frontiers | Frontiers in Earth Science

TYPE Original Research
PUBLISHED 25 January 2023
DOI 10.3389/feart.2022.1014918

Check for updates

OPEN ACCESS

EDITED BY
Guiting Hou,
Peking University, China

REVIEWED BY
Liang Qiu,
China University of Geosciences, China
Dan Ma,
China University of Mining and Technology, China
Lei Li,
Xi'an University of Science and Technology, China

*CORRESPONDENCE
Xiaorong Zhai,
zhaixiaorong@sina.com

SPECIALTY SECTION
This article was submitted to Structural Geology and Tectonics, a section of the journal Frontiers in Earth Science

RECEIVED 09 August 2022
ACCEPTED 25 November 2022
PUBLISHED 25 January 2023

CITATION
Gu C, Zhai X, Wu J, Li G, Wang X, Tan P and Hao H (2023), Structures, deformation history and dynamic background of the Qianyingzi Coal Mine in the Huaibei Coalfield, eastern China. *Front. Earth Sci.* 10:1014918. doi: 10.3389/feart.2022.1014918

Structures, deformation history and dynamic background of the Qianyingzi Coal Mine in the Huaibei Coalfield, eastern China

Chengchuan Gu[1], Xiaorong Zhai[1]*, Jiwen Wu[1], Guangping Li[2], Xin Wang[2], Pengfei Tan[1] and Hongjun Hao[1]

[1]School of Earth and Environment, Anhui University of Science and Technology, Huainan, China,
[2]Qianyingzi Coal Mine, Anhui Hengyuan Coal and Electric Co., Ltd., Suzhou, China

The Qianyingzi Coal Mine is located in the west of the Suxian Mining District of the Huaibei Coalfield, eastern China. The study on structural development patterns and genetic mechanisms in this mine lays an important foundation for safe and efficiently underground mining, and is also the key to understanding the regional tectonic evolution. In this study, based on the analysis of three-dimensional seismic, drilling and underground measured data and regional tectonic correlation, the structures, evolution history and dynamic background of the Qianyingzi Coal Mine are discussed. The Carboniferous-Permian coal measure strata in the mine are generally a gentle syncline with a NNE-trending axis, and cut by a series of faults. The faults developed in this mine are mainly medium- and small-sized with a throw of less than 20 m, and the number of reverse faults is significantly greater than that of normal faults. The strikes of reverse and normal faults are both mainly NE, followed by NNE and nearly N–S. According to the characteristics of structural geometry, tectonic association, fault property and cross-cutting relation, the structural deformation of coal measure strata in the Qianyingzi Coal Mine can be divided into five stages, and the corresponding tectonic stress fields are NWW–SEE compressive stress, nearly E–W compressive stress, NW–SE compressive stress, nearly E–W and NW–SE extensional stresses, respectively. It developed the Fengjia Syncline with a NNE-trending axis in the first stage and nearly N–S-striking reverse faults in the second stage, which were the results of foreland deformation and subsequent continent-continent collision during the convergence of the North China Craton and South China Plate in the Indosinian period. The NNE-striking reverse sinistral faults and NE-striking reverse faults developed in the third stage is related to the rapid oblique subduction of the Izanagi Plate toward the East Asian continental margin at the beginning of the Early Cretaceous in the western Pacific region. Later, the fourth and fifth stages of the nearly N–S- and NE-SW-striking normal faults were developed under the backarc extensional background in eastern China during the Early Cretaceous. These new results can be used to guide the rational arrangement for underground mining and also provide a new understanding for regional tectonic evolution of the Huaibei Coalfield.

KEYWORDS

fault, fold, tectonic stage division, tectonic stress field, Qianyingzi Coal Mine

Introduction

The geological structures of the coal mine not only control the occurrence of coal seams, but also have a significant impact on geothermal distribution, coal and gas outburst, mine water inrush and other mining conditions (Li and Wu, 2002; Hou et al., 2012; Wang et al., 2013; Pan et al., 2014; Ma et al., 2022a; Ma et al., 2022b). Finding out the development degree, nature, distribution characteristics and superposition relationship of geological structures in the coal mine can lay an important foundation for safe and efficiently underground mining, and is also the key to understanding the regional tectonic evolution.

The eastern China is located in the intersection zone of the Paleo-Tethys tectonic domain and the Paleo-Pacific tectonic domain, and experienced transition of two tectonic regimes during the Mesozoic (Zhao et al., 2004; Dong et al., 2015; Zhu et al., 2020). The Huaibei Coalfield is located in the southeastern margin of the North China Craton, with the Tan-Lu Fault Zone and Sulu Orogen to the east (Figure 1A). The eastern part of the Huaibei Coalfield is the Xu-Su Arc Nappe Belt, while the middle and the west are covered by Cenozoic basins. It is an ideal area to record the superposition of the two tectonic regimes, due to its special geotectonic location. A large number of valuable geological data in the hidden areas, such as drilling, three-dimensional seismic and underground measured data from the Huaibei Coalfield, have been accumulated over the years, which can provide important evidence for the analysis of structural comparison, tectonic evolution history and geodynamic background.

Previous studies have been carried out on a series of mine structures in the Huaibei Coalfield, but the understanding on the regional tectonic deformation history after coal-forming period is still controversial. Qu et al. (2008) considered that the Huaibei Coalfield was successively subjected to N–S compression in Indosinian period, NWW–SEE compression in late Indosinian and early Yanshanian periods, NNW–SSE compression in middle Yanshanian period, and regional extension in Late Yanshanian and Himalayan periods. Zhang (2011) thought that the Huaibei Coalfield has experienced four stages of compressional stress fields after coal-forming period, namely N–S, NW–SE, NE–SW and nearly E–W. Peng (2015) divided a large number of faults in the Huaibei Coalfield into five stages, namely the E–W-striking faults in Indosinian period, the NNE-striking faults and the Xu-Su arc-shaped thrust faults in early Yanshanian period, the N–S- to NE-striking tensional faults in late Yanshanian period, the E–W-striking faults in early Himalayan period and the N–S-striking faults in late Himalayan period. Fang et al. (2017) held the view that the Huaibei Coalfield had experienced at least three tectonic events, namely N–S compression in Indosinian period, NWW–SEE compression in early Yanshanian period and NWW–SEE extension in late Yanshanian period. Liu (2017) divided the main structural deformation in Huaibei Coalfield into four stages: nearly N–S compression with weak influence in Indosinian period, NW–SE compression with strong influence in early Yanshanian period, nearly E–W extension in late Yanshanian period, and nearly N–S extension in Himalayan period.

The Qianyingzi Coal Mine is located in the west of the Suxian Mining District in Huaibei Coalfield, with Suzhou City only 15 km away to the northeast (Figure 1B). Previous studies on this mine mainly focused on the mine hydrogeology (Li and Gao, 2015; Li, 2016), gas geology (Wei et al., 2011), occurrence characteristics of coal seam (Li et al., 2011) and geothermal distribution (Wu et al., 2013). During the exploration and mining, it is revealed that the fold and fracture structures are relatively developed in Qianyingzi Coal Mine, and the mining face is significantly affected by them. Therefore, based on the latest geological data including three-dimensional seismic, drilling, and underground measured data, this paper studies the structural characteristics, formation mechanisms, deformation history and regional dynamic background of the Qianyingzi Coal Mine through the statistics of structures, analysis of tectonic combination and staging, and regional structural comparisons.

Geological setting

The Carboniferous-Permian period is the first major coal-forming period in the North China Craton, and the coal accumulation scale under the sedimentary background of the craton basin is very high. From the end of Late Paleozoic to early Mesozoic, the North China Craton collided with a series of surrounding plates successively, which not only ended the marine sedimentary activities, but also caused strong tectonic deformation and uplift and denudation of the sedimentary cover due to the strong plate collision dynamics (Zhu et al., 2020). During the middle to late Mesozoic, a large-scale lithospheric thinning event occurred in the eastern part of the North China Craton, resulting in the development of a large number of metamorphic core complexes, rift basins and intense magmatic activities (Zhu G. et al., 2012; Zhu R. X. et al., 2012; Zhu et al., 2015). Controlled by the subduction of the Paleo-Pacific Plate in the western Pacific region during the Mesozoic, a large number of NNE- to NE-trending tectonic traces were superimposed and developed on the continental margin of East Asia (Xu et al., 1987; Zhang et al., 2018; Zhu et al., 2018; Zhang et al., 2020; Zhu et al., 2021).

