

Distinguishing between faults and coal collapse columns based on sediment dating: a case study of the Huainan coal field, China

Fengtian Yang¹ · Zhonghe Pang² · Zhongfeng Duan³

Received: 15 January 2016 / Accepted: 18 May 2016 / Published online: 2 June 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract Coal collapse columns are special geologic structures developed in the coal fields in North China. Water bursting related to the columns is characterized by large flow rates and is difficult to be predicted. In some cases, it is difficult to distinguish coal collapse columns and faults. Here, we propose a method based on sediment dating combined with borehole drilling and geophysical surveys. By application of the method to the Guqiao coal mine in the Huainan coal field, we recognized a significant offset of the Quaternary units around a geologic structure, and inferred that it cannot result from coal collapse columns but by faulting, and determined the ages of the faults.

Keywords Distinguishment · Faults · Coal collapse columns · Sediment dating · Coal field

Introduction

Coal collapse columns are a special type of karst collapse formed in the geologic time, which are an accumulation of crushed rocks formed by karst and subsequent collapse, forming a buried vertical inlay structure in coal-bearing

strata. Although several mechanisms have been proposed for the origin of coal collapse columns, such as gypsum dissolution (Qian 1960), collapse of multilayer karst caves (Wang 1982), vacuum suction (Xu and Zhao 1990), gravitational collapse (Kang 1992), and hydrothermal dissolution (Chen 1993), it has been a consensus that coal collapse columns are the result of continuous upward collapse of large span karst caves in soluble rocks (mainly carbonate rocks) underlying coal-bearing strata. In North China, carbonates with a large thickness (up to 5000 m) developed widely in the Early Phanerozoic. These strata are mainly of the Cambrian and Ordovician periods, since sediments of the Silurian and Devonian are mostly missing due to uplifting in the Silurian and Late Phanerozoic (Wan 2012), resulting in direct contact of the carbonate rocks with the overlying coal-bearing strata of the Carboniferous, Permian, and Jurassic. As karst are highly developed in these carbonate rocks, especially along water-conducting faults, most coal collapse columns also distribute along water-conducting faults and are widely encountered in more than 20 coal fields in Shanxi, Hebei, Henan, Shaanxi, Shandong, Jiangsu, and Anhui provinces in North China (Fig. 1) (He 2012).

Profile shapes of coal collapse columns are controlled by the mechanical properties of the rocks it passes through and mostly appears to be irregular or serrate shaped (Si et al. 2001). In hard homogenous strata with well-developed fissures, the columns usually have an inverse funnel profile shape (Fig. 2a), while in unconsolidated formations the profiles are usually funnel shaped (Fig. 2b). In strata consisting of hard rocks interlayered with relatively soft rocks, the columns are usually irregularly shaped (Fig. 2c). In the coal fields in North China, most coal collapse columns (up to ca. 96 %) discovered have a profile shape of the inverse funnel, with a few having the other profile shapes, and in

✉ Fengtian Yang
yangfengtian@jlu.edu.cn

¹ Key Laboratory of Groundwater Resources and Environment, Ministry of Education, Jilin University, Changchun 130021, China

² Key Laboratory of Shale Gas and Geoenvironment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

³ School of Geosciences, China University of Petroleum (Huadong), Qingdao 266580, China

