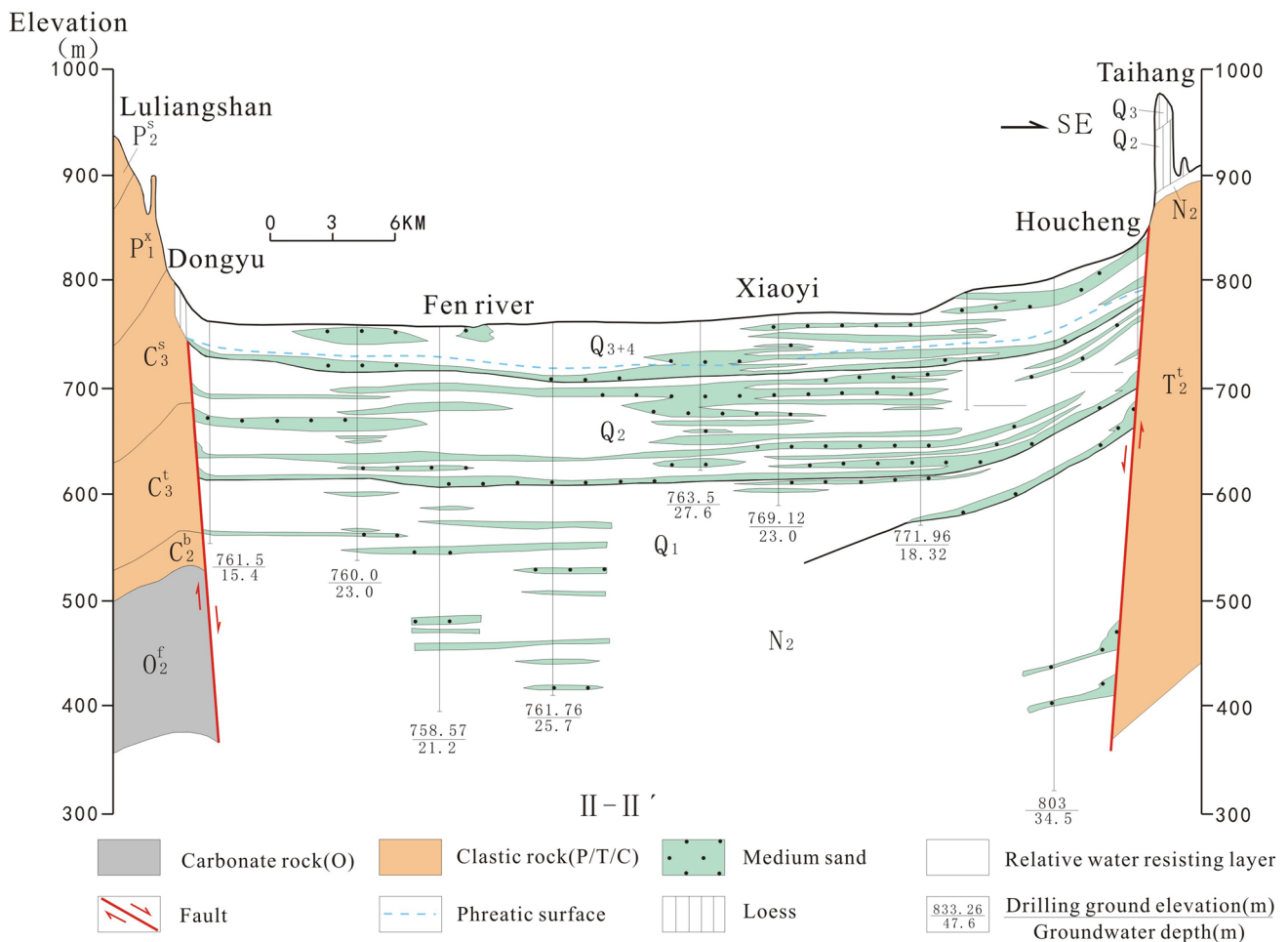


Fig. 4 Hydrogeological profile (II-II') in the Taiyuan basin, for profile position see Fig. 1

southern wall, with a maximum surface displacement of approximately 45 cm (see Fig. 7b). The road on the eastern side of the Dongguan substation was built in 2000, and the road was flat at the time. Due to the vertical activity of the earth fissures, the vertical displacement of the road surface in 2009 was 42 cm (see Fig. 7c). Based on the deformation of the road surface and the duration of earth fissure activity, it is estimated that the vertical velocity of the fissure is approximately 3 cm/year. In our survey, we also observed numerous secondary fissures to the south of fissure  $f_1$  near the Dongguan substation, i.e., in a direction at an angle of 75°–95°, parallel to the main fissure, with a length greater than 300 m (Fig. 6). Secondary fissures on the surface mainly manifest as bead-like pits, with the largest pit having a diameter of 1.2 m (Fig. 7d). According to our measurements, the fracture zone of the earth fissure and secondary fissures at Dongguan substation is 30–50 m wide.

In 2009, construction of the Daxi high-speed railway began, which resulted in a small angle intersection with

earth fissure  $f_1$  to the north of the substation. The Daxi high-speed railway was originally designed to cross earth fissure  $f_1$  on a bridge, which was later changed to a roadbed (Fig. 7e). After the opening of the high-speed railway in July 2014, the train's speed was reduced from 250 to 70–80 km when passing through the fissure area to ensure the safety of the train.

To probe the profile structure near the surface of the earth fissures, a trench (TC01) was excavated perpendicular to the fissure on the western side of the Dongguan substation (length of 80 m, top width of 10 m, depth of 8 m). The trench's position is shown in Fig. 6, and the trench is shown in Fig. 8a. The trench revealed that the main fissure has a trend of approximately 75°, with a width of 0.2–1.2 m, and it is wide on the top and narrow at the bottom. The fissure's surface was close to vertical, but tilted slightly south, and exhibited the development of branched fissures (Fig. 8b). The vertical displacement of the strata revealed by the trench was obvious, i.e., the southern wall had dropped. The vertical displacement was small near the ground and gradually