The Huaibei Coalfield is located in the southeastern margin of the North China Craton and covers the front and outer edges of

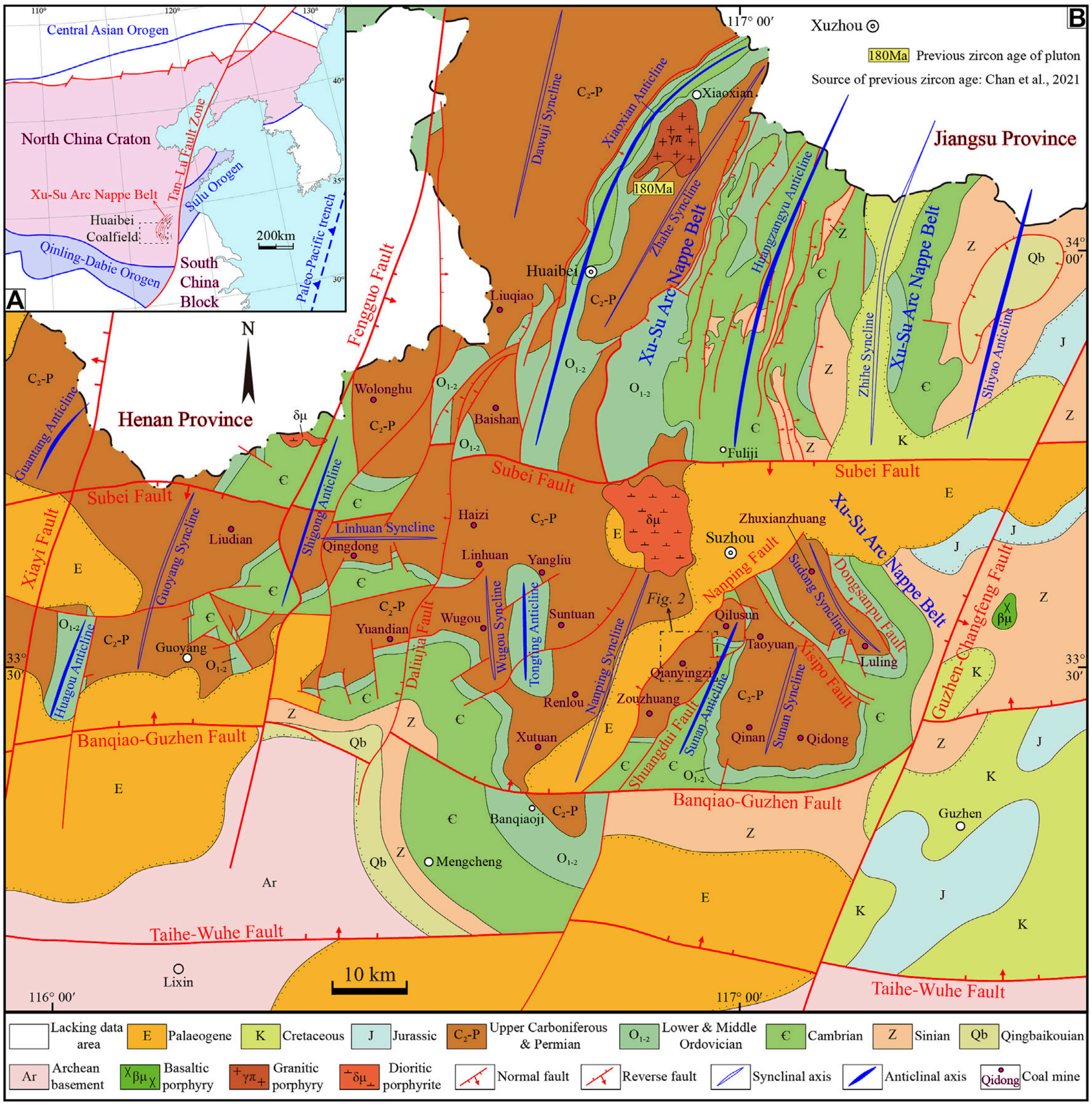

FIGURE 1
(A) Tectonic map of eastern China (modified after Zhang et al., 2020). **(B)** Outline map of bedrock structures in the Huaibei Coalfield (modified after Xie et al., 2015).

the Xu-Su Arc Nappe Belt and the northeast of the Hehuai subsidence area, which is sandwiched between the Bengbu and Fengpei uplifts by the Taihe-Wuhe Fault in the south and the Fengpei Fault in the north, and connected with the Zhoukou Basin by the Xiayi Fault in the west, and adjacent to the Sulu Orogenic Belt by the Tan-Lu Fault Zone in the east, respectively (Figure 1B). Due to the superposition of nearly E–W-striking large faults (such as Subei Fault, Banqiao-Guzhen Fault), NNE-striking large faults (such as Fengguo Fault, Guzhen-Changfeng Fault) and Xu-Su Arc Nappe Belt, the Huaibei Coalfield is divided into multiple fault blocks horizontally, while vertically it can be divided into the nappe system and underlying *in-situ* system (Qu et al., 2008; Xie et al., 2015). Taking the Subei Fault as the boundary, the northern fault block of the Huaibei Coalfield is the outcropping area of the Xu-Su Arc Nappe Belt. The hanging wall system of the nappe is composed of a series of parallel imbricate thrust faults with eastward inclination and Jura-type folds. The direction of tectonic trace gradually changes from NE to nearly N–S, and protrudes to the west in an arc (Shu et al., 2017; Li et al., 2018). The west of the Xiaoxian Anticline is the underlying *in-situ* system of the Xu-Su Arc Nappe Belt, with weak deformation and broad and gentle NNE-trending folds (Figure 1B).

It is covered by Neogene and Quaternary unconsolidated sediments to the south of Subei Fault. The NW-striking Xisipo

Thrust Fault and the Sudong Syncline to the east are the southern extension ends of the hanging wall system of the Xu-Su Arc Nappe Belt. The west of the Xisipo Thrust Fault is the underlying *in-situ* system of the arc nappes, which develops a series of NNE- and N–S-trending broad and gentle short-axis folds. From east to west, it mainly includes the Sunan Syncline, Sunan Anticline, Nanping Syncline, Tongting Anticline, Wugou Syncline, Shigong Anticline and Guoyang Syncline (Figure 1B) (Ju and Wang, 2002; Fang et al., 2017). Taking the Nanping and Fengguo faults as boundaries, the southern block of the Subei Fault is further divided, from east to west, into the Suxian, Linhuan and Guoyang mining districts. The Huaibei Coalfield mainly developed two periods of magmatic activity, namely the Neoproterozoic basic dyke swarms (Liu et al., 2006; Wang et al., 2012; Cai et al., 2018) and Mesozoic intermediate-acid intrusive rocks (Xu et al., 2004; Yang et al., 2008; Chan et al., 2021).

The Qianyingzi Coal Mine is located in the west limb of the Sunan Anticline in the Suxian Mining District. It is sandwiched in the fault block between the Nanping and Shuangdui faults, together with the Zouzhuang Coal Mine in the south and Qilusun exploration area in the north (Figure 1B). The exposed strata in the mine include Ordovician, Carboniferous, Permian, Paleogene, Neogene and Quaternary. The Ordovician System is distributed in the hanging wall of the DF200 reverse fault on the eastern boundary of the mine, overlying the Permian System, and its main lithology is dolomitic limestone. The Shanxi, Lower Shihezi and Upper Shihezi formations in the Permian are the main coal-bearing strata, which the lithologic association dominantly consists of interbedded mudstones, sandstones, siltstones and coal seams. The minable coal seams include coal seam 3_2, 5_1, 5_2, 5_3, 6_2, 7_2, 8_2 and 10, among which coal seam 3_2 is the main minable seam of the mine. The Paleogene is only found to be distributed in the hanging wall of the Nanping fault to the northwest, with a maximum thickness of more than 550 m, and its lithology is terrestrial clastic rock. The Neogene and Quaternary unconsolidated sediments are distributed throughout the whole region, and are in angular unconformity contact with the underlying strata. There are a large range of magmatic intrusions in 7_2, 8_2 and 10 coal seams in the mine. The intrusive body is veinous or layered, and the lithology is porphyritic intermediate rock.

Structures of mine

Folds

The coal measure strata in the mine are generally in a broad and gentle syncline (hereinafter referred to as the Fengjia Syncline) with a hinge plunging to NNE, and cut by a series of nearly N–S-, NNE- to NE-striking faults (Figure 2). In the seismic sections, the two limbs of the Fengjia Syncline are asymmetrically developed (Figures 3A–D). The west limb is longer, and the strata generally dips to the east. Affected by the faults, the east limb is short, and the occurrences of strata are variable. To the north of exploration line 43, the syncline disappears, and the coal measure strata show a monocline dipping eastward (Figure 3E). In general, the dip angles of the strata in the mine are relatively gentle, mostly in the range of 5°–16°. The west limb of the Fengjia Syncline is affected by F25, F22 and other faults, and the maximum dip angle exceeds 20°. The strata in the east limb are gentle, and the dip angles become steeper only close to the F17 fault, locally even nearly vertical.

There are three secondary folds in the mine. Among them, the Yaotangzi anticline is located in the west limb of the Fengjia Syncline close to the mine boundary, with a NEE-trending axis and axial length of about 3 km, and is cut by the Nanping and F22 faults (Figure 2). In the seismic sections, the hinge zone of Yaotangzi anticline is always located at the common wall between the F25 reverse fault and F22 normal fault, and occurs close to the F25 reverse fault (Figures 3B,C). The west limb of the anticline is short and mostly incomplete, while the east limb is longer, which is the extension of the west limb of the Fengjia Syncline. Therefore, the Yaotangzi anticline should be an asymmetric secondary fold formed by the drag and bending of F25 reverse fault in the west limb of the Fengjia Syncline. The large throw of the F22 normal fault increases the wave height of the anticline to a certain extent.