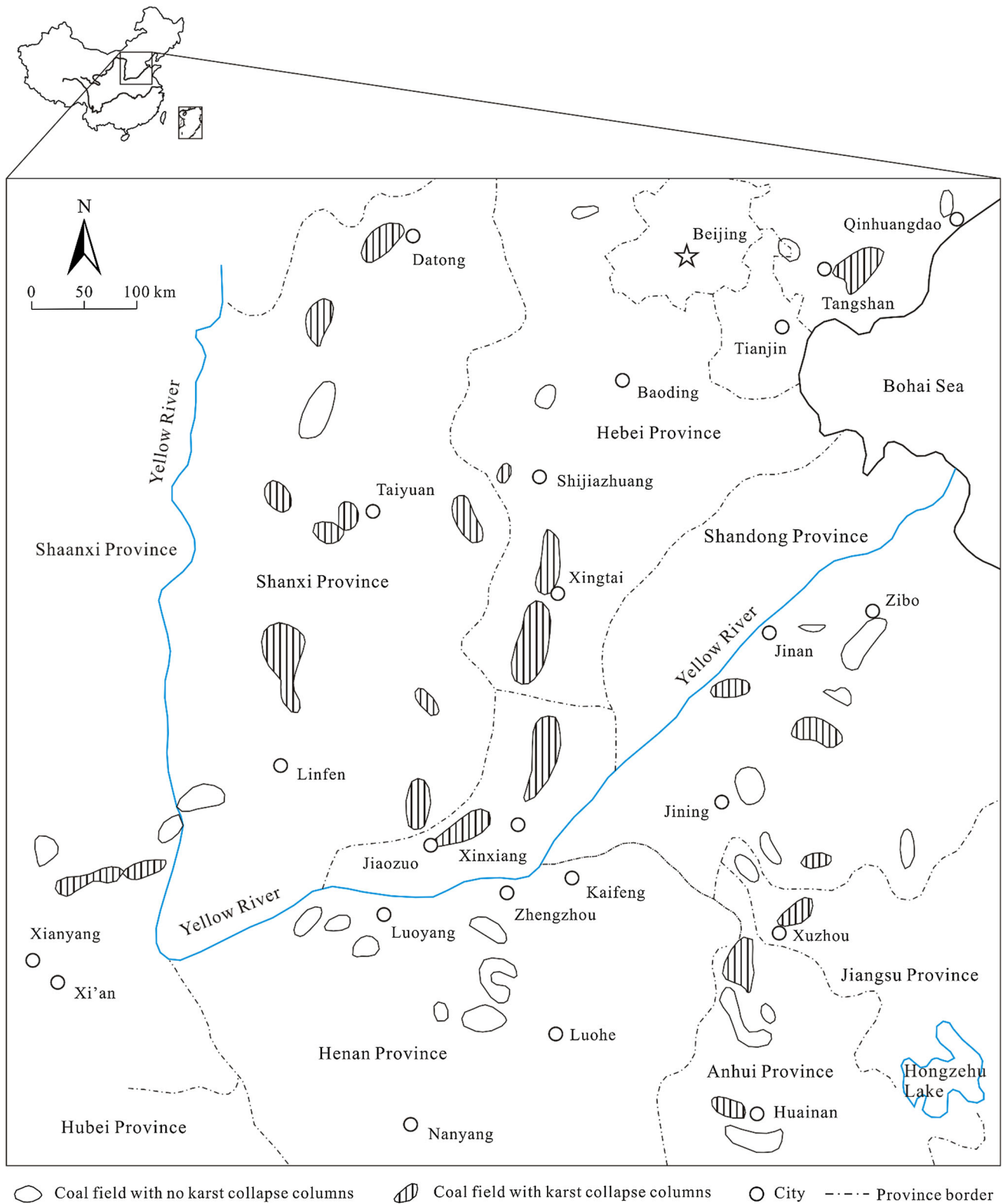


Fig. 1 Distribution of karst collapse columns in coal fields in North China

some particular cases, controlled by stratigraphic attitude and gliding faults near the roof or bottom of the coal beds, coal collapse columns may have inclined or cylinder-

shaped profiles (Fig. 2d, e). Most coal collapse columns have a circular or oval plane shape and are quite different in area. The long axis of large columns can reach up to