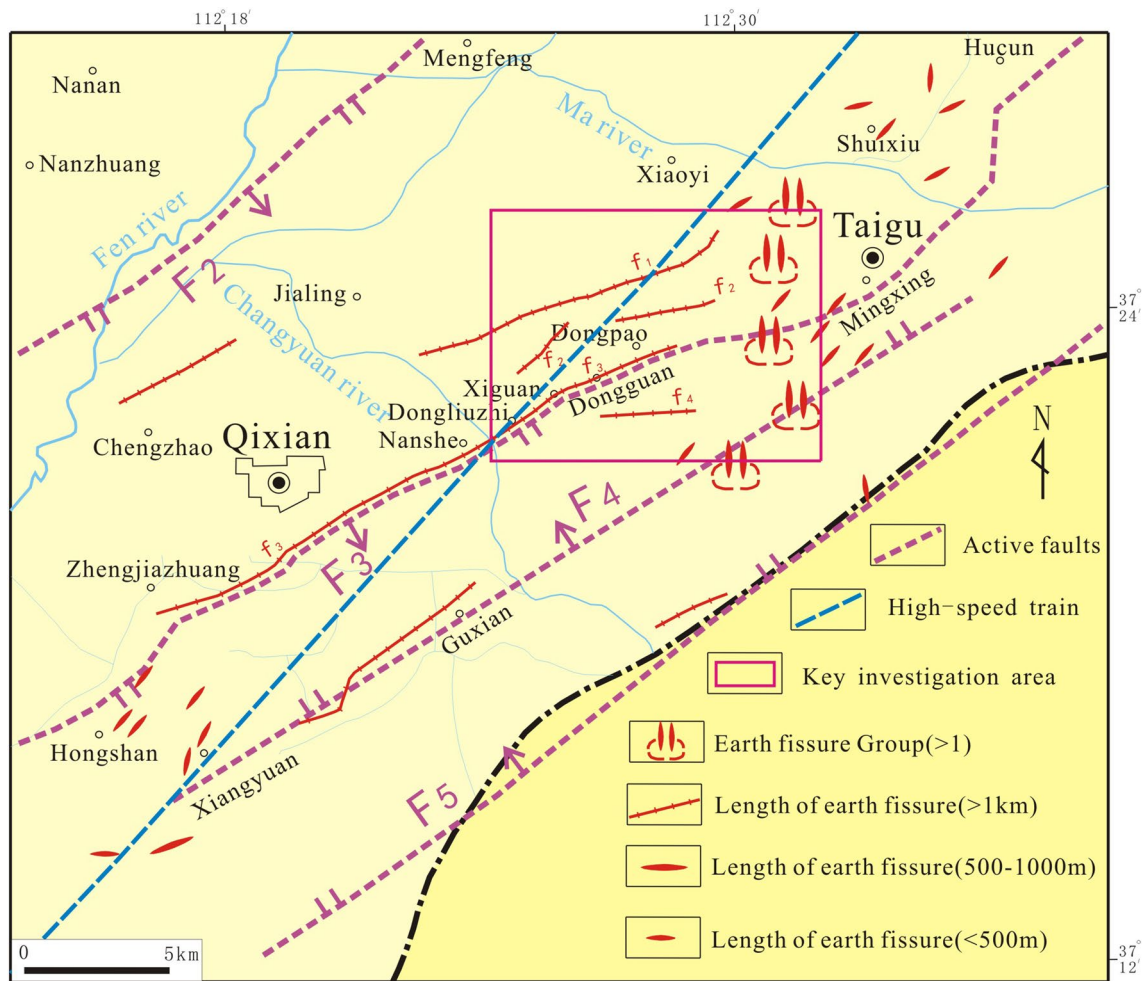


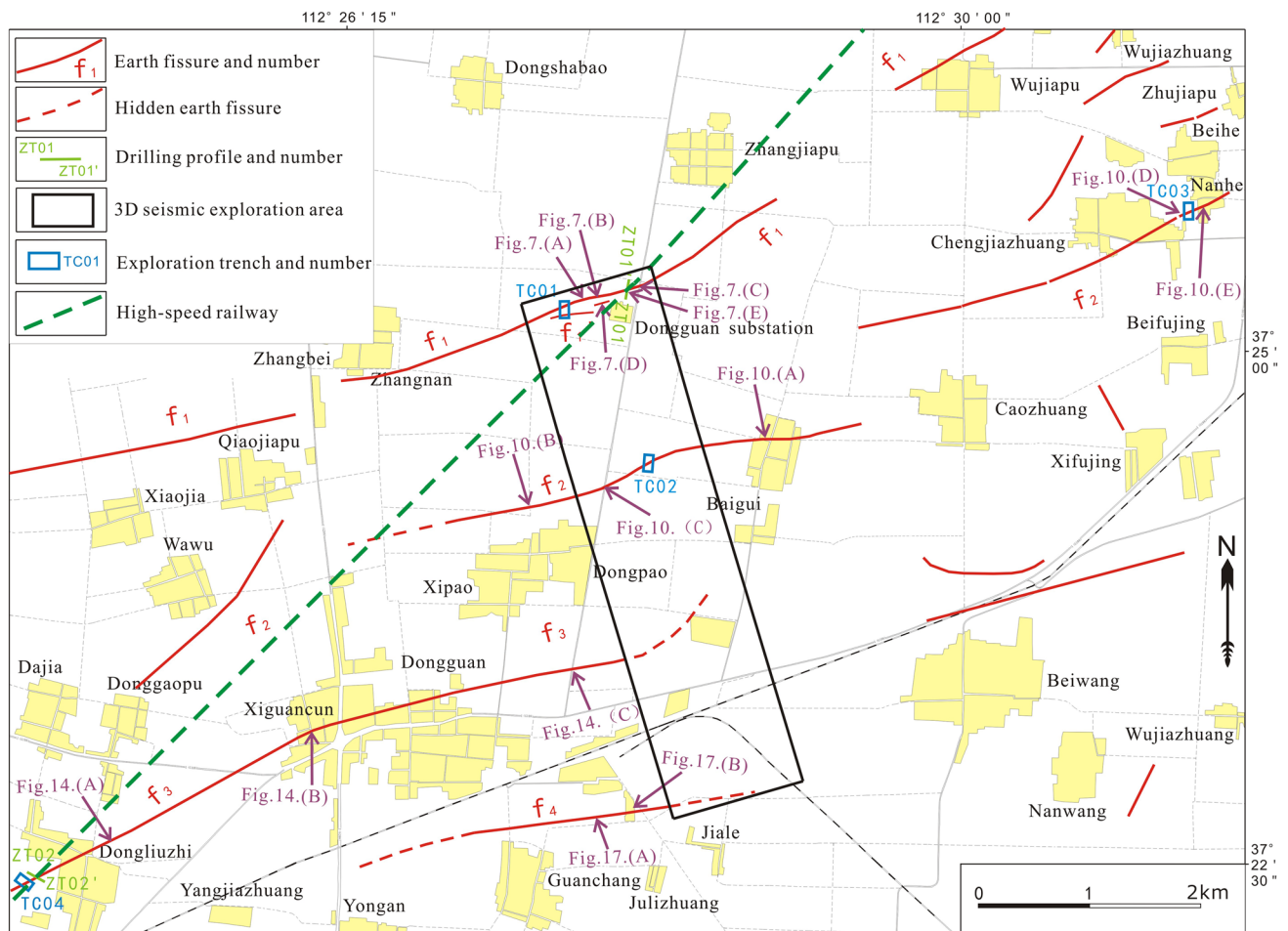
Fig. 5 Distribution of the earth fissures in the Taigu-Qixian territory

increased with increasing depth, e.g., the displacement of layer 3 (the silty clay layer) was 35 cm, while the displacement of layer 5 (the fine sand layer) was 40 cm at (Fig. 8c). A secondary fissure that developed 40 m southward from the main fissure (Fig. 8d) is parallel to the main fracture and exhibits the following characteristics: mainly horizontal displacement, insignificant vertical displacement, fissure width of 0.2–1.0 m, nearly vertical, tilted slightly south.

The drilling profile of earth fissure  $f_1$  (number ZT01–ZT01', shown in Fig. 6) shows that the strata on both sides of the main fissure have been significantly disrupted (Fig. 9). The displacement is small at the top and large at the bottom, which is characteristic of a syn-sedimentary fault. In addition, the groundwater levels on both sides of the earth fissures vary significantly. The groundwater level on the south of the earth fissure is approximately 747 m, while the groundwater level on the north side of the earth fissure is approximately 730 m, i.e., a water level difference of 17 m (Fig. 9).

### Baigui earth fissure $f_2$

The Baigui earth fissure ( $f_2$ ) can be divided into three sections: the western section across the northern Donggaobao village–Wawu village–southern Qiaojiapu village; the middle section across northern Xipao village–northern Dongpao village–Baigui village; and the eastern section across Caozhuang village–Chengjiazhuang village–Nanhe village. Its overall trend is NE, approximately 1500 m on average north of the earth fissure  $f_1$ , see Fig. 6. The western part of the earth fissure first appeared in 1995 with an overall trend of  $40^\circ$  and length of 2.45 km, which resulted in the destruction of 320 mu of arable land. Currently, the western section of the earth fissure is not active. The middle section of the earth fissure first appeared in 1998 with an overall trend of  $\sim 74^\circ$ , an NW dip, the northern wall dropped, and a length of approximately 4.0 km. In recent years, the vertical activity in the middle section of the earth fissure has become stronger, resulting in serious damage to buildings in Baigui village (see Fig. 10a). The width of the affected



**Fig. 6** Distribution of the earth fissures in Dongguan town and surrounding areas; and locations of exploratory trenches, drilling sections, and three-dimensional seismic exploration

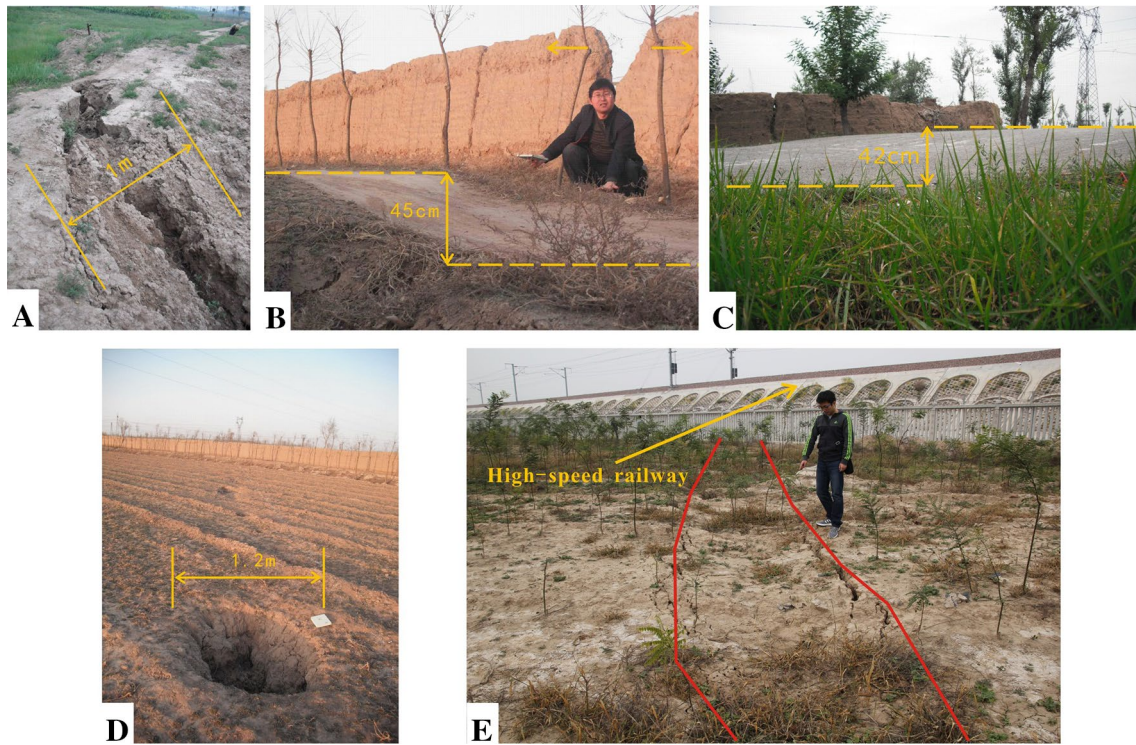
land is approximately 20 m. The vertical displacement of an unsurfaced road in northern Dongpao village is 43 cm (Fig. 10b), and the vertical displacement of a highway in eastern Dongpao village is 30–40 cm (Fig. 10c). It is estimated that the vertical velocity of the fractures is 2–3 cm/year. The eastern part of the earth fissure first appeared in 1975 an overall trend of 67°, an NW dip, the northern wall dropped, and a length of approximately 3.6 km. The activity of the eastern part of the earth fissure is strong, a pit with a maximum diameter of 1.5 m appeared to the west of Nanhe village (see Fig. 10d), and the width of the fractured zone is approximately 12 m. The vertical displacement of the earth fissures has caused serious damage to properties in the village of Nanhe (see Fig. 10e). The width of the affected zone is approximately 30 m.