The Dongpingji anticline and Lizhai syncline are two continuous secondary folds located between the F17 and DF200 faults in the east limb of the Fengjia Syncline (Figure 2). Their axial directions are NNE, parallel to the F17 fault. The hinges are both plunging to NNE, with an axial length of about 3.8 km, which roughly distribute between exploration lines 28 and 38. In the seismic sections, the hinge zone of the Dongpingji anticline is always located in the hanging wall of the F17 reverse fault. Its west limb is short or even undeveloped, while the east limb is longer, and is cut by a series of NNE- to NE-striking reverse faults (Figures 3B,C). The east limb of the Lizhai syncline is also incompletely developed, due to the cutting of the DF200 fault. Therefore, the Dongpingji anticline and Lizhai syncline should be formed by simultaneous shortening deformation with F17 reverse fault and a series of parallel reverse faults to the east. Among them, the Dongpingji anticline is significantly controlled by the thrust dragging of the F17 reverse fault.

Two types of small folds are relatively developed in the roof and floor of coal seam 3_2 during the mining. The first type is a gentle fold with a large interlimb angle and an amplitude of mostly less than 30 m, and the overall distribution regularity is not obvious. The other type is the drag fold associated with the fault, and the two limbs are asymmetrically developed. The development of the latter is controlled by the scale and displacement of the fault.

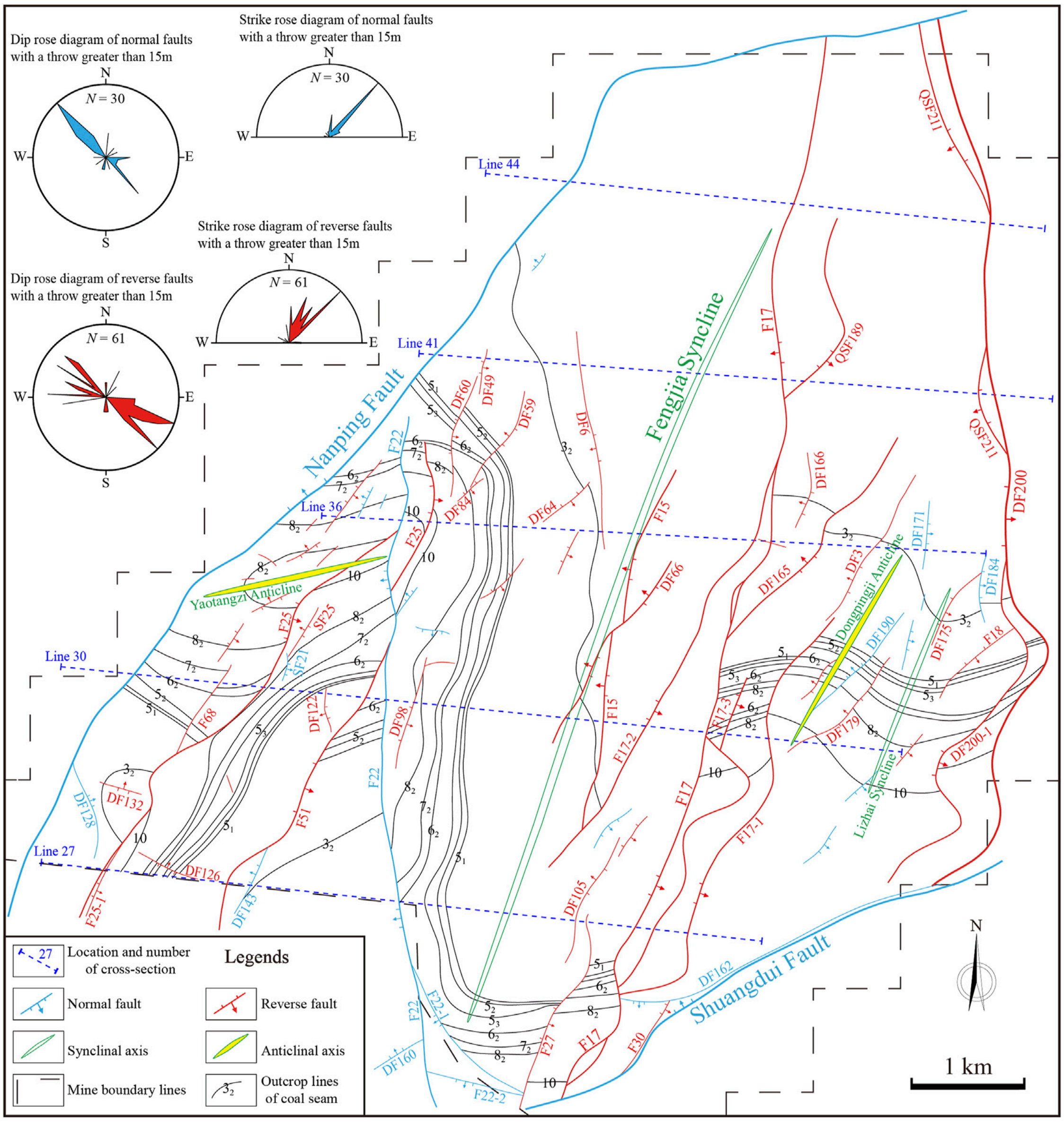

FIGURE 2
Structural outline map interpreted from -650 m horizontal seismic section of the Qianyingzi Coal Mine.

Faults

Combined with three-dimensional seismic, drilling and logging data, a total of 458 faults were revealed in the Qianyingzi Coal Mine, including 158 normal faults and 300 reverse faults. Among the normal faults, there are 5 faults with a throw of more than 100 m, 13 faults with a throw of more than 20 m and less than 100 m, and 140 faults with a throw of less than 20 m. For reverse faults, there are 10 faults with a throw of more than 100 m, 28 faults with a throw of more than 20 m and less than 100 m, and 262 faults with a throw of less than 20 m. Therefore, this mine mainly develops reverse faults, accounting for about two-thirds of the total. Among the two types of faults, the medium- and small-sized faults with a drop of less than 20 m comprise the greatest proportion, accounting for 87.8% of the total.

In this study, the occurrence statistics were performed for faults with a drop of more than 15 m (Figure 2). The results show that the number of reverse faults in the NE strike is the greatest, followed by NNE strike and nearly N–S strike. In terms of inclination, NE- and NNE-striking reverse faults are mainly dipping toward SE. The normal faults are mainly NE strike,

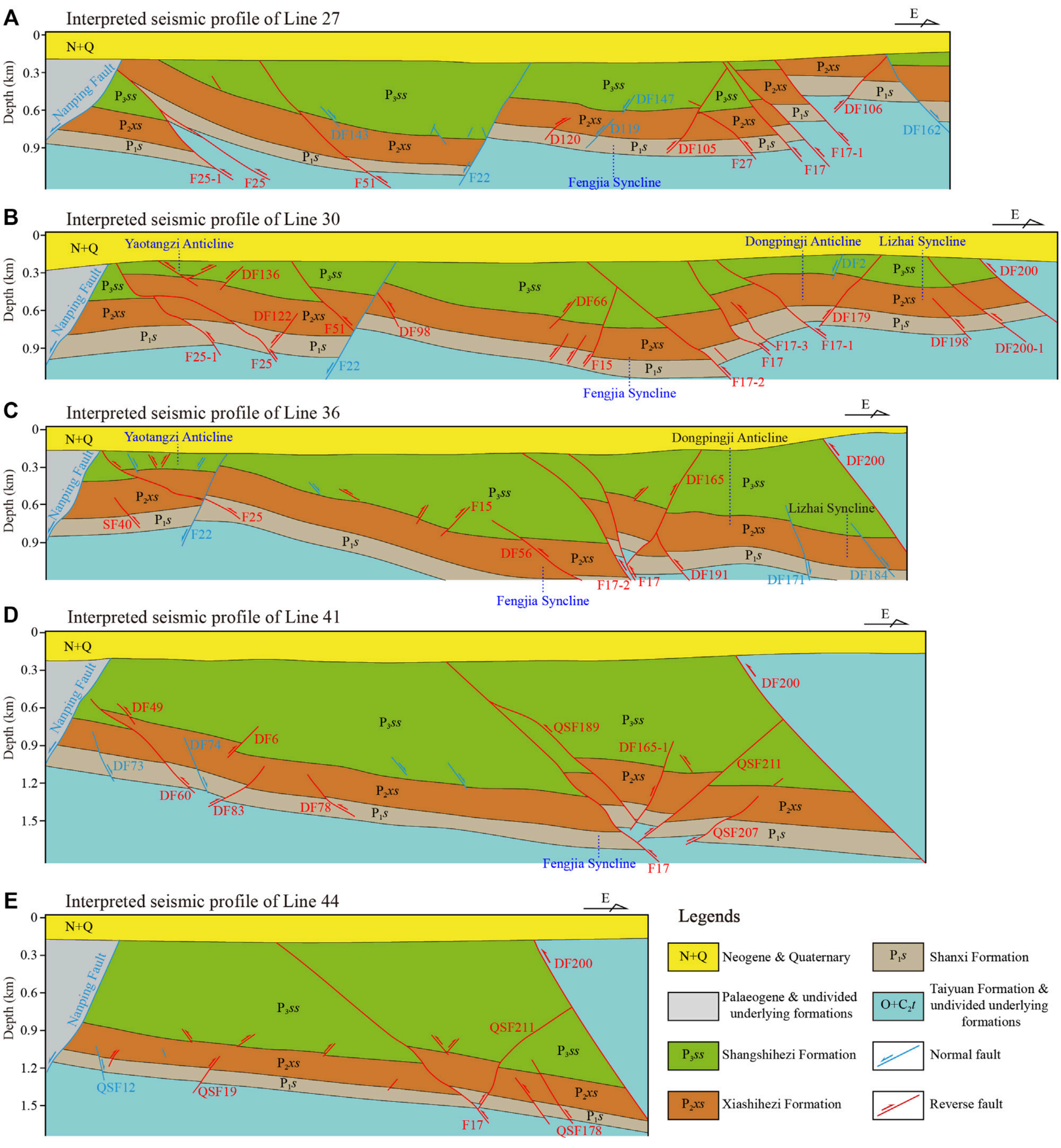

FIGURE 3
(A–E) Geological cross-sections interpreted from the seismic profiles of Line 27, 30, 36, 41, 44. The profile location is marked in Figure 2.

followed by NNE strike (close to N–S direction), and tend to dip toward NW.