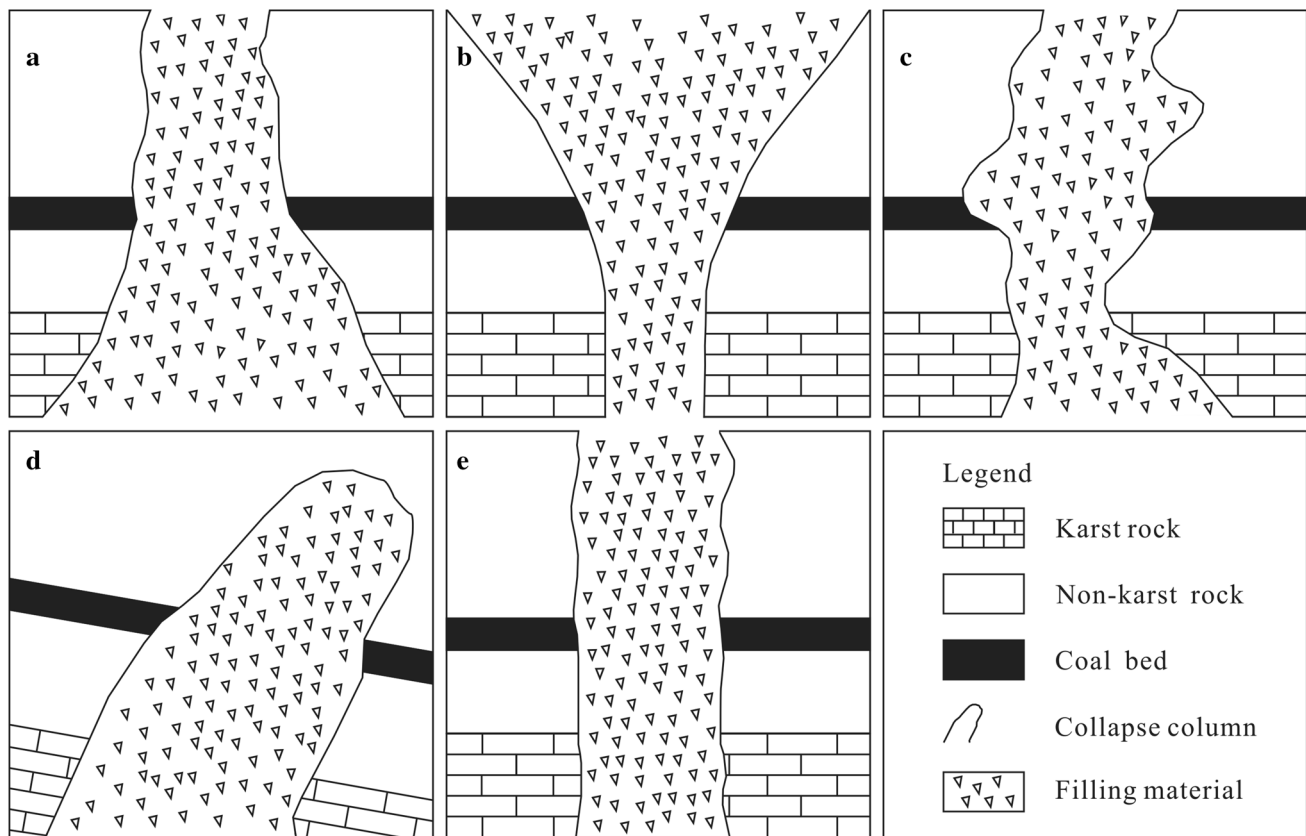


Fig. 2 Profile shapes of coal collapse columns. **a** Inverse funnel shaped; **b** funnel shaped; **c** irregular shaped; **d** inclined shaped; and **e** cylinder shaped (adapted from Si et al. 2001)

600 m, while the smaller ones can be less than 10 m, covering an area from several tens to several thousands of meters. The height of the coal collapse columns also varies significantly, which depends on the scale of the columns. Groundwater flow in larger columns is more active, and fissures around the columns are more developed, resulting in larger scale of karst collapse and larger height of the columns. Most coal collapse columns have a height of 10–100 m, while a few that reach to the ground surface may have a great height, such as those in the Yangquan, Fenxi coal mines in the Shanxi province, where the height reaches up to several hundred meters. Generally, the filling in coal collapse columns is crushed rocks from the overlying coal-bearing strata and is accumulated disorderly, which is the result of slow collapse of the roof of the karst caves. However, in some cases the roof of the karst caves falls abruptly, and the rocks above the caves may drop as a whole, which are very similar to faults and may be misjudged.

The occurrence of coal collapse columns not only disturbs the distribution of coal beds and the arrangement of mining areas, but also can result in mine water bursting if the columns are water conductive and revealed by mining.

Water bursting is often catastrophic and is a universal problem faced by all the coal-producing countries. In China, ca. 27 % of the coal resources are threatened by groundwater, and water bursting happens frequently (Yin et al. 2004). One most famous event happened in the Fangezhuang coal mine in Tangshan city in year 1984 when water rushed into the roadway through a large coal collapse column with a maximum flow rate of 2053 m³/min, resulting in submergence of the mine in 21 h (Zhang et al. 2016). Since water bursting related to coal collapse columns is characterized by large flow rates and is difficult to be predicted, it is of great importance to identify coal collapse columns accurately to ensure mining safety.

At present, the main methods for detection of coal collapse columns are geophysical surveys and borehole drilling. Geophysical surveys are characterized by a strong ability and high efficiency of detection and have an advantage in the detection of coal collapse columns. The three-dimensional morphology of coal collapse columns can be depicted by using high-resolution 3D seismic exploration, but it is very expensive. By using controlled source audio-frequency magnetotellurics (CSAMT) and direct current prospecting, the distribution area of the coal