A trench (TC02) was excavated along the vertical fissures on the northeastern side of Dongpao village (length 32 m, top width 4 m, depth 4 m). The trench's position is shown in Fig. 6, and the trench is shown in Fig. 11a. The trench revealed that the main fissures trend approximately 70° and

are tilted slightly northward. Secondary fissures have developed on both sides of the main fissures. The width of the main fissure is 0.2–1.0 m. It is wide on the top and narrow at the bottom. The trench also revealed that the stratum is obviously disrupted on both sides of the main fracture, the northern wall has dropped, and the displacement is small in the shallow layers and larger in the deeper layers. For example, the displacement at the bottom of the gray-yellow layer (layer 2) is 35 cm (Fig. 11b), while the displacement is approximately 60 cm at the top of the silt layer (layer 4) (Fig. 11c).

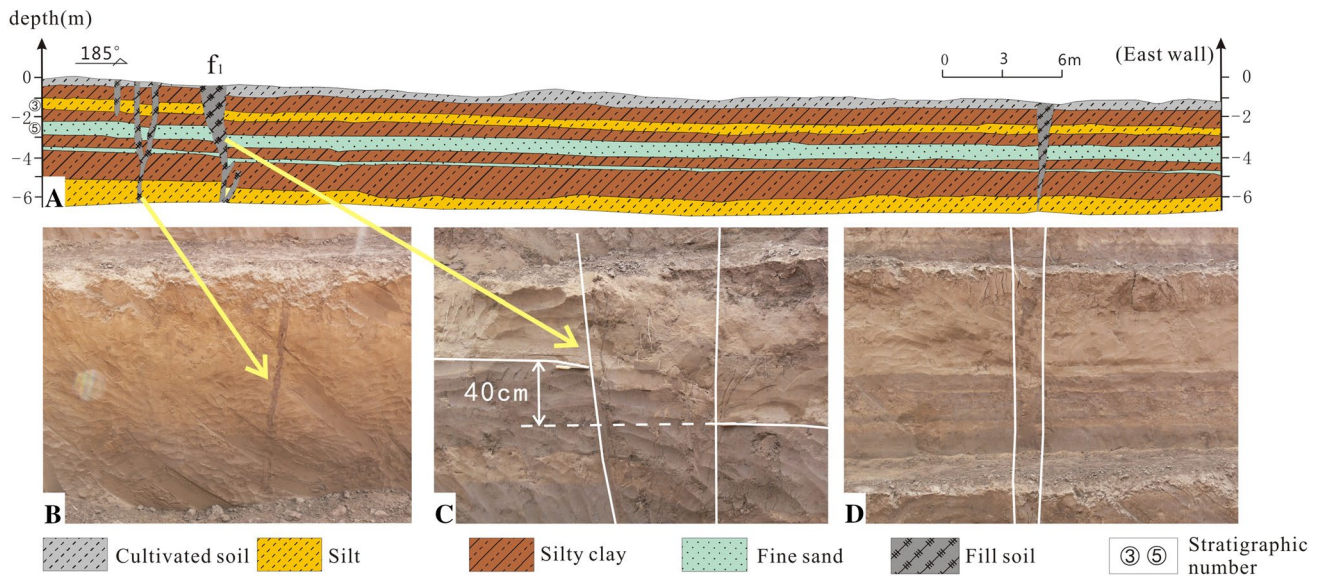
A trench (TC03) was excavated perpendicular to the fissure on the southwestern side of Nanhe village (length 20 m, top width 10 m, depth 10 m). The trench's position is shown in Fig. 6, and the trench is shown in Fig. 12. The trench revealed that the main fissure has a trend of approximately 66°, is tilted slightly northward, and that two secondary fissures have developed on the northern side of the main fissures. The width of the main fissure is 0.2–0.4 m, and it is wide on the top and narrow at the bottom. The earth fissures





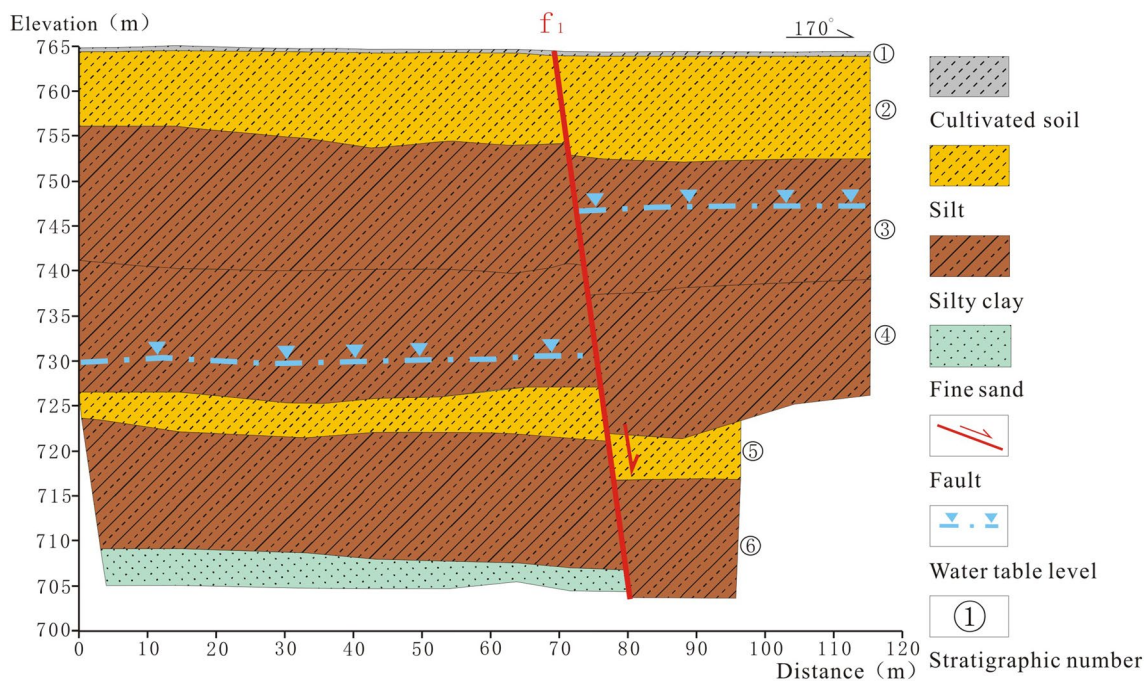
**Fig. 7** **a** Ground surface cracking due to fissure  $f_1$ ; **b** vertical differential settling of the unsurfaced road due to fissure  $f_1$ ; **c** vertical differential settling of the highway due to fissure  $f_1$ ; **d** secondary fissures

manifesting as bead-like pits; and **e** roadbed across fissure  $f_1$ . The location of each picture is indicated in Fig. 6



**Fig. 8** **a** Profile of trench's east wall at a depth of 0–8 m; **b** branched fissures of fissure  $f_1$ ; **c** vertical displacement of 40 cm in layer 5, the fine sand layer, due to fissure  $f_1$ ; and **d** a secondary fissure





**Fig. 9** Drilling profile of earth fissure  $f_1$

are filled with brown–red silty clay. There is no obvious vertical displacement on either side of the main fissure.

Based on the cross-fissure, short-leveling, monitoring profile established in Nanhe village, the subsidence of the northern wall of the earth fissure is much greater than that of the southern wall (Fig. 13), and a sudden-change in the subsidence zone has occurred near the earth fissures.