The structural framework of the Qianyingzi Coal Mine is significantly controlled by several medium- and large-sized faults, which have large throw and deep cutoff, and bear a great impact on the division of mining areas, development of shafts and roadways, and layout of working faces. The characteristics of each major fault are shown in Table 1. Among them, the Nanping and Shuangdui faults are both large-scale regional normal faults with NE strike and NW dip,

TABLE 1 Statistics of major fault characteristics in the Qianyingzi Coal Mine.

Name of faults	Type	Location	Classification	Strike	Dip	Dip angle (°)	Maximum throw (m)	Length (m)
Nanping	Normal	Western border	First grade	NE	NW	70	>1000	75000
Shuangdui	Normal	Southeastern border	First grade	NE	NW	70	>1000	>3000
F22	Normal	Western limb of Fengjia Syncline	Second grade	N-S	W	65–75	350	>6500
DF200	Reverse	Eastern border	Second grade	N-S	E	45–50	>1500	10000
QSF211	Reverse	Close to eastern border	Third grade	N-S	W	35–55	200	3000
F25	Reverse	Close to western border	Third grade	NE	SE	45–50	160	5000
F51	Reverse	Western limb of Fengjia Syncline	Third grade	NE	SE	50–55	135	3000
F15	Reverse	Western limb of Fengjia Syncline	Third grade	N-S	W	45–50	65	3400
F17	Reverse	Eastern limb of Fengjia Syncline	Second grade	N-S ~ NNE	E~SEE	50–55	300	10000
F17-1	Reverse	Eastern wall of F17	Third grade	NNE	SEE	50–55	110	3900
F17-2	Reverse	Western wall of F17	Third grade	NNE	SEE	50–55	135	3900
DF165	Reverse	Eastern wall of F17	Third grade	NNE	NWW	50–55	55	1700
QSF189	Reverse	Eastern wall of F17	Third grade	NE	SE	35–55	80	1700

and a throw of more than 1 km, which are the first-grade fault structures in the region. In the seismic sections, both have faulted the Carboniferous-Permian strata, and have not cut into the Neogene (Figures 3A–E). From the perspective of the plane, the Nanping and Shuangdui faults cut main secondary faults in the mine such as DF200, F17, and F22 (Figure 2). It is comprehensively shown that their normal faulting activities are earlier than Neogene, and later than other major faults in the mine.

The DF200 fault strikes near the N–S direction and inclines to the east. As the eastern boundary fault of the mine, it pushes the deep Ordovician System over the Permian coal measure strata. Together with DF200-1, F17-1, F17, F17-2 and other reverse faults, it divides the east limb of the Fengjia Syncline into multiple imbricated fault blocks (Figures 3A,B). A large number of reverse faults in the mine are mainly distributed in the two limbs of the Fengjia Syncline, and relatively few are located near the axis. The F17 fault, located in the east limb, intersects the entire mine from north to south, with the northern section striking near N-S and the southern section (south of exploration line 38) striking NNE, and the fault plane dipping toward east. A series of NNE- to NE-striking branch faults (such as F17-1, F17-2, DF165, QSF189) and secondary faults are developed near the east and west sides of the F17 fault, which mainly dip to the east and a few dip to the west. Some secondary faults are also distributed in the NNE direction with an en-echelon pattern, such as F17-2, DF105 and F27 faults, roughly parallel to the F17 fault (Figure 2). In the overlapping segments of the DF165 and F17-2, the two branch faults combined with the F17 fault to form a positive flower structure (Figure 3C). Based on the above characteristics, it can be concluded that the F17 fault has significant transcurrent activity in addition to thrust activity.

The F25 and F51 faults are two parallel large-sized reverse faults located in the west limb of the Fengjia Syncline, which both strike NE and dip SE. The dip angle of the F51 fault is slightly steep, and extends southward into the Zouzhuang Coal Mine. The F22 fault, which strikes near N–S and steeply dips to the west, is the largest normal fault within the mine with a maximum throw of more than 300 m, and offsets the F25 and F51 faults (Figures 2, 3B,C).

Most medium- and small-sized faults in this mine are roughly parallel to medium- and large-sized faults or intersect at a small angle. On the plane, the medium- and small-sized faults can be in the form of parallel, en-echelon or y-shaped pattern. In the sections, it can be seen that there are step-like, horst and graben, Y-shaped, imbricate or flower-like combinations.

Tectonic stages and stress mechanism analysis

According to the characteristics of structural geometry, tectonic association, fault property and cross-cutting relation, the structural deformation of coal measure strata in the Qianyingzi Coal Mine can be divided into five stages. According to Anderson's tectonic stress regimes (Anderson, 1951), the direction of the horizontal minimum principal stress in the extensional regime is perpendicular to the strike of the normal fault, and the direction of the horizontal maximum principal stress in the reverse-fault regime is perpendicular to the strike of the reverse fault, while in the strike-slip fault regime, the direction of the horizontal maximum principal stress intersects the strike of strike-slip fault at an acute angle. Based on these principles, we analyze the paleo-stress regimes of the Qianyingzi

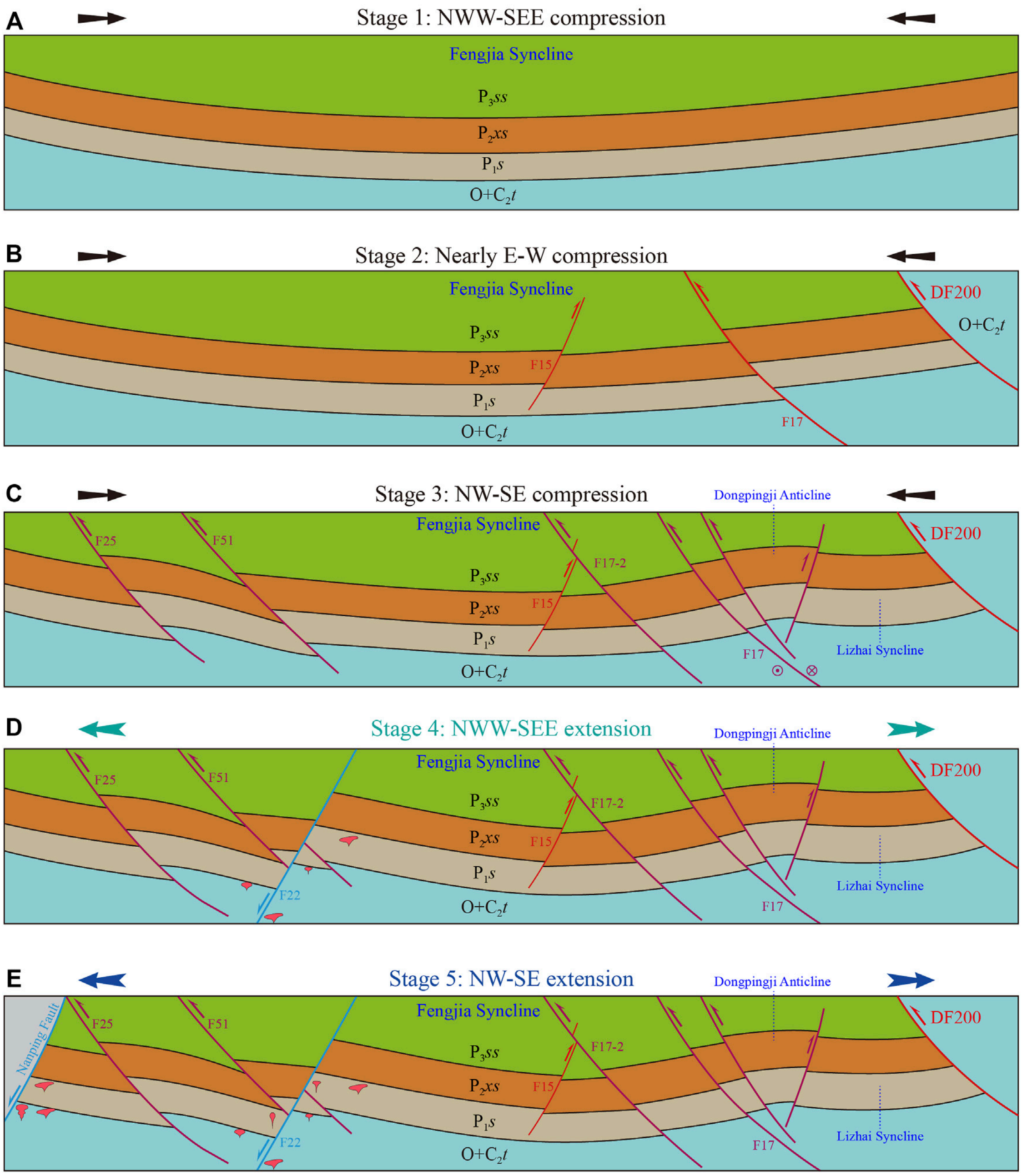

FIGURE 4
Schematic diagrams of the development history of major folds and faults in the Qianyingzi Coal Mine. **(A)** It developed the Fengjia Syncline with a NNE-trending axis under NWW–SEE compressive stress in the first stage. **(B)** It developed a series of nearly N–S-striking reverse faults under nearly E–W compressive stress in the second stage. **(C)** The NNE-striking reverse sinistral faults and NE-striking reverse faults developed under NW–SE compressive stress in the third stage. **(D)** The nearly N–S-striking normal faults were developed under nearly E–W extensional stress in the fourth stage. **(E)** The NE–SW-striking normal faults were developed under NW–SE extensional stress in the fifth stage.