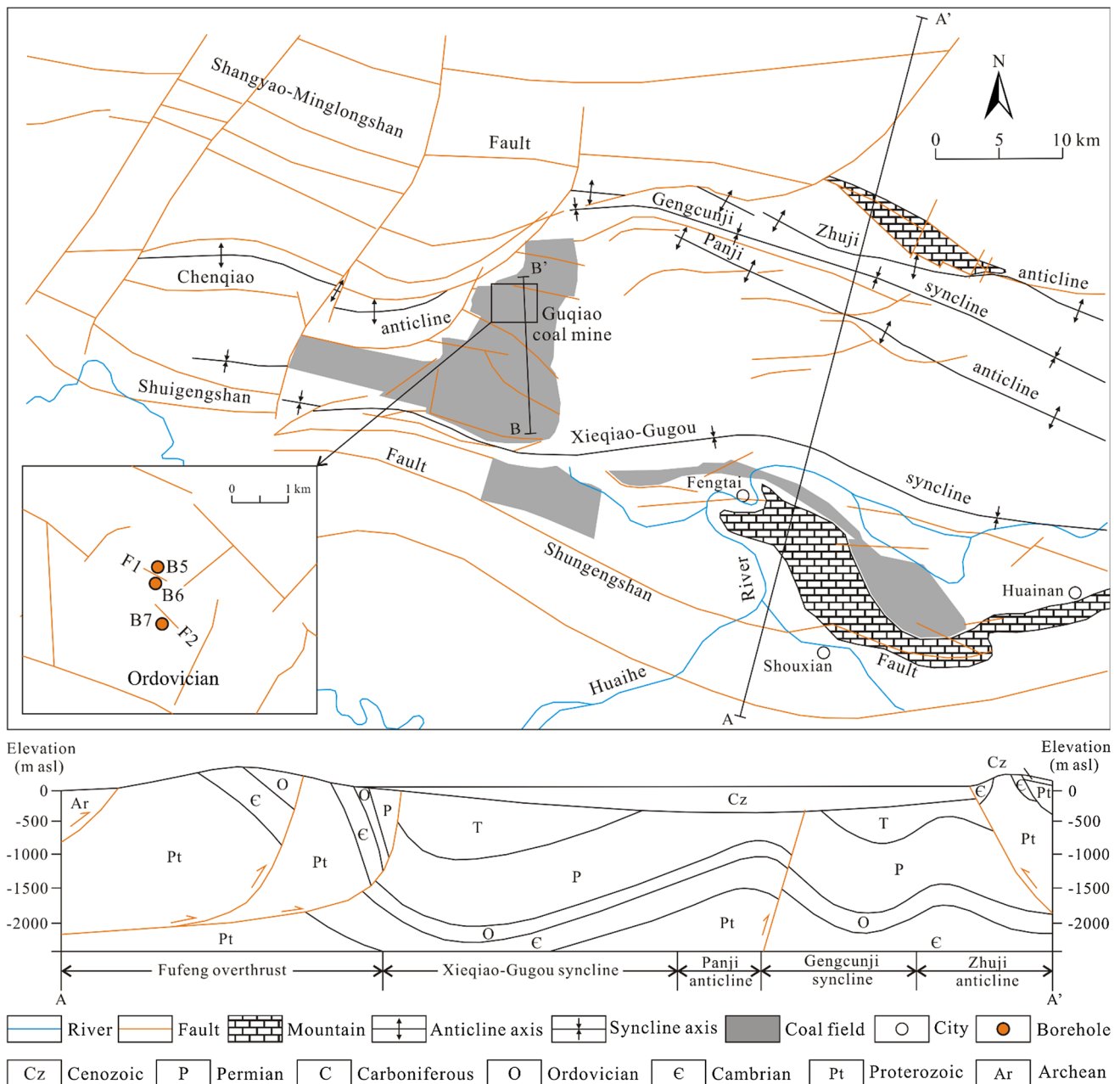


Fig. 3 Schematic geological map of the substratum below the Cenozoic sediments, Huainan coal field

collapse columns can be determined (Yang 2013). Borehole drilling is more direct and accurate for detection, but the detection area is limited, and a lot of drilling has to be done to find out the boundary of the column. Furthermore, as the genesis mechanism and morphology of coal collapse columns are various, such as that when the rocks above the karst caves drop as a whole, the fillings in the columns remain as layers and can lead to the missing of some strata in the boreholes, and it can easily be misjudged as caused by faults. In this case, drilling must be used with other

methods for identification of coal collapse columns and faults. In a mining area in the Guqiao coal mine, Huainan city which is the largest in Asia, such a geologic structure was discovered by 2D seismic exploration, and since there was only one survey line that passed through the structure, it is hard to distinguish the structure between coal collapse columns and faults. Here, based on drilling, we propose a method that is a combination of sediment dating and borehole seismic inversion and apply it to the identification of the structure.

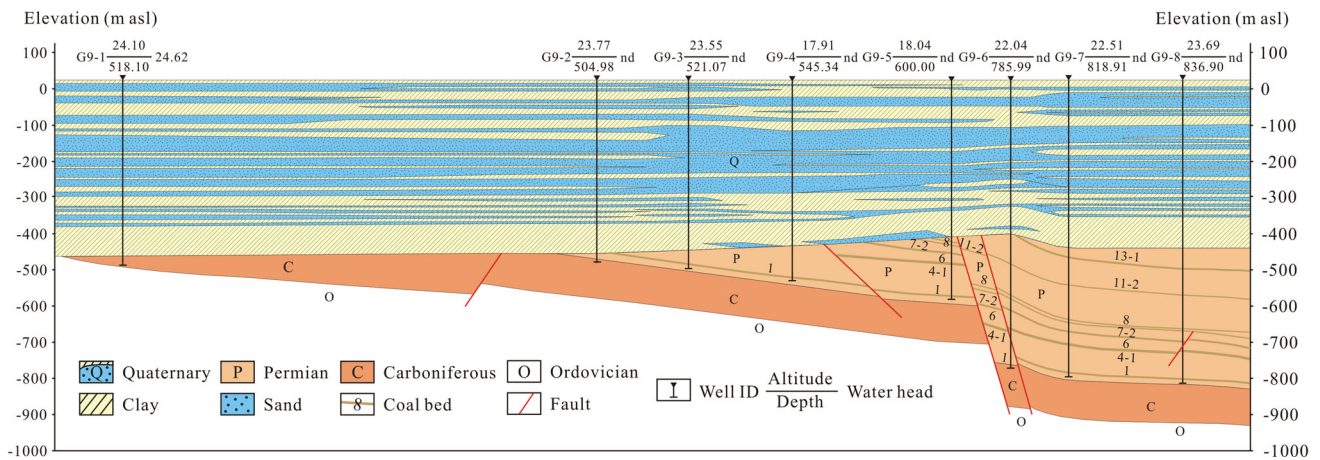


Fig. 4 Schematic hydrogeological cross section (B–B' in Fig. 3) of the Huainan coal field