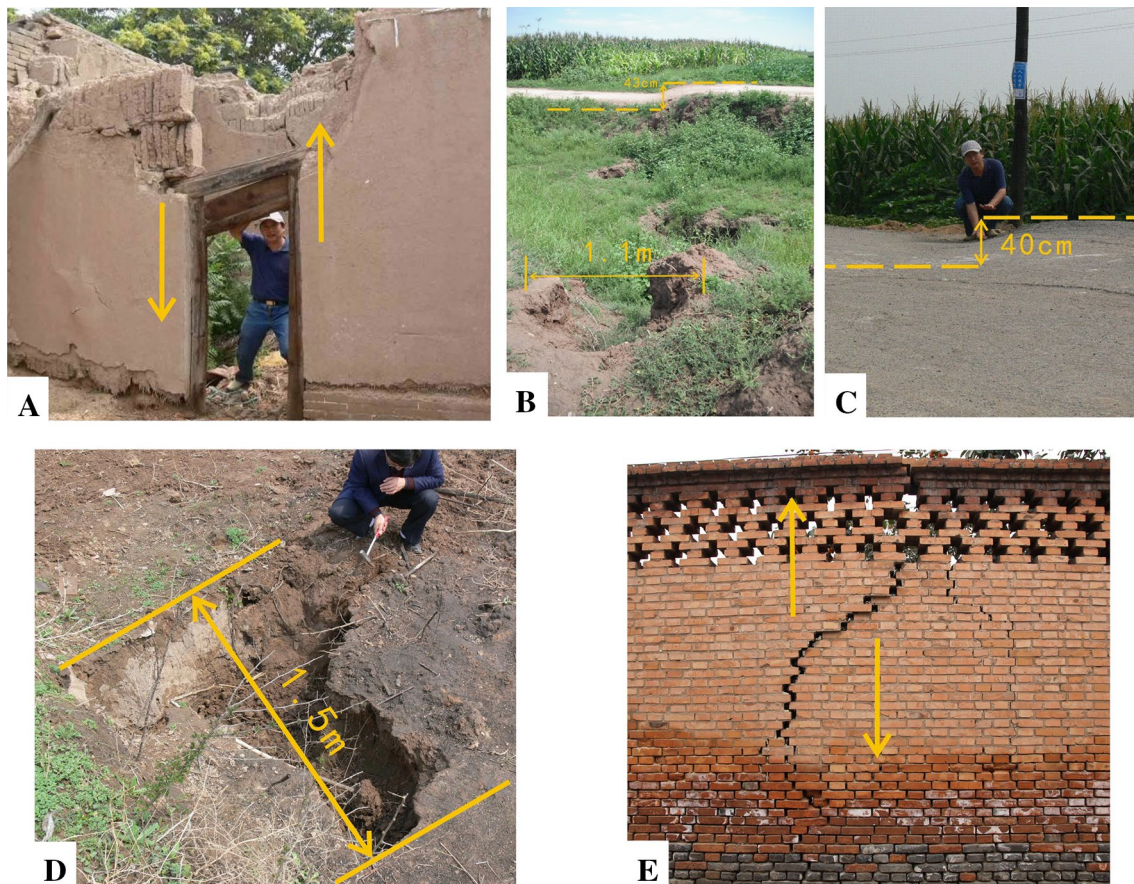
### Dongliuzhi earth fissure $f_3$

The Dongliuzhi earth fissure ( $f_3$ ) first appeared in 1979, extending west from Zhengjiazhuang village in Qixian county, extending east through Nanshe village, Dongliuzhi village, Xiguan village, and Dongguan town, and ending in southern Dongpao village. A linear extension is observed, approximately 1300 m from earth fissure  $f_2$  to the north. The fissure has a length of 22.4 km (see Fig. 5), and a width of 0.3–2 m, the southern wall has dropped, the width of the fractured zone is approximately 10–15 m, and the overall trend is  $65^\circ$ . The fissure is not obvious on either side of the Changyuan river, whereas in other areas, the earth fissure is exposed on the surface (see Fig. 14a). The vertical displacement of the earth fissure has caused severe damage to buildings (see Fig. 14b), and the width of the affected zone is approximately 30–50 m. The Dongliuzhi earth fissure crosses the north–south trending road on the eastern side of Dongguan town nearly at a right angle. Over the past 10 years, due to intensified activity, a vertical displacement of approximately 30 cm has occurred on the road (Fig. 14c),

with the southern wall dropping. It is estimated that the vertical displacement rate is approximately 1–2 cm/year.

A trench (TC04) was excavated perpendicular to the fissure on the southwestern side of Dongliuzhi village (length 21 m, top width 7 m, depth 6 m). The trench's position is shown in Fig. 6, and the trench is shown in Fig. 15a. The trench revealed that the main fissure trends  $67^\circ$ , the width of the main fissure is 4–60 cm, it is wide at the top and narrow at the bottom, it is tilted  $137^\circ$  at an angle of  $65^\circ$ – $80^\circ$  (Fig. 15b), and it has developed branch fissures. The trench also revealed that the earth fissures mainly exhibit horizontal displacement, with no significant vertical displacement. Localized displacement (4–10 cm) was observed. For example, the displacement of the silty sand layer (layer 4) to the south is 8 cm (Fig. 15c). In terms of the structure of the strata on both sides of the fissure, the northern strata are relatively horizontal, while overall, the southern strata are tilted southward. The tilted section of the strata should be in the deformation zone of the earth fissure. The strata in the southern wall are relatively low.

The drilling profile of fissure  $f_3$  (No. ZT02–ZT02', position shown in Fig. 6) reveals obvious stratum displacement between the two sides of the main fissure (Fig. 16). The displacement gradually becomes larger with depth. This is characteristic of a syn-sedimentary fault. The changes in the groundwater level on either side of the earth fissure are also obvious, i.e., the groundwater level on the southeastern side of the earth fissure is approximately 759 m, while the groundwater level on the northwestern side of the earth



**Fig. 10** **a** Damage done to building in Baigui village by fissure  $f_2$ ; **b** the vertical differential settling of an unsurfaced road due to fissure  $f_2$ ; **c** the vertical differential settling of a highway due to fissure  $f_2$ ; **d**

fissure  $f_2$  manifesting as bead-like pits; and **e** damage to a building in Nanhe village due to fissure  $f_2$ . The location of each picture is indicated in Fig. 6

fissure is approximately 753 m, resulting in a difference in water level of approximately 6 m. In addition, the borehole profile (Fig. 16) reveals that there may be hidden fissures on the northern side of the main fracture.

#### Guanchang earth fissure $f_4$

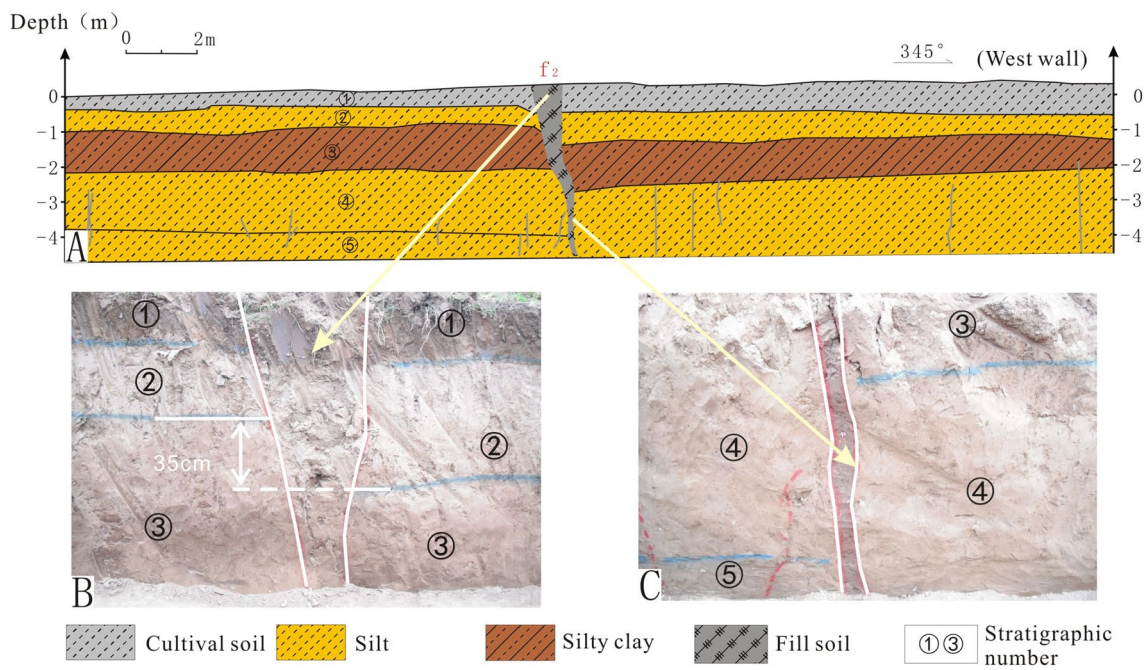
Guanchang earth fissure  $f_4$  first appeared in 1975, extending west from northern Guanchang village, and extending eastward toward northern Jiale village (see Fig. 6). It is located approximately 1400 m from earth fissure  $f_3$  to the north, is 4.0 km in length, has a trend of approximately  $80^\circ$ , the southern wall has dropped, and exhibits a strip or beaded-pit surface structure (Fig. 17a). The vertical displacement of the earth fissure has caused damage to buildings (Fig. 17b). The width of the affected zone is approximately 20 m, and the activity has intensified over the past 10 years.