Coal Mine by determining the properties and preferred strike orientations of each stage faults. Here, we also inferred the paleo-stress regime of the buckle folds according to their axial surfaces or trace orientations, which is perpendicular to the direction of maximum shortening (Ramsay, 1967).

The axial NNE Fengjia Syncline is the first-grade fold in the mine, and cut by a series of nearly N–S- and NNE- to NE-striking reverse and normal faults, which is consistent with the occurrence and scale of the broad and gentle syncline developed in the Zouzhuang Coal Mine (Tian, 2016). In fact, it is one integrate syncline structure spanning two coal mines, which is also called Suxi Syncline with an axial direction parallel to the Sunan and Nanping synclines (Figure 1B) (Lv, 2017), and sandwiched between the Nanping and Shuangdui faults in the region. It should be noted that the coal measure strata in the region are developed by regional NWW–SEE compressive stress after sedimentation, representing the first stage structure in the mine (Figure 4A).

The nearly N–S-striking reverse faults represented by the DF200 and F15 faults and the northern segment of the F17 fault are developed at the boundary and inside of the mine, which significantly transform the occurrence of coal measure strata in the mine. In addition, NNE- to NE-striking reverse faults are the most numerous faults in the mine, represented by the F25 and F51 faults in the west limb, the southern segment of F17 fault and its associated faults on both sides in the east limb. They control the development of secondary folds in the mine, have a great impact on the distribution of coal seams in the mine, and significantly increase the complexity of the mine structure. Through three-dimensional seismic interpretation, the NE-striking reverse faults in the mine offset the nearly N–S-striking reverse faults, for example, the F15 fault is cross-cut by the F17-2 fault (Figures 2, 3B), indicating that the development of the NE-striking reverse fault is later than the nearly N–S-striking reverse fault. Therefore, they should represent the results of two stages of regional compressive stress in the near E–W direction and NW–SE direction successively after the development of the Fengjia Syncline (Figures 4B,C). The strike of the F17 fault changes from nearly N–S direction in the northern segment to NNE direction in the southern segment. At the same time, significant strike-slip activity components are developed in the southern segment. The geometric and kinematic features are also consistent with the above conclusion, for example, the northern segment of F17 fault was formed under nearly E–W compressive stress, then reactivated under NW-SE compressive stress and expanded southwards in the form of reverse sinistral faulting, which was accompanied by a series of NE-striking secondary reverse faults.

As mentioned above, the nearly N–S-striking F22 fault offsets the NE-striking F25 and F51 faults, but it was then cross-cut by the NE-striking Nanping fault. Therefore, the normal faulting of F22 should occur after the reverse faulting of NE-striking faults, but be earlier than the normal faulting of NE-striking Nanping fault. That is to say, the NW–SE compressive stress was followed by the nearly E–W and NW–SE extensional stress regimes (Figures 4D,E).

Dynamic background

In the Middle Triassic, the southern margin of the North China Craton collided with the South China Plate and formed the Qinling-Dabie-Sulu Orogenic Belt (Hacker et al., 1998, 2000; Zheng, 2012). This event not only ended the depositional activities of the coal measure strata since the Late Paleozoic in the southeastern margin of the North China Craton, but also caused strong foreland deformation of the coal measure strata (Zhu et al., 2020) (Figure 5A). Previous studies have revealed that the Tan-Lu Fault Zone originated from the convergence process between the North China Craton and South China Plate during the Indosinian period, and was accompanied by vertical tearing of the South China Plate (Zhao et al., 2016). The continent-continent collision between the two blocks along the Dabie Orogen was earlier than that along the Sulu Orogen, while the South China Plate was torn along the promontory in front of the Dabie Orogen, and the eastern torn block continued to subduct northwards and finally collided with the North China Craton along the Sulu Orogen (Figure 5B). The Xu-Su Arc Nappe Belt in the east of the Huaibei Coalfield has been considered as a position for the original northwestern corner of the Sulu Orogen in the Indosinian period, which is a foreland arcuate thrust fold belt caused by the corner collision of the Sulu Orogen (Zhu et al., 2009; Zhao et al., 2016).

The Huaibei Coalfield spans the front zone of the Xu-Su Arc Nappe Belt and the *in-situ* system of the footwall. The Xu-Su Arc Nappe Belt, which protrudes to the west overall and dips to the east, is a strongly deformed thin-skinned structure (Xu et al., 1993; Shu et al., 2017; Li et al., 2018), indicating that the compression force originates from the east side. Deformation of the *in-situ* system is relatively weak, and a series of nearly N–S- to NNE-trending gentle and brachy-axis folds are developed. The Sunan Syncline in the east of the Suxian Mining District was faulted by the Xisipo Fault (Figure 1B), indicating that the formation of the Xu-Su Arc Nappe Belt was slightly later than the weak deformation of the *in-situ* system (Fang et al., 2017). The Dingli granitic pluton in the south of Xiao County, with an emplacement age of 180 Ma (Chan et al., 2021), is a stitching pluton intruded into the Xu-Su Arc Nappe Belt (Figure 1B). It indicates that the deformation time of the arcuate nappe should be after the deposition of coal measure strata and before the Early Jurassic. Therefore, it is considered that the weakly deformed *in-situ* system in the west of the Huaibei Coalfield and the Xu-Su Arc Nappe Belt to the east are the results of foreland deformation and subsequent collision orogenic deformation during the Indosinian period, respectively. Among them, the broad and gentle folds in nearly N–S to NNE direction should be the result of foreland deformation under the background of active continental margin before the continent-continent collision (Figure 5A), while the Xu-Su Arc Nappe Belt should be formed in the intense westward compressive stress generated by the corner collision between the torn South China Plate and North China Craton (Figure 5B). The formation of the Fengjia Syncline with a NNE-trending axis and nearly N–S-striking reverse faults (such as DF200 fault) in the Qianyingzi Coal Mine should correspond to the above tectonic background respectively.

At the beginning of the Early Cretaceous, the Izanagi Plate in the western Pacific region subducted rapidly and obliquely to the East