Study area

The Huainan coal field is located in the southern part of the North China Plate (Fig. 1). The main tectonic structure is a W–E stretched faulted-folding ramp belt formed by collision of Yangtze and North China plates in the Late Permian to Triassic. It includes three subunits, i.e., the Bagongshan–Shungengshan nappe tectonic belt in the south which thrusted from south to north, the Minglongshan–Shangyao nappe tectonic belt in the north which thrusted from north to south, and the Huainan synclinorium in the center which constitutes the main part of the Huainan coal field (Fig. 3). The intense compression and overthrust have resulted in faulting of the coal-bearing strata, controlling the structural framework and morphology of the coal field (Song et al. 2005; Zhang 2010). The main tectonic lineament strikes NWW and is cut by the other one which strikes NNE. In the central part of the Huainan synclinorium, there are a series of gentle folds, i.e., the Xieqiao–Gugou syncline, Chenqiao anticline, Panji anticline, Guqiaoji syncline, and the Zhuji anticline. The study area at the Guqiao coal mine is situated at the joint region of the Chenqiao and Panji anticlines, and the main structure is a monocline that strikes NS and dips to the east. The strata slope gently with a dip angle of 5°–15°. In the Guqiao coal mine, the whole area is covered by loose sediments of the Quaternary, with a thickness of 224–576 m. The underlying strata include the Permian which is coal bearing, the Carboniferous composed of limestone and mudstone interlayered by siltstone, the Ordovician composed of dolomitic limestone, the Cambrian composed of limestone, dolomite, shale, and conglomerate, the basement of the Proterozoic composed of phyllite, quartzite, and shale, and the Archean mainly composed of gneiss and granulite (Fig. 3). There are in total 26 coal beds with a thickness of ca. 750 m (Fig. 4), in

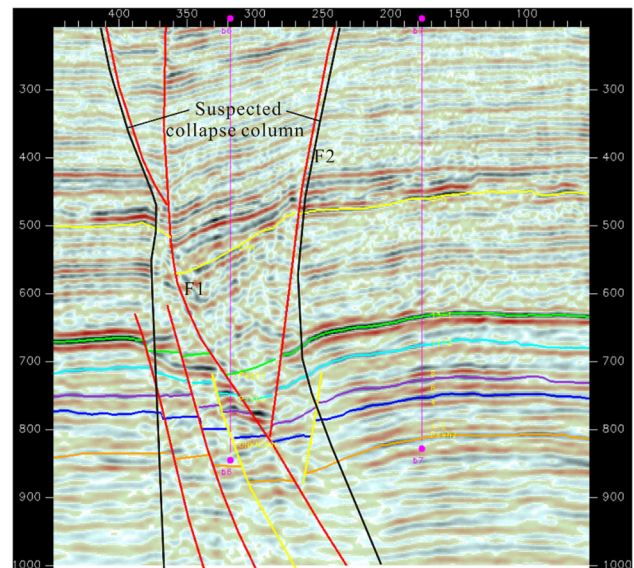


Fig. 5 2D seismic image and interpretation results for the suspected coal collapse column, Guqiao coal mine (Wang et al. 2009)

which #1, #6, #8, and #11-2 buried at the depth of 30–2000 m have been mined (Zhu and Sun 2001).

In the central part of the Huainan synclinorium where the Guqiao coal mine is located, there are four aquifers which can be summarized from the top to the bottom as follows (Fig. 4): (1) the Quaternary aquifer consisting mainly of sand and clay. The specific yield is 45–167 m³/day, and the elevation of the water table is 21.6–26.6 m. (2) The Permian aquifer consisting of coal-bearing sandstones interlayered with mudstones. The aquifer has a poor recharge condition due to weak hydraulic connection with the overlying Quaternary aquifer as they are separated by a cemented conglomerate layer with a thickness of 3–5 m. Furthermore, with a low

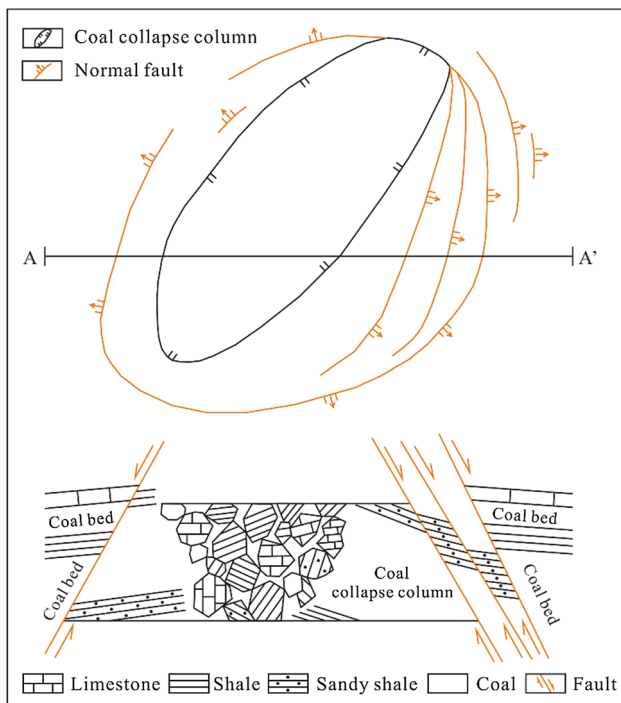


Fig. 6 Accompanying faults of coal collapse columns (adapted after Chu 1998)