#### Deep characteristics of the earth fissures and their relationships

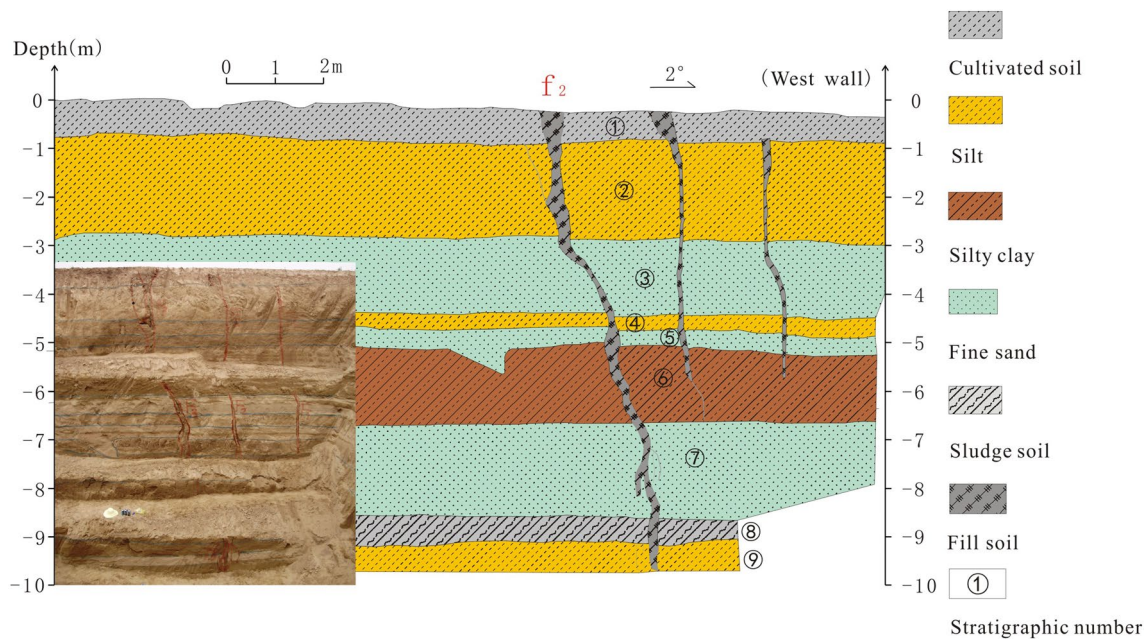
To clarify the relationship between the earth fissures and hidden faults, a high-precision, three-dimensional, seismic survey (position shown in Fig. 6) was conducted across earth fissures  $f_1$ ,  $f_2$ ,  $f_3$ , and  $f_4$  from east of Dongguan town to the area between Dongpao village and Baigui village to determine the location and distribution of the underground hidden faults.

The three-dimensional seismic exploration revealed a total of 11 hidden faults, all of which were normal faults that were parallel to each other, trending ENE and dividing the strata into horst and graben structures (Fig. 18). The results of the three-dimensional seismic exploration survey were analyzed. Fault DF2 is hidden under earth fissure  $f_1$ , and  $f_1$  and DF2 are connected and dip SE. Fault DF6 is hidden under earth fissure  $f_2$ , and  $f_2$  and DF6 are connected and dip NW. Fault DF9 is hidden under earth fissure  $f_3$ ,  $f_3$  and DF9 are connected and dip SE. Fault DF11 is hidden under earth





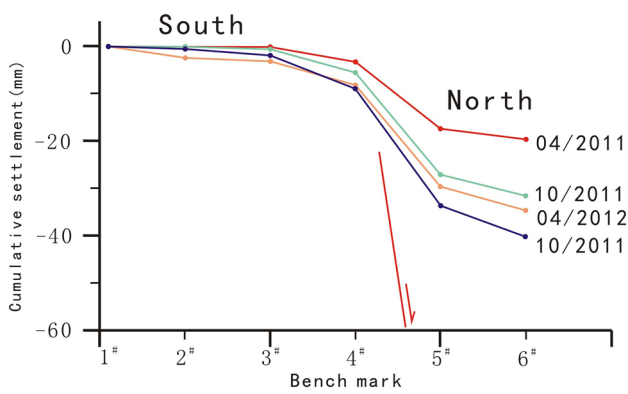
**Fig. 11** a Profile of the trench’s western wall at a depth of 0–4 m; b vertical displacement of 35 cm in layer 2, the gray-yellow silt layer, due to fissure  $f_2$ ; c vertical displacement of 60 cm in layer 4, the silt layer, due to fissure  $f_2$



**Fig. 12** Profile of the trench’s western wall at a depth of 0–6 m

fissure  $f_4$ , and  $f_4$  and DF11 are connected and dip SE. The ground surface survey of earth fissure  $f_3$  indicates a length of 22.4 km and the displacement of underlying DF9 fault is obvious; therefore, it is speculated that DF9 is the Qixian

fault. The results of the three-dimensional seismic exploration survey indicate that the depth of the hidden faults is more than 700 m, far more than the maximum depth of mining or the depth of the local aquifer, and the four massive



**Fig. 13** The short-leveling, monitoring profile across the fissure in Nanhe village

earth fissures connect with the hidden faults, indicating that the formation of the earth fissures in Taigu–Qixian is linked to the tectonics of the area.

Based on the above investigation and exploration results, the four massive earth fissures developed around Dongguan village mainly exhibit vertical displacement. They also exhibit horizontal displacement. They trend northeast parallel to each other and are generally separated by equal distances, which results in the formation of ridges and depressions in the landscape. The deeper the strata on both sides

of the earth fissures, the greater the displacement. The faults are connected with the underlying hidden faults, which is characteristic of the tectonic properties of syn-sedimentary faults. This connection results in the obstruction of groundwater runoff.

## Discussion

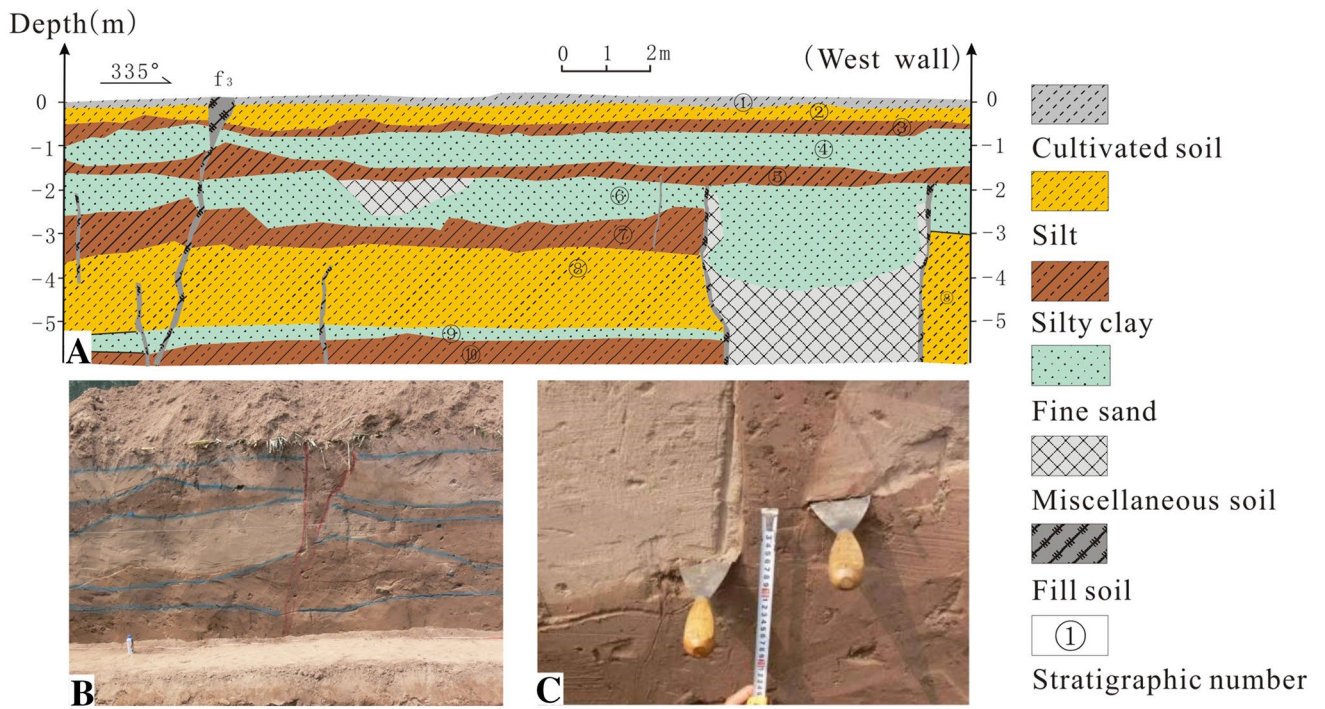
### Relationship between earth fissure formation and the basin’s structure

The Taiyuan basin trends north–east, and the listric faults on the edges of the basin play a controlling role in the rift basin. The maximum vertical displacement of the Jiaocheng fault on the northwestern boundary of the basin since the Cenozoic is 4200 m, while that of the Hongshan–Fancun fault on the southeastern boundary of the basin is only 1200 m (Wang et al. 1996). Such a large difference in displacements tilts and breaks the foundational fault block of the rift basin along the hidden Qixian fault. The tilted foundational fault block of the Taiyuan basin not only causes the thickness of the Cenozoic sediments decreasing gradually from northwest to southeast, resulting in a wedge-shaped profile (Fig. 2), but it also places the top of the Quaternary strata above Qixian fault under an extensional stress. This provides favorable