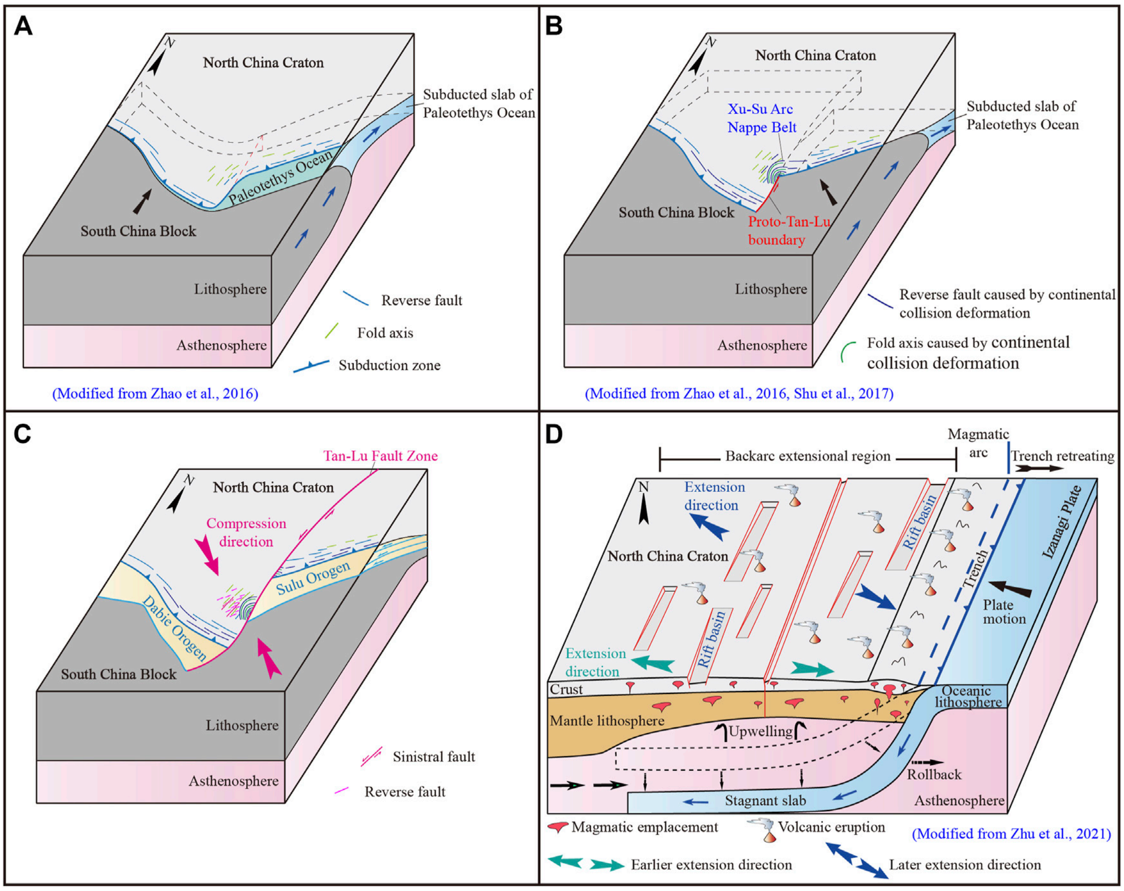

FIGURE 5
Schematic Mesozoic geodynamic evolution model of the Huaibei Coalfield. **(A)** In the first stage, a series of NNE-trending gentle asymmetrical folds were developed in the Huaibei Coalfield due to foreland shortening deformation during the subduction of the Paleotethys Ocean. **(B)** In the second stage, the Xu-Su Arc Nappe Belt as well as the nearly N–S-striking reverse faults in the Qianyingzi Coal Mine were formed in the intense westward compressive stress generated by the corner collision of the Sulu Orogen during the Indosinian Movement. **(C)** In the third stage, the NE-SW–striking reverse and nearly N-S–striking sinistral faults were developed under a NW–SE compressive stress regime in response to the subduction of the Izanagi Plate during the earliest Early Cretaceous. **(D)** Backarc extension under slab rollback of the Izanagi Plate resulting in nearly E–W extension of the fourth stage and NW-SE extension of the fifth stage successively, regionally accompanied by intense magmatic activity and the development of widespread rift basins.

Asian continent at a low angle (Engebretson et al., 1985; Maruyama et al., 1997; Qiu et al., 2018; Kong et al., 2020; Qiu et al., 2022; Wu et al., 2022). Against this background, a series of NNE- to NE-striking sinistral strike-slip faults developed in the East Asian continental margin (Xu et al., 1987; Wang and Lu, 2000; Zhu et al., 2005; Zhang et al., 2018). The Tan-Lu Fault Zone, which originated from the Indosinian collisional orogeny, underwent large-scale sinistral strike-slip activities at this time (Zhu et al., 2005; Zhang and Dong, 2008; Zhu et al., 2010; Gu et al., 2016; Zhu et al., 2016; Liu et al., 2018; Zhu et al., 2018), offsetting the Sulu Orogen northward to its present position (Figure 5C). The NNE- to nearly N–S-striking F17 fault in the Qianyingzi Coal Mine is roughly parallel to the Wuhe-Tancheng segment of the Tan-Lu Fault Zone. Combined with its significant strike-slip activities and a large number of associated and paragenetic NE-striking reverse faults, it considers that such faults in the Qianyingzi Coal Mine were developed under a NW–SE compressive stress regime in the earliest Early Cretaceous.

Two groups of normal faults were developed after the NE-striking reverse fault activity in the Qianyingzi Coal Mine, namely a series of nearly N–S- to NNE-striking normal faults represented by the F22 fault and NE-striking normal faults represented by the Nanping and Shuangdui faults, of which the latter developed later and had a larger scale. In other mines of the Huaibei Coalfield, the normal faults also developed in both directions, and the scale and quantity of NE normal faults are the greatest (Jiang et al., 2014; Peng, 2015; Xie et al., 2015; Fang et al., 2017). A large range of intermediate magmatic intrusions occurred in coal seam 7_2 and below in the mine. The hypabyssal intrusions are relatively developed in the Huaibei Coalfield, mostly buried under the Cenozoic, and mainly distributed in NNE direction (Wei et al., 2021). In recent years, the zircon U-Pb dating results of many intermediate and acid intrusions in the Huaibei Coalfield are in the range of 126–132 Ma (Xu et al., 2004; Yang et al., 2008; Zhang, 2017; Zhou et al., 2019; Chan, 2020; Wang and Chan, 2020; Wei et al., 2021).

After the earliest Early Cretaceous compression event, strong extension and magmatic activity occurred in eastern China. A series of metamorphic core complexes, extensional domes and rift basins developed in the central and eastern part of the North China Craton (Zhu R. X. et al., 2020; Zhu et al., 2021). Previous studies on Hefei Basin (Zhu G. et al., 2012), Yishu Graben (Zhang et al., 2003; Zhu G. et al., 2012), Linglong extensional dome (Wu et al., 2020) and a series of metamorphic core complexes in North China Craton (Zhu et al., 2021) indicate that the regional principal extensional stress direction during the Early Cretaceous was NWW–SEE to NW–SE. Zhu G. et al. (2012) divided extensional activity into two stages during the Early Cretaceous, namely NWW–SEE extension in the early stage and NW–SE extension in the late stage, through the stress field inversion study on the normal faults in the basins along the Tan-Lu Fault Zone. It shows an eastward younging trend for the initial volcanic eruption and rifting initialization of the Early Cretaceous basins in the northern North China Craton (Zhu et al., 2021). Therefore, it is inferred that the Early Cretaceous extensional and magmatic activity in eastern China were related to the intense backarc extension process caused by the large-scale retreat of the Izanagi Plate (Figure 5D). In conclusion, this paper considers that the Qianyingzi Coal Mine and even the Huaibei Coalfield as a whole underwent regional extensional event in Early Cretaceous, and developed a large number of nearly N–S- and NE–SW-striking normal faults and strong magmatic activities. The initial extension time was from Hauterivian to Barremian ages (126–132 Ma) in the Early Cretaceous, which was controlled by the backarc extensional background under the subduction of the Paleo-Pacific Plate.

Conclusion

In this study, through the analysis of the structural development characteristics and evolution history of the Qianyingzi Coal Mine, the following main conclusions are drawn.

(1) The coal measure strata in the Qianyingzi Coal Mine generally present a broad and gentle syncline, and an eastward dipping monocline near the northern edge of the mine. Several secondary folds are also developed in the two limbs of the Fengjia Syncline, and are significantly controlled by medium- and large-sized faults in the mine.
(2) The faults in the mine are relatively developed, mainly including medium- and small-sized faults with a throw of less than 20 m, and the number of reverse faults is significantly greater than that of normal faults. The strike of the reverse fault is mainly NE, followed by NNE and nearly N–S. The strike of the normal fault is also mainly NE, followed by NNE (close to N–S).
(3) Stress fields of the tectonic deformation in the Qianyingzi Coal Mine can be divided into five stages: NWW–SEE compressive stress, nearly E–W compressive stress, NW–SE compressive stress, nearly E–W and NW–SE extensional stresses, respectively.
(4) The formations of the Fengjia Syncline and nearly N–S-striking reverse faults are the results of foreland deformation and subsequent continent-continent collisional deformation during the convergence of the North China Craton and South China Plate in the Indosinian period. The rapid oblique subduction of the Izanagi Plate toward the East Asian continental margin at the beginning of the Early Cretaceous resulted in NW–SE compressive stress in the Huaibei Coalfield. Later, during the Early Cretaceous, the eastern China was in a backarc extensional setting under the subduction of the Paleo-Pacific Plate, superimposing nearly E–W and NW–SE extensional stress.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

First author CG designed and wrote this manuscript; XZ and JW guided the work and modified manuscript; GL and XW checked the manuscript and geological interpretation; PT and HH drew figures. All authors have contributed to the article and approved the submitted version.

Funding

This study was financially supported by the National Natural Science Foundation of China (grant number: 41902212) and the Research and Development Project of Anhui Hengyuan Coal and Electric Co., Ltd.

Acknowledgments

The authors gratefully acknowledge Editor Guiting Hou, and three reviewers for their constructive reviews and comments which greatly improved this manuscript.

Conflict of interest

GL and XW are employed by Qianyingzi Coal Mine, Anhui Hengyuan Coal and Electric Co., Ltd. The authors declare that this study received funding from the Research and Development

Project of Anhui Hengyuan Coal and Electric Co., Ltd., China. The funder had the following involvement in the study: study design and data collection.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Anderson, E. M. (1951). *The dynamics of faulting and dyke formation with application to Britain*. Edinburgh: Oliver & Boyd.