permeability resulted by calcareous fillings and locally developed fractures in the sandstone, it is characterized by a weak water yield of 1–4 m³/day. The maximum elevation of the water head is 27.4 m. (3) The Carboniferous aquifer consisting of limestone interlayered with mudstone, siltstone, and thin coal beds. It is close to the overlying coal bed #1, with a thickness of ca. 16–20 m and a water head of 23.0–27.1 m, which is regionally higher than the overlying Permian aquifer, being a recharge source though leakage and water-conducting faults. It has no hydraulic connection with the Quaternary aquifer. (4) The Ordovician aquifer consisting of limestone with karst and fractures developed in the middle and lower part. It outcrops in the southeastern and northeastern part of the Huannan coal mine area (Fig. 3) and is characterized by a weak to moderate water yield of 0.3–240 m³/day (He 2015) and is the main recharge source of the overlying Carboniferous aquifer. As the thrust faults in both limbs of the Huainan synclinorium are water blocking, there is no recharge from the mountainous areas to the south and north of the synclinorium and the groundwater flow is slow, which is also identified by the water type of Cl–K·Na with a relatively high TDS of ca. 2 g/L of the pre-Quaternary aquifers. Most of the faults in the coal field are filled by cemented fragments of mudstone and siltstone and are flow inhibiting (Zhu and Sun 2001).

Materials and methods

A geologic structure has been detected in the Guqiao coal mine during a 2D seismic exploration. The seismic image shows that the structure is located in the area around boreholes B6 and B7 between lines F1 and F2 with an extension of ca. 700 m (Figs. 3, 5). The strata in it are inclined and are discontinuously contacted with the wall rock, shaped like a column. It is difficult to distinguish of line F1 and F2 between faults and column walls. Here, we call the structure as a “suspected coal collapse column.” In order to distinguish it between faults and coal collapse column, we propose a method based on sediment dating.

According to previous studies, usually a series of concentric faults formed during karst collapse will exist around coal collapse columns, which are named “accompanying faults.” These faults usually form a fault zone around the column with a width of 10–40 m and a fault throw of no more than 2 m (Fig. 6) (Chu 1998; Qiu 2001). In the coal collapse column and the accompanying fault zone, the strata are destroyed and are moved with the faults, but in the area beyond the zone the occurrence of the strata is not interrupted, i.e., the same strata located to both sides of the column are not cut off and thus have no separation. This is a good point to distinguish between coal collapse columns and faults since if the strata are cut by faults, there would be significant separation between the two fault walls. However, if the faults cut into the overlying unconsolidated Quaternary sediments, it is usually hard to determine by lithology whether the sediments to both sides of coal collapse columns or faults are the same layer. Here, we make a hypothesis that within a small area, the Quaternary sediments were deposited under weak hydrodynamic conditions, so that the sediments at the same depth belong to the same layer, and thus have the same age. Based on this hypothesis, we can determine whether the strata have been cut off by faults through sediment dating.

By application of the proposed method, we try to determine whether the two lines of F1 and F2 around the detected structure are common faults or walls of coal collapse columns. Three boreholes numbered as B5, B6, and B7 were drilled. B5 is located to the north of F1, B7 is located to the south of F2, and B6 is located between F1 and F2. The depth of B5, B6, and B7 are 771.7, 1036.4, and 1038.9 m, respectively. The distance is 275 m between B5 and B6 and 707 m between B6 and B7. Both B5 and B7 are more than 50 m from F1 and F2; thus, if the structure is a collapse column, B5 and B7 are beyond the occurrence area of the accompanying faults. Sediments of the Quaternary were sampled from the boreholes in 2007. Sediment layers of alluvial and lacustrine clay, silt, and fine sands were sampled with a thickness of more than

Table 1 ESR and TL dates for sediments from the Guqiao coal mine

B5		B6		B7		Method
Depth (m)	Age (Ka)	Depth (m)	Age (Ka)	Depth (m)	Age (Ka)	
20.0	62.69 ± 5.33	20.9	59.61 ± 5.07			TL
52.1	99.72 ± 8.45	50.3	76.74 ± 6.52			TL
100.8	274 ± 27	101.6	165 ± 16	152.5	223 ± 22	ESR
200.3	558 ± 55	200.2	303 ± 30	200.2	346 ± 35	ESR
416.3	907 ± 90	482.8	722 ± 72	382.3	695 ± 69	ESR