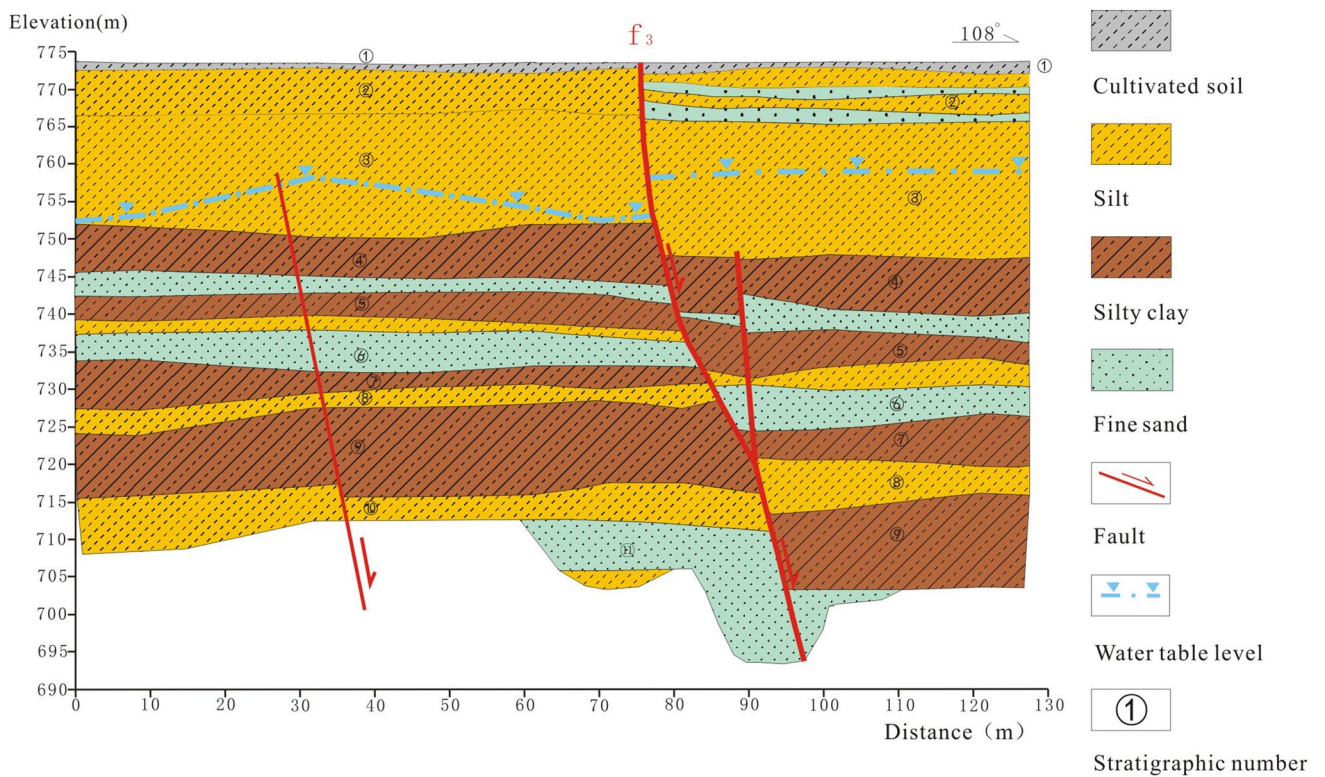
**Fig. 14** **a** Ground surface cracking due to fissure  $f_3$ ; **b** damage to a building in Xiguan village due to fissure  $f_3$ ; **c** vertical differential settling of the road due to fissure  $f_3$ . The location of each picture is indicated in Fig. 6







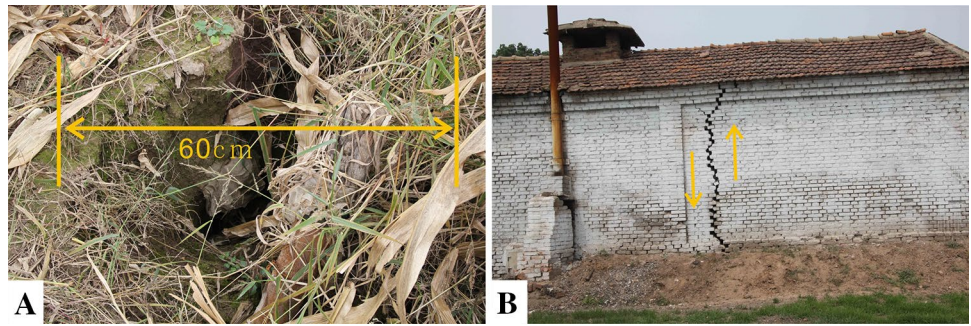
**Fig. 15** a Profile of the trench’s western wall at a depth of 0–6 m; b earth fissure  $f_3$ ; c vertical displacement of 8 cm in layer 4, the fine sand layer, due to fissure  $f_3$



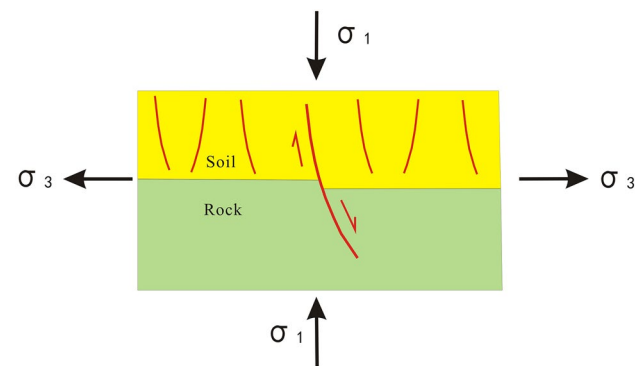
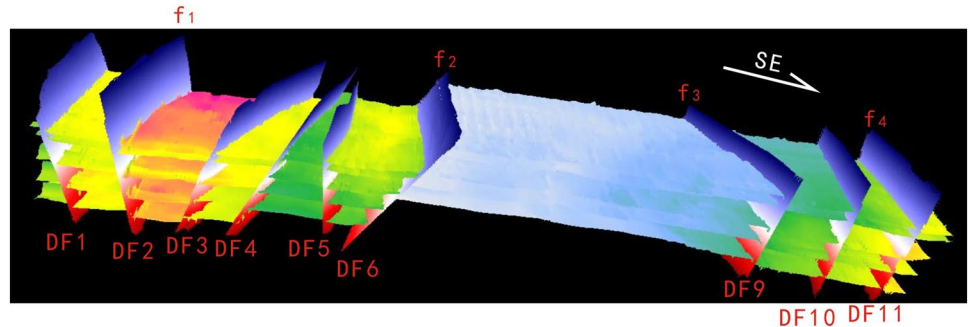
**Fig. 16** Drilling profile of earth fissure  $f_3$



**Fig. 17** **a** Fissure  $f_4$  manifesting as bead-like pits; and **b** damage to building in Guanchang village due to fissure  $f_4$ . The location of each picture is indicated in Fig. 6



**Fig. 18** The results of the three-dimensional seismic exploration



**Fig. 19** The mechanical mechanism of the hidden faults

conditions for the formation of earth fissures, which explains why large-scale fractures occur in Taigu–Qixian.

We believe that when motion on the Qixian fault is transferred to the shallow loose soil layer, due to the soil’s looseness, heterogeneity, and anisotropy characteristics, many superimposed faults are formed in the shallow surface layer (Fig. 18), i.e., hidden earth fissures. The mechanical mechanism is shown in Fig. 19.

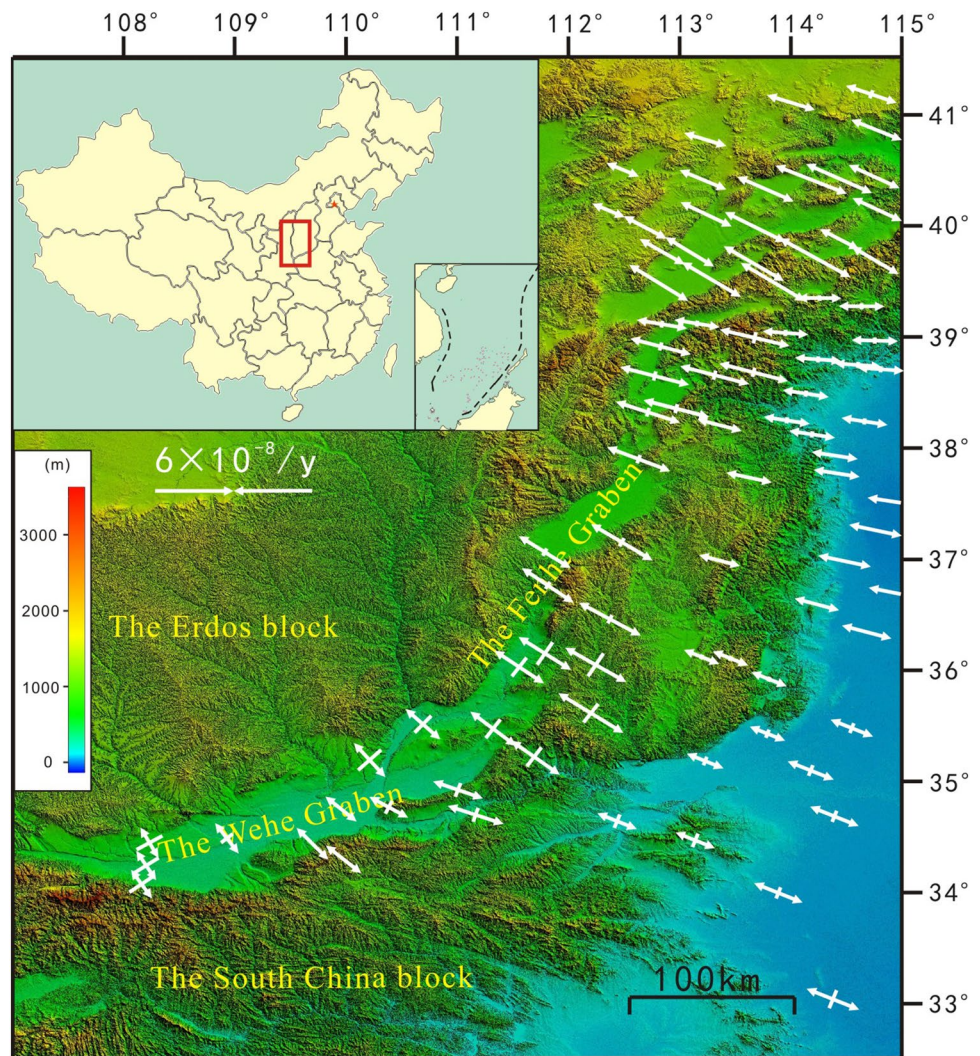
**Relationship between earth fissure formation and the regional tectonic stress field**

A high-density, high-precision GPS net was laid throughout the Shanxi rift basin and the surrounding area. We used the resultant GPS data to establish a model of the regional changes. The principal strain eigenvalue was calculated using the model, and the vector was drawn (Fig. 20). The results indicate that the Shanxi rift basin is mainly extending in an NW–SE direction, indicating a right-handed state, which is basically the same as the regional modern focal mechanism solution (Yang et al. 2000, 2002).