Cai, Y. T., Zhang, J., Dong, Z. D., Cao, Z. Q., Xiao, S. Y., Li, S., et al. (2018). Neoproterozoic basic magmatism in the north of Anhui Province: Evidence from whole-rock geochemistry and U−Pb geochronology of Diabase in Langan area. *Geol. China* 45 (2), 351–366. [in Chinese]. doi:10.12029/gc20180210

Chan, S. W., Zhang, J. J., and Zhu, Y. K. (2021). Geological and geochemical characteristics and LA-ICP-MS zircon U-Pb dating age of Dingli granite in Anhui. *Min. Resour. Geol.* 35 (2), 249–257. [in Chinese]. doi:10.19856/j.cnki.issn.1001—5663.2021.02.010

Chan, S. W. (2020). Inherited zircon U-Pb chronology and geological significance of the Early Cretaceous diorites in Xuhuai area. *J. Geol.* 44 (3), 258–264. [in Chinese]. doi:10.3969/j.issn.1674-3636.2020.03.004

Dong, S. W., Zhang, Y. Q., Zhang, F. Q., Cui, J. J., Chen, X. H., Zhang, S. H., et al. (2015). Late jurassic-early cretaceous continental convergence and intracontinental orogenesis in East Asia: A synthesis of the yanshan revolution. *J. Asian Earth Sci.* 114, 750–770. doi:10.1016/j.jseaes.2015.08.011

Engebretson, D. C., Cox, A., and Gordon, R. G. (1985). Relative motions between oceanic and continental plates in the pacific basin. *Geol. Soc. Am. Spec. Pap.* 206, 1–59. doi:10.1130/SPE206

Fang, T., Xie, G. A., Wang, B., Zhang, Q. L., Xie, S. Y., Zou, X., et al. (2017). The structure features and forming mechanism of Huaibei coalfield. *Coal Geol. Explor.* 45 (03), 1–6+12. [in Chinese]. doi:10.3969/j.issn.1001-1986.2017.03.001

Gu, C. C., Zhu, G., Zhai, M. J., Lin, S. Z., Song, L. S., and Liu, B. (2016). Features and origin time of mesozoic strike-slip structures in the yilan-yitong Fault Zone. *Sci. China Earth Sci.* 59, 2389–2410. doi:10.1007/s11430-016-5334-4

Hacker, B. R., Ratschbacher, L., Webb, L., Ireland, T., Walker, D., and Dong, S. W. (1998). U/Pb zircon ages constrain the architecture of the ultrahigh-pressure Qinling-Dabie Orogen, China. *Earth Planet. Sci. Lett.* 161 (1–4), 215–230. doi:10.1016/S0012-821X(98)00152-6

Hacker, B. R., Ratschbacher, L., Webb, L., Mcwilliams, M. O., Ireland, T., Clavert, A., et al. (2000). Exhumation of ultrahigh-pressure continental crust in east central China: Late Triassic-Early Jurassic tectonic unroofing. *J. Geophys. Res.* 105 (B6), 13339–13364. doi:10.1029/2000jb900039

Hou, Q. L., Li, H. J., Fan, J. J., Ju, Y. W., Wang, T. K., Li, X. S., et al. (2012). Structure and coalbed methane occurrence in tectonically deformed coals. *Sci. China Earth Sci.* 55 (11), 1755–1763. doi:10.1007/s11430-012-4493-1

Jiang, T., Jiang, B., and Huang, H. B. (2014). Structural features and evolution in Wugou coalmine, Huaibei coalfield. *Coal Geol. China* 26 (04), 11–16. [in Chinese]. doi:10.3969/j.issn.1674-1803.2014.04.03

Ju, Y. W., and Wang, G. L. (2002). Tectonic characteristics and evolution of the sulin mine area in the Huaibei coalfield. *J. Liaoning Tech. Univ. Nat. Sci.* 21 (03), 286–289. [in Chinese].

Kong, R. Y., Yan, D. P., Qiu, L., Wells, M. L., Wang, A. P., Dong, X. Y., et al. (2020). Early Cretaceous tectonic transition and SW-ward basin migration in northern Liaodong Peninsula, NE China: Sedimentary, structural, and geochronological constraints. *Geol. J.* 55, 5681–5702. doi:10.1002/gj.3620

Li, Y., and Gao, C. (2015). Preliminary analysis on water damage from limestone nappe of DF200 thrust fault in the Qianyingzi Mine. *Energy Technol. manage.* 40 (02), 45–46. [in Chinese]. doi:10.3969/j.issn.1672-9943.2015.02.019

Li, D., and Wu, Q. (2002). Research on Genesis and influencing factors of Nanding geothermal field. *J. China Univ. Min. Technol.* 31 (01), 56–60. [in Chinese].

Li, M., Yang, W. F., Liu, X., and Wang, Y. (2011). Occurrence characteristics and stability evaluation of 3_2 coal in the Qianyingzi Coal Mine. *Saf. Coal Mines* 42 (08), 159–161. [in Chinese]. doi:10.13347/j.cnki.mkaq.2011.08.002

Li, F. H., Xie, G. A., Tian, R. S., Arkin, A., Li, T., and Li, Z. (2018). Physical modeling of Xu-Huai thrust-fold belt on the southeastern margin of North China Block. *Geol. Bull. China* 37 (6), 1087–1100. [in Chinese]. doi:10.12097/j.issn.1671-2552.2018.06.012

Li, M. D. (2016). Calculation of waterproof coal pillar on the DF200 reverse fault in Dongyi mining field of Qianyingzi Coal Mine. *Energy Technol. manage.* 41 (02), 107–109. [in Chinese]. doi:10.3969/j.issn.1672-9943.2016.02.041

Liu, Y. Q., Gao, L. Z., Liu, Y. X., Song, B., and Wang, Z. X. (2006). Zircon U–Pb dating for the earliest Neoproterozoic mafic magmatism in the southern margin of the North China Block. *Chin. Sci. Bull.* 51 (19), 2375–2382. doi:10.1007/s11434-006-2114-0

Liu, C., Zhu, G., Zhang, S., Gu, C. C., Li, Y. J., Su, N., et al. (2018). Mesozoic strike-slip movement of the dunhua–mishan Fault Zone in NE China: A response to oceanic plate subduction. *Tectonophysics* 723, 201–222. doi:10.1016/j.tecto.2017.12.024

Liu, J. (2017). *The tectonic evolution and its effect on mine structure in Huaibei Coalfield*. Doctoral dissertation. Xuzhou: China University of Mining and Technology. [in Chinese].

Lv, F. J. (2017). Structural characteristics and genetic analysis of Suxian mining area in the Huaibei Coalfield. *Energy Technol. manage.* 42 (04), 7–8+28. [in Chinese]. doi:10.3969/j.issn.1672-9943.2017.04.003

Ma, D., Duan, H. Y., and Zhang, J. X. (2022a). Solid grain migration on hydraulic properties of fault rocks in underground mining tunnel: Radial seepage experiments and verification of permeability prediction. *Tunn. Undergr. Space Technol.* 126, 104525. doi:10.1016/j.tust.2022.104525

Ma, D., Duan, H. Y., Zhang, J. X., Liu, X. W., and Li, Z. H. (2022b). Numerical simulation of water–silt inrush hazard of fault rock: A three-phase flow model. *Rock Mech. Rock Eng.* 55, 5163–5182. doi:10.1007/s00603-022-02878-9

Maruyama, S., Isozaki, Y., Kimura, G., and Terabayashi, M. C. (1997). Paleogeographic maps of the Japanese islands: Plate tectonic synthesis from 750 Ma to the present. *Isl. Arc* 6 (1), 121–142. doi:10.1111/j.1440-1738.1997.tb00043.x

Pan, R. K., Cheng, Y. P., Yuan, L., Yu, M. G., and Dong, J. (2014). Effect of bedding structural diversity of coal on permeability evolution and gas disasters control with coal mining. *Nat. Hazards* 73 (2), 531–546. doi:10.1007/s11069-014-1086-7

Peng, T. (2015). *The fault system and its evolution mechanism of Huaibei coalfield*. Doctoral dissertation. Huainan: Anhui University of Science and Technology. [in Chinese].

Qiu, L., Kong, R. Y., Yan, D. P., Wells, M. L., Wang, A. P., Sun, W. H., et al. (2018). The Zhayao tectonic window of the Jurassic Yuantai thrust system in Liaodong Peninsula, NE China: Geometry, kinematics and tectonic implications. *J. Asian Earth Sci.* 164, 58–71. doi:10.1016/j.jseaes.2018.06.012

Qiu, L., Kong, R. Y., Yan, D. P., Mu, H. X., Sun, W. H., Sun, S. H., et al. (2022). Paleo–Pacific plate subduction on the eastern Asian margin: Insights from the Jurassic foreland system of the overriding plate. *Geol. Soc. Am. Bull.* 134 (9–10), 2305–2320. doi:10.1130/B36118.1

Qu, Z. H., Jiang, B., Wang, J. L., and Li, M. (2008). Characteristics of tectonic evolution and its controlling effects on coal and gas in Huaibei area, [in Chinese]. *Coal Geol. China* 20 (10), 34–37.

Ramsay, J. G. (1967). *Folding and fracturing of rocks*. New York: McGraw-Hill.

Shu, L. S., Yin, H. W., Faure, M., and Chen, Y. (2017). Mesozoic intracontinental underthrust in the SE margin of the North China block: Insights from the xu-huai thrust-and-fold belt. *J. Asian Earth Sci.* 141, 161–173. doi:10.1016/j.jseaes.2016.08.020

Tian, N. C. (2016). *Assessment of transmissibility and aquosity of F25 fault as well as measure of prevention in Zouzhuang coal mine*. Doctoral dissertation. Huainan: Anhui University of Science and Technology. [in Chinese].

Wang, W., and Chan, S. W. (2020). LA-ICP-MS U-Pb Chronologic and geochemical characteristics of zircons from the Xulou rock mass in the Huaibei area, Anhui Province. *Geol. Anhui* 30 (1), 7–13. [in Chinese].