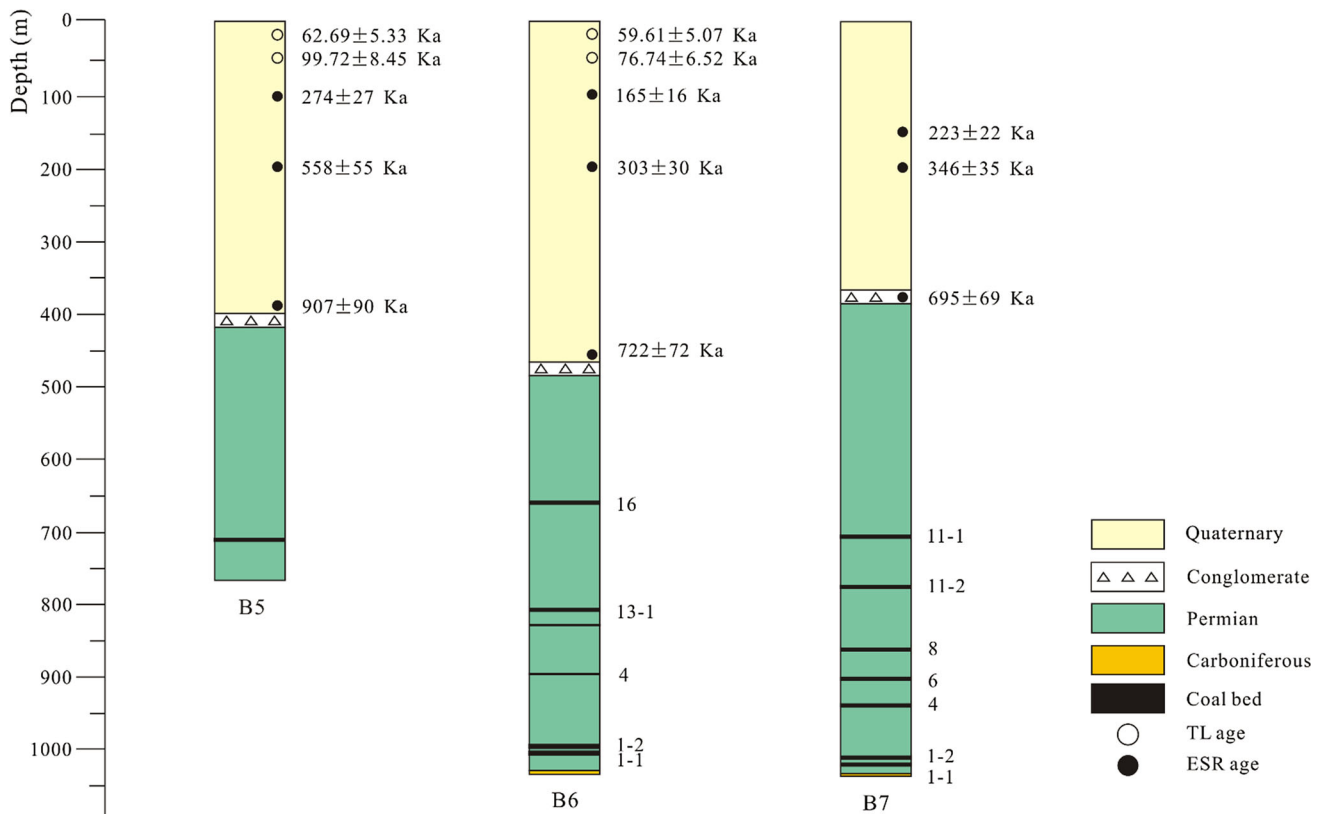


Fig. 7 ESR and TL dates for sediments from borehole B5, B6, and B7, Guqiao coal mine

5–60 cm. The sampled layers are characterized by a homogeneous lithology, being well sorted and with micro-beddings. The weight of each sample is 500 g, and in total 14 samples were obtained in the buried depth of 20.0–482.8 m (Table 1). The samples were packed in light-preventing plastic films and are placed in iron tins. The ages of the samples were analyzed by electron spin resonance (ESR) and thermoluminescence (TL) dating (Aitken 1985; Grün 1989) at the Laboratory of Neotectonics and Chronology, Institute of Geology and Institute of Crustal Dynamics, both affiliated to China Earthquake Administration, respectively. ESR dating of quartz allows assessment of the last time of sunlight exposure of hydraulic or eolian deposits in the time range back to a few thousand to a few million years, with an average error range of 10 %,

while TL dating gives time range back to a few tens of thousands to a few million years for the 4–11 and 90–250 μm grains of the samples, with an average error range of 3–10 %.

Results and discussion

Well loggings, including density, natural gamma ray, apparent resistivity, spontaneous potential, and acoustic and core loggings for the boreholes, show that strata from top to bottom in B5 are Quaternary with thickness of 417.0 m, a conglomerate layer of 3.0 m between Quaternary and bedrock, while in B6 the strata are Quaternary for 482.7 m, a conglomerate layer of 4.8 m, Permian for