The linear extensional characteristics of the earth fissures in Taigu–Qixian are obvious. Generally, they trend NE and ENE, reflecting a correspondence between the extensive development of earth fissures and the regional NW–SE tensile stress field.

**Relationship between the formation of earth fissures and the over-exploitation of groundwater**

According to the available research data, the activity rate of the southern Hongshan–Fancun fault since the Pleistocene is 0.25 mm/a; the activity rate of the Qixian fault since the Pleistocene is 0.07 mm/a (Wang et al. 1996), while the activity rate of the earth fissures investigated in this study reaches 3 cm/a, which significantly exceeds the activity of the active

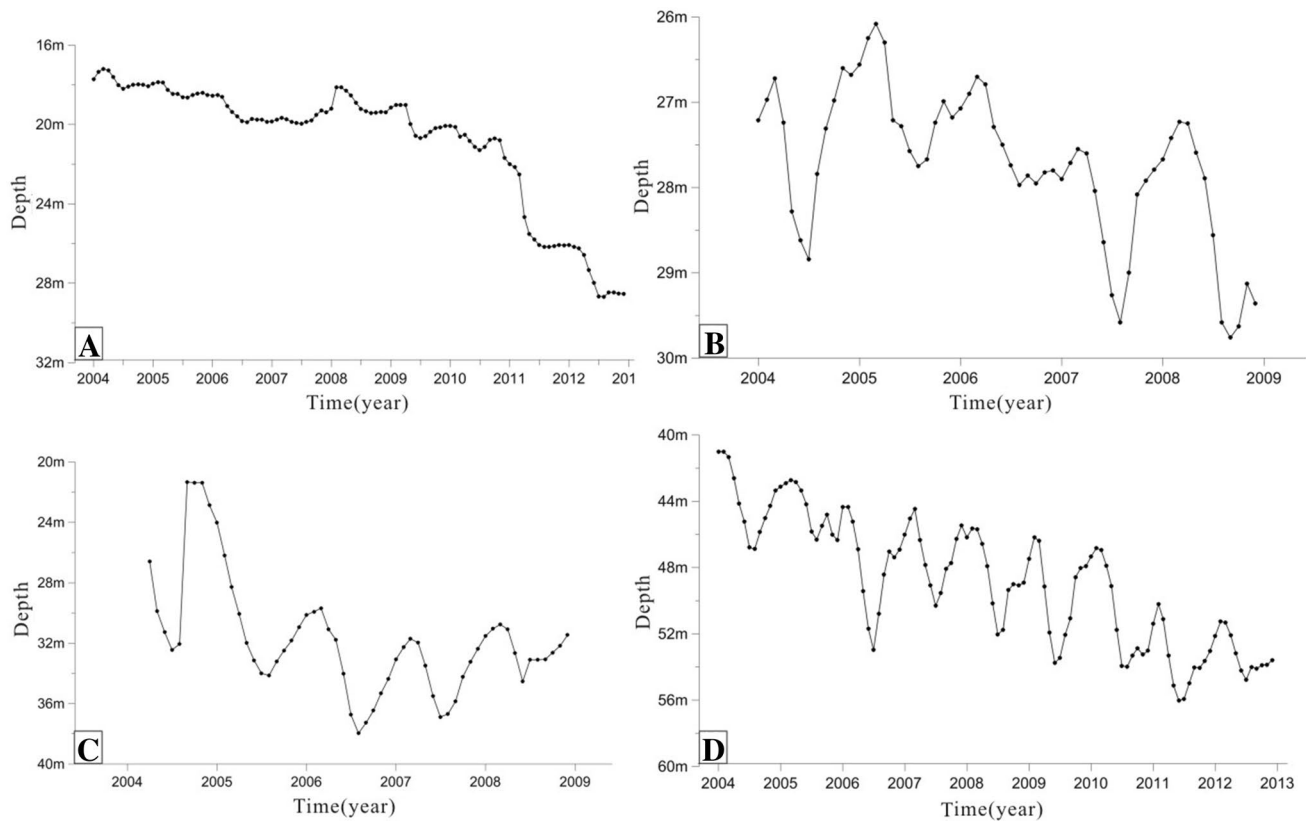
**Fig. 20** Distribution of the principal strain

faults. Thus, the current activity rate of the fissures cannot be entirely explained by fault activity.

Limited to production technology, irrigated farmland mainly used surface water and shallow groundwater in ancient times. In modern society, industrial water consumption has increased greatly, except for agriculture and domestic water. Surface water and shallow underground water are far from meeting the needs. Because without external water supplement, the middle to deep confined aquifers are the main groundwater source used for regional mining in the Taiyuan basin.

Taigu and Qixian areas have experienced the over-extraction of groundwater. The average groundwater exploitation coefficient is 1.5 (Gao 2008; Yang 2009). Excessive extraction of groundwater results in ineffective replenishment and restoration of groundwater resources has resulted in the continual decline in local groundwater levels over the last decade (Fig. 21a–d). With the continuous over-extraction of groundwater in the Taigu and Qixian areas, the

groundwater level is declining. The pore water pressure in the soil decreases with the discharge of water from the pores, and the effective stress will gradually increase. With increasing effective stress, the pore volume of the soil continuously compresses, which results in consolidation and deformation of the soil, and consequently, ground subsidence. Figure 22a shows the corresponding annual average subsidence rates of the Taigu–Qixian area from 2003 to 2010. As can be seen from Fig. 22a, there is a serious ground subsidence phenomenon occurring in the Taigu–Qixian area. The sedimentation rate of Hucun town, Shuixiu, and Xiaoyi is relatively high, i.e., 40 mm/a. The annual average rate of the Dongguan town area is 20 mm/a, and the settling rate of Taigu county and Qixian county is relatively low with an average sedimentation rate less than 10 mm/a. Due to relative impermeability of the ground fissures, the over-extraction of groundwater results in the difference in compressibility of middle to deep confined aquifer on either side of the ground fissure. It drags the hidden fault or ground fissures, transferring to ground



**Fig. 21** **a** Water level curve for the observation hole in Changtou village; **b** water level curve for the observation hole in Baigui village; **c** water level curve for the observation hole in Xiaoyi village; and **d** water level curve for the observation hole in Mingxing town

surface and formatting the earth fissure. The results of the water level measurements carried out along the Daxi high-speed railway line when it was under construction show that subsidence is very common (Fig. 22b). The maximum settling rate of Dongguan town is more than 30 mm/a, causing strong vertical activity on fissure  $f_1$ , which seriously threatens the construction and normal operation of the high-speed railway.