Wang, Z. H., and Lu, H. F. (2000). Ductile deformation and $^{40}Ar/^{39}Ar$ dating of the Changle–Nanao ductile shear zone, southeastern China. *J. Struct. Geol.* 22 (5), 561–570. doi:10.1016/S0191-8141(99)00179-0

Wang, Q. H., Yang, D. B., and Xu, W. L. (2012). Neoproterozoic basic magmatism in the southeast margin of North China Craton: Evidence from whole-rock geochemistry, U-Pb and Hf isotopic study of zircons from diabase swarms in the Xuzhou-Huaibei area of China. *Sci. China Earth Sci.* 55 (9), 1461–1479. doi:10.1007/s11430-011-4237-7

Wang, H. F., Wang, L., Cheng, Y. P., and Zhou, H. X. (2013). Characteristics and dominant controlling factors of gas outburst in Huaibei coalfield and its countermeasures. *Int. J. Min. Sci. Technol.* 23, 591–596. doi:10.1016/j.ijmst.2013.07.019

Wei, J. G., Cui, H. Q., Ma, D. X., and Li, X. X. (2011). Study on gas geological law and outburst prediction of Qianyingzi 3_2 coal seam. *Coal Mine Mod.* 21 (01), 39–41. [in Chinese]. doi:10.13606/j.cnki.37-1205/td.2011.01.037

Wei, S., Yang, Z., Deng, Y. F., Cheng, P. S., Chan, S. W., Mao, S. B., et al. (2021). Geochronology of skarn type Au-Fe-Cu deposits and related intermediate-acid intrusive rocks in the northern Anhui section, Xu-Su arcuate structural area, [in Chinese]. *Acta Pet. Mineral.* 40 (02), 395–410.

Wu, S. Z., Peng, T., and Guo, Y. (2013). Ground temperature distribution pattern and its abnormal factor analysis in Qianyingzi coalmine, northern Anhui, [in Chinese]. *Coal Geol. China* 25 (06), 30–35. doi:10.3969/j.issn.1674-1803.2013.05.07

Wu, X. D., Zhu, G., Yin, H., Su, N., Lu, Y. C., Zhang, S., et al. (2020). Origin of low-angle ductile/brittle detachments: Examples from the Cretaceous Linglong metamorphic core complex in Eastern China. *Tectonics* 39, TC006132. doi:10.1029/2020TC006132

Wu, J., Lin, Y. A., Flament, N., Wu, J. T. J., and Liu, Y. (2022). Northwest Pacific-Izanagi plate tectonics since Cretaceous times from Western Pacific mantle structure. *Earth Planet. Sci. Lett.* 583, 117445. doi:10.1016/j.epsl.2022.117445

Xie, G. A., Dong, C. J., Li, F. R., Liu, W., Zhu, C. F., Fang, T., et al. (2015). Structural features and evolution in suntuan coalmine, Huaibei coalfield. *Coal Geol. China* 27 (03), 1–5+11. [in Chinese]. doi:10.3969/j.issn.1674-1803.2015.03.01

Xu, J. W., Zhu, G., Tong, W. X., Cui, K. R., and Liu, Q. (1987). Formation and evolution of the tancheng-lujiang wrench fault system: a major shear system to the northwest of the pacific ocean. *Tectonophysics* 134, 273–310. doi:10.1016/0040-1951(87)90342-8

Xu, S. T., Tao, Z., and Chen, G. B. (1993). The xuzhou-huainan nappe—a further discussion. *Geol. Rev.* 39 (5), 395–403+477. [in Chinese].

Xu, W. L., Wang, H. Q., Liu, X. C., Wang, D. Y., and Guo, J. H. (2004). Chronology and sources of mesozoic intrusive complexes in the xuzhou-huainan region, central China: Constraints from SHRIMP zircon U-Pb dating. *Acta Geol. Sin. Engl. Ed.* 78 (01), 96–106.

Yang, D. B., Xu, W. L., Pei, F. P., Wang, Q. H., and Gao, S. (2008). Chronology and Pb isotope compositions of Early Cretaceous adakitic rocks in Xuzhou-Huaibei area, central China: Constraints on magma sources and tectonic evolution in the eastern North China Craton. *Acta Pet. Sin.* 24 (8), 1745–1758. [in Chinese].

Zhang, Y. Q., and Dong, S. W. (2008). Mesozoic tectonic evolution history of the Tan-Lu fault zone, China: Advances and new understanding, [in Chinese]. *Geol. Bull. China* 27 (9), 1371–1390.

Zhang, Y. Q., Dong, S. W., and Shi, W. (2003). Cretaceous deformation history of the middle Tan-Lu fault zone in Shandong Province, eastern China. *Tectonophysics* 363 (3), 243–258. doi:10.1016/S0040-1951(03)00039-8

Zhang, S., Zhu, G., Liu, C., Li, Y. J., Su, N., Xiao, S. Y., et al. (2018). Strike-slip motion within the yalu river Fault Zone, NE Asia: The development of a shear continental margin. *Tectonics* 37 (6), 1771–1796. doi:10.1029/2018TC004968

Zhang, S., Zhu, G., Xiao, S. Y., Su, N., Lu, Y. C., Wu, X., et al. (2020). Temporal variations in the dynamic evolution of an overriding plate: Evidence from the Wulong area in the eastern North China Craton, China. *Geol. Soc. Am. Bull.* 132 (9–10), 2023–2042. doi:10.1130/B35465.1

Zhang, J. K. (2011). *Coalfield structures and tectonic coal-controlling of Anhui Province*. Doctoral dissertation. Beijing: China University of Mining and Technology. [in Chinese].

Zhang, X. (2017). *Geochemical studies on Yanshan magmatic rock and Fe (Cu-Au) deposit in the southeastern of NCC: Take the case of Liguo deposit, Xuhuai area*. Doctoral dissertation. Hefei: University of Science and Technology of China. [in Chinese].

Zhao, Y., Xu, G., Zhang, S. H., Yang, Z. Y., Zhang, Y. Q., and Hu, J. M. (2004). Yanshanian movement and conversion of tectonic regimes in East Asia, [in Chinese]. *Earth Sci. Front.* 11 (03), 319–328.

Zhao, T., Zhu, G., Lin, S. Z., and Wang, H. Q. (2016). Indentation-induced tearing of a subducting continent: Evidence from the tan–Lu fault Zone, east China. *Earth. Sci. Rev.* 152, 14–36. doi:10.1016/j.earscirev.2015.11.003

Zheng, Y. F. (2012). Metamorphic chemical geodynamics in continental subduction zones. *Chem. Geol.* 328, 5–48. doi:10.1016/j.chemgeo.2012.02.005

Zhou, H., Shang, D. F., Chan, S. W., and Chen, J. (2019). Zircon U-Pb dating, petrogenesis and geological significance of the Banjing Pluton in Xuhuai area. *Mineral. Pet.* 39 (3), 9–16. [in Chinese]. doi:10.19719/j.cnki.1001—6872.2019.03.02

Zhu, G., Wang, Y. S., Liu, G. S., Niu, M. L., Xie, C. L., and Li, C. C. (2005). $^{40}Ar/^{39}Ar$ dating of strike-slip motion on the Tan–Lu fault zone, East China. *J. Struct. Geol.* 27 (8), 1379–1398. doi:10.1016/j.jsg.2005.04.007

Zhu, G., Liu, G. S., Niu, M. L., Xie, C. L., Wang, Y. S., and Xiang, B. W. (2009). Syn-collisional transform faulting of the Tan-Lu fault zone, East China. *Int. J. Earth Sci.* 98 (1), 135–155. doi:10.1007/s00531-007-0225-8

Zhu, G., Niu, M. L., Xie, C. L., and Wang, Y. S. (2010). Sinistral to normal faulting along the tan-Lu fault Zone: Evidence for geodynamic switching of the East China continental margin. *J. Geol.* 118 (3), 277–293. doi:10.1086/651540

Zhu, G., Chen, Y., Jiang, D. Z., and Lin, S. Z. (2015). Rapid change from compression to extension in the North China craton during the early cretaceous: Evidence from the yunmengshan metamorphic core complex. *Tectonophysics* 656, 91–110. doi:10.1016/j.tecto.2015.06.009

Zhu, G., Wang, W., Gu, C. C., Zhang, S., and Liu, C. (2016). Late mesozoic evolution history of the tan-Lu fault Zone and its indication to destruction processes of the North China craton. *Acta Pet. Sin.* 32 (4), 935–949. [in Chinese].

Zhu, G., Liu, C., Gu, C. C., Zhang, S., Li, Y. J., Su, N., et al. (2018). Oceanic plate subduction history in the Western pacific ocean: Constraint from late mesozoic evolution of the tan-Lu fault Zone. *Sci. China Earth Sci.* 61, 386–405. doi:10.1007/s11430-017-9136-4

Zhu, R. X., Zhu, G., and Li, J. W. (2020). *The North China craton destruction*. Beijing: Science Press.

Zhu, G., Lu, Y. C., Su, N., Wu, X. D., Yin, H., Zhang, S., et al. (2021). Crustal deformation and dynamics of early cretaceous in the North China craton. *Sci. China Earth Sci.* 64 (9), 1428–1450. doi:10.1007/s11430-020-9749-0

Zhu, G., Jiang, D. Z., Zhang, B. L., and Chen, Y. (2012). Destruction of the eastern North China Craton in a backarc setting: Evidence from crustal deformation kinematics. *Gondwana Res.* 22 (1), 86–103. doi:10.1016/j.gr.2011.08.005

Zhu, R. X., Xu, Y. G., Zhu, G., Zhang, H. F., Xia, Q. K., and Zheng, T. Y. (2012). Destruction of the North China craton. *Sci. China Earth Sci.* 55, 1565–1587. doi:10.1007/s11430-012-4516-y