543.7 m, and Carboniferous for 5.2 m, and in B7, the strata are Quaternary for 380.6 m, a conglomerate layer of 1.0 m, Permian for 654.6 m, and Carboniferous for 2.7 m. At the depth of 716.5–1031.2 m in B6, there are 12 fracture zones and coal beds #6, #8, and #11-2 are missing, while in B5 and B7 fracture zones were, relatively, not developed. The ESR and TL dating results of the sediments are shown in Table 1 and Fig. 7, indicating that the ages of the sediments increase with depth in each borehole. At the buried depth of 20.0 m, the ages of the sediments are nearly the same for the three boreholes, while at the buried depth of 100.0 m, the ages show significantly difference, the sediment in B5 is the oldest. At the buried depth of 200.0 m, the ages of the sediments in B6 and B7 are similar, while the sediment in B5 is older. The ages of the conglomerate layer are similar for B5, B6, and B7 and can be regarded as the same layer, but the buried depth of the layer is significantly different, i.e., 416.3 m in B5, 482.8 m in B6, and 382.3 m in B7. The differences in ages of the sediments at the same depth below depth of 100 m indicate significant displacements in the strata around the “suspected coal collapse column.” Based on our hypotheses, it can be inferred that the strata between B5 and B6 and B6 and B7 had been cut off by common faults, i.e., the discontinuous interface of F1 and F2 are faults and are not walls of a coal collapse column. As the ages of the sediments at buried depth of 20.0 m in B5 and B6 are the same, the age can be regarded as the upper limit of F1, and the ages of the sediments at buried depth of 100.0 m can be regarded as the lower limit; thus, the age of F1 is 165.00–59.61 Ka in the Middle Pleistocene, while the age of F2 is 303–695 Ka in the Middle Pleistocene and Late Pleistocene using the ages of the sediments at buried depth of 200.0 m in B6 and B7 as the upper limit and the ages of the conglomerate layer as the lower limit. As the structure has been identified as common faults, 2D inversion and interpretation using the method of EPS and JASON were performed for B6 and B7 (Wang et al. 2009). In the interpretation, the faults were detected by instantaneous phase section and coherence section, while the lithologic pinch out by instantaneous phase section. The results are in accordance with drilling and sediment dating, and fault F1 was revealed by B6 at the buried depth of 716.5 m (Fig. 5).

Conclusions

On the basis of drilling, combined with dating of loose Quaternary sediments, the distribution of strata around coal collapse columns or faults can be determined; thus, the structure that cannot be interpreted as coal collapse columns or common faults by drilling or 2D seismic data can

be distinguished. These results provide a geological basis for strata calibration and geological structure interpretation for cross-hole seismic data inversion. This method based on sediment dating combined with borehole drilling and geophysical surveys has the potential to be a new tool for effective identification of coal collapse columns as shown by application to the case of the Guqiao coal mine in the Huainan coal field, North China.

References

- Aitken MJ (1985) Thermoluminescence dating. Acad Press, London
- Chen SP (1993) A discussion on the genesis of karst collapse columns in Fengfeng area, Hebei Province. *Carsol Sin* 12:233–244
- Chu ZZ (1998) The characteristics of the accompanying faults of collapse column and the prediction of collapse column. *Coal Geol Explor* 26:6–28
- Grün R (1989) Electron spin resonance (ESR) dating. *Quatern Int* 1:65–109
- He ZH (2012) Study on development characteristic of karst collapse column and water Inrush mechanism in Shuangliu Mine. Ph.D.'s Dissertation, Chin Univ Coal Min Tech
- He JH (2015) Study of structural control mechanism on Groundwater in the north mining area of Huainan coal field. Master's Thesis, Anhui Univ Sci Tech
- Kang YR (1992) Collapse-causing models in karstic collapse process. *Hydrogeol Eng Geol* 4:31–46
- Qian XB (1960) The characteristics of Karst in Xianxi Plateau. *Hydrogeol Eng Geol* 3:19–23
- Qiu XF (2001) The structures around caved pillar by coal layer detached. *Xishan Sci Tech* 2:1–3
- Si SP, Ma JM, Hu DX (2001) Genesis and distribution of collapse column coal-bearing strata. *Fault Block Oil Gas Field* 8:15–18
- Song CZ, Zhu G, Liu GS, Niu ML (2005) Identification of structure and its dynamics control of Huainan coal field. *Coal Geol Explor* 33:11–15
- Wan TF (2012) The tectonics of China: data, maps and evolution. Springer, Berlin
- Wang R (1982) Genesis of karst collapse columns in North China. *Hydrogeol Eng Geol* 1:37–41
- Wang Y, Lu J, Shi Y (2009) Neotectonics and its detail survey of the Guqiao coal mine, Huainan coal field. *Inst Geol Geophys. Chin Acad Sci, Beijing*
- Xu WG, Zhao GR (1990) Genesis of karst collapse columns and water bursting in coal fields in North China. *Hydrogeol Eng Geol* 6:41–43
- Yang WY (2013) Integrated geophysical prospecting principle and method of exploring the water enrichment of coal mine collapse column. *J Min Saf Eng* 30:45–50
- Yin SX, Wang SX, Wu Q (2004) Water inrush patterns and theoretic criteria of karstic collapse columns. *Chin J Rock Mech Eng* 23:964–968
- Zhang CL (2010) Characteristics and forming mechanism of karstic collapse columns (belts) at coal field in Huainan. Master's Thesis. Hefei Univ Tech
- Zhang JJ, Zhu YM, Zhou XG (2016) Formation process and prediction of karst collapse column in Fangezhuang coal mine. *Coal Eng* 48:88–91
- Zhu WW, Sun MY (2001) Geological suvery report of the Guqiao coal mine. Huainan Min Group, Huannai