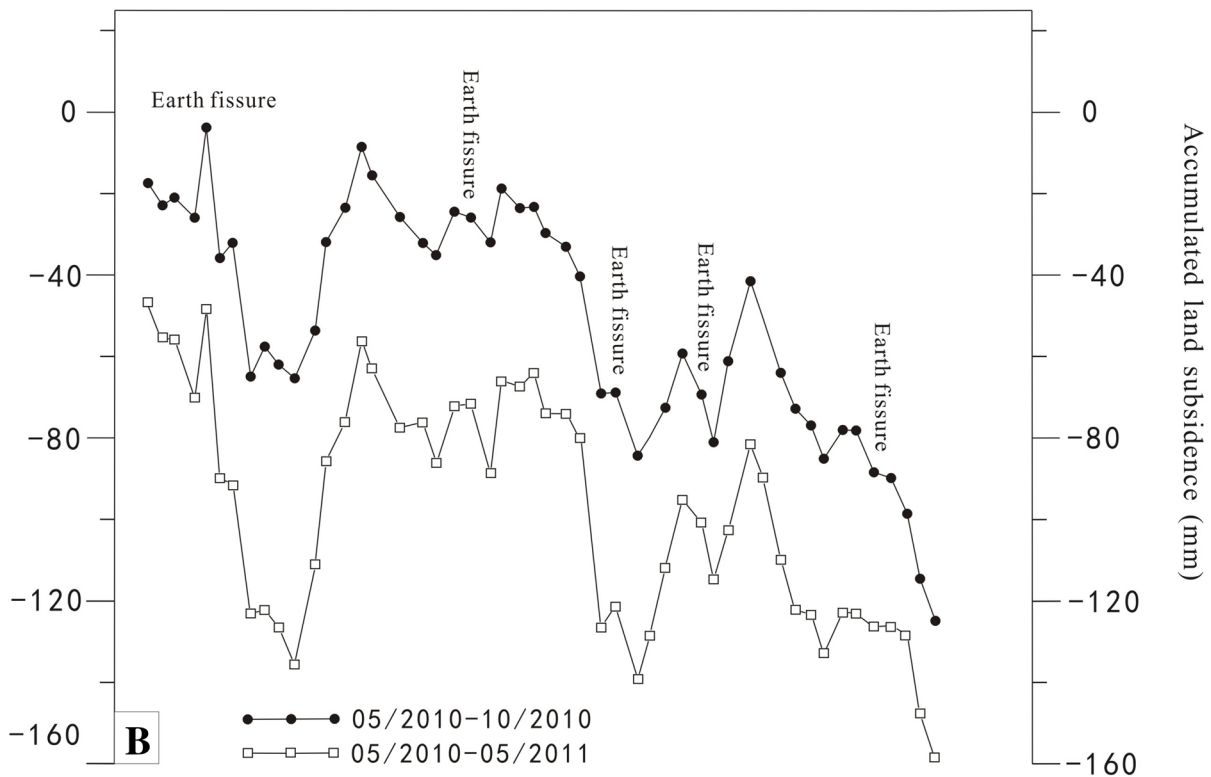
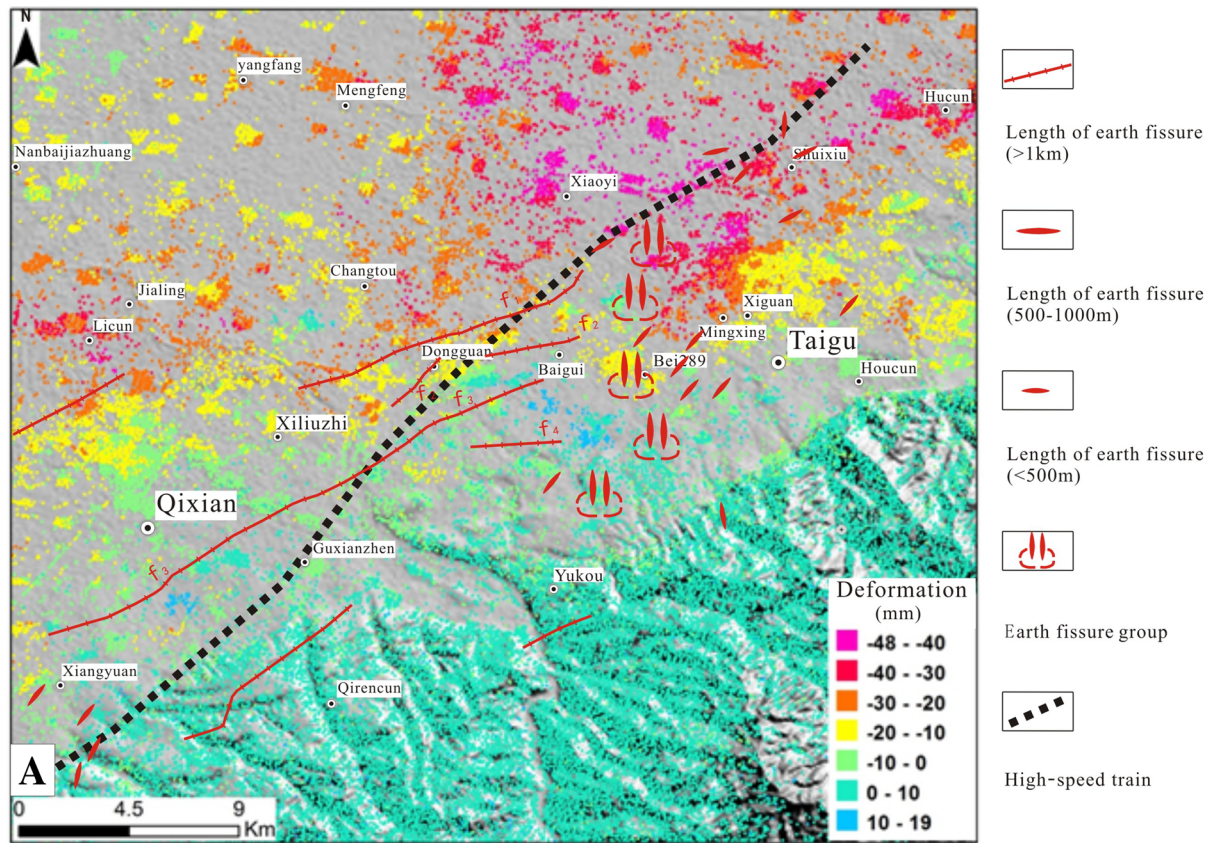
In summary, the Taiyuan basin is affected by the regional tectonic structure and the tilting of the foundational fault block; the basin is in a horizontal NW–SE trending tensile stress state. In the basin, the hidden Qixian fault is undergoing extension, causing the overlying Quaternary strata to fracture from bottom to top, forming several hidden faults. Since the 1970s, serious over-exploitation of groundwater has occurred in the Taigu–Qixian area. The groundwater level in the confined aquifer continued to fall, leading to the formation of a ground subsidence funnel. The water loss in the aquifer on both sides of the hidden fault caused

the pressure to increase, and the surface soil was stretched allowing the upward extension of part of the hidden fault, exposing the surface, and forming the earth fissure group. The formation mechanism is shown in Fig. 23.

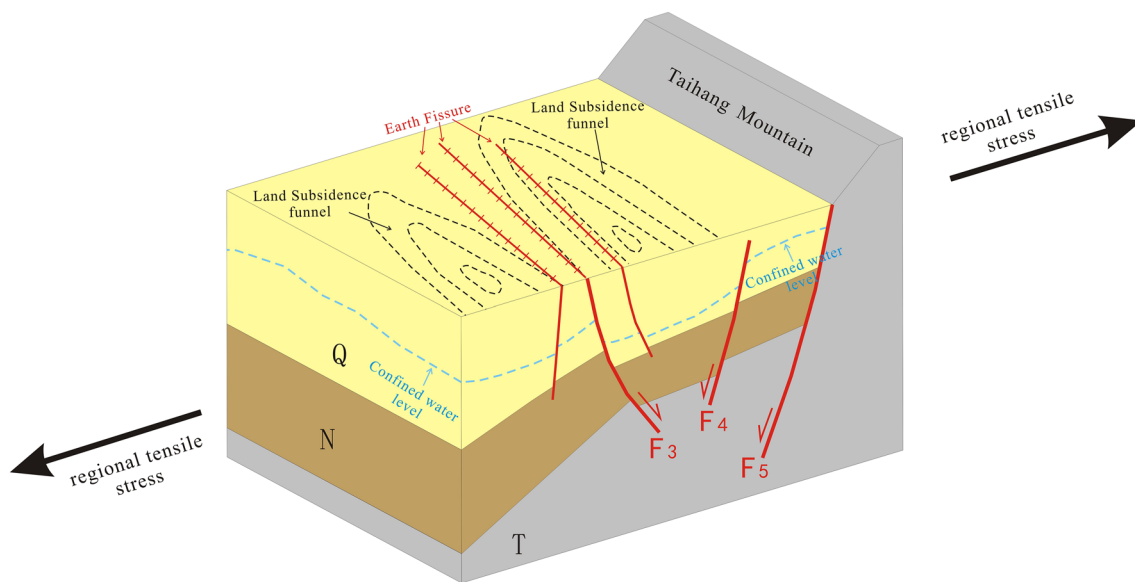
## Conclusions

We believe that the Taigu–Qixian fissure group resulted from tilting of the Taiyuan basin's foundational fault block and extension and movement of the basin's hidden fault. When over-exploitation of groundwater was added to the tectonic factors, the earth fissure group was exposed on the surface and continues to be active, i.e., tectonic activity is the internal cause of the formation of the earth fissures and the over-exploitation of groundwater is the external cause of the fissure group. Both internal and external factors are required to form the Taigu–Qixian earth fissure group. If





**Fig. 22 a** The annual average subsidence rates for the Taigu-Qixian area from 2003 to 2010; and **b** the land subsidence profile along the Daxi high-speed railway line



**Fig. 23** Mechanism for the formation of the Taigu–Qixian earth fissure group. F<sub>3</sub>, Qixian fault; F<sub>4</sub>, Pingyao–Taigu fault; and F<sub>5</sub>, Hongshan–Fancun fault

there was tectonic activity in the basin, but no over-exploitation of groundwater, the earth fissures would remain hidden, and it would not be possible for the fissures to be exposed on the surface over such a large scale. Similarly, if there was over-exploitation of groundwater, but no tectonic activity, small fissures may appear on the edge of the ground subsidence, but there would be no massive regional fissures trending in the same direction as the regional tectonic structures. Therefore, the Taigu–Qixian fissure group is caused by the composite cause of “coupling of the basin’s hidden fault movement + over-extraction of groundwater”.

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