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Full Length Article

Paleocene spatiotemporal structure and evolution of the Dongying depression in the eastern Bohai Bay Basin: Evidence from seismic interpretation and basalt 40Ar/39Ar dating

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A B S T R A C T

The Paleocene marked a critical structural transition period from tectonic subduction to extensional rifting in the Bohai Bay Basin. To reconstruct the spatiotemporal structural framework, evolutionary process, and basin prototype during the Paleocene Kongdian period of the Dongying Depression in the eastern Bohai Bay Basin, this study integrated seismic interpretation, core observation, $^{40}Ar/^{39}Ar$ dating, and structural restoration. The $^{40}Ar/^{39}Ar$ dating of basalts (approximately 57.58 ± 0.77 Ma) revealed that the depression entered an active rifting stage with intense volcanism in the early Paleocene Kongdian period. Regional faults, including the Chennan, Wangjiagang Shicun, and Gaocheng faults, were well developed during the first member of the Kongdian sedimentary stage. Their activity indicates rapid rift expansion and resulted in a half-graben pattern characterized by faulting in the north and onlap in the south. Structural restoration showed that the stretching ratio during the Paleocene Kongdian period was approximately 7.3%, which reflects rapid rifting. The development of the early Paleocene rift has important implications for deep hydrocarbon exploration in the Bohai Bay Basin.

1. Introduction

The geological structure and evolution of the Bohai Bay Basin in eastern China have been deeply influenced by the westward subduction of the Pacific Plate along the eastern margin of Asia during the Mesozoic period and the collision between the Indian and Eurasian plates during the Cenzoic period (Dong et al., 2021, 2024; Gao et al., 2025a,b; Li et al., 2010; Xiang and Gang, 2019; Zhang and Dong, 2019). Some scholars have argued that the Bohai Bay Basin originated during the period from Late Jurassic to Early Cretaceous (Hou et al., 1998; Li et al., 2015) and that its evolutionary history is triggered by large-scale regional geodynamic processes (Li et al., 2011a,b; Liu and He, 2019; Zhou et al., 2022).

The Dongying Depression is one of the most hydrocarbon-rich sub-depressions in the Jiyang sag in the eastern Bohai Bay Basin (Liu et al., 2023; Wang et al., 2002). Previous studies have suggested that the tectonic evolution of the Jiyang Depression might have experienced the Indosinian compression, Mesozoic extensional faulting and uplift denudation, and fault depression activity from the Paleogene to Neogene (Li et al., 2011a,b; Song, 2019; Xia et al., 2007). The stratigraphic framework of the Dongying Depression shows distinct zonation linked to rift formation and fault subsidence (Lin et al., 2005; Mao et al., 2020; Peng et al., 2010, 2019; Tan et al., 2014, 2021; Xia et al., 2006), and the tectonic evolution can be divided into pre-rift, syn-rift, fault depression, and post-rift stages (Tang et al., 2021; Xia et al., 2006). Despite previous studies, the spatiotemporal structure and evolution of the incipient rift remain unclear, particularly regarding its interaction with syn-rift magmatism. The basaltic rocks in the Kongdian Formation indicate a deep crust-mantle extensional background (Huo et al., 2019; Liu and Xie, 2003; Lu et al., 2006; Mao et al., 2020; Peng et al., 2010; Sun et al., 2024; Xing et al., 2019) and are associated with deep geodynamic processes (Liu and Xie, 2003; Sun et al., 2024), including lithospheric thinning (Huo et al., 2019; Lu et al., 2006), mantle upwelling (Lu et al., 2006; Xing et al., 2019), and mantle thermal erosion (Chen et al., 1992).

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Determining the timing of basaltic eruptions is essential for establishing a chronological framework of rift basin development.

Thus, the aim of this study was to reconstruct the Paleocene spatiotemporal structure and evolution of the Dongying Depression by focusing on the temporal and spatial relationships between faulting and volcanism, and their implications for basin evolution. To address these questions, we combined fault system analysis, structural restoration, core observation, and basalt $^{40}Ar/^{39}Ar$ dating, with the latter providing critical temporal constraints on basin initiation and evolution. This integrated approach provided insights into deep hydrocarbon exploration in the Bohai Bay Basin and a case study for understanding transitional extensional regimes across East Asia.

2. Geological background

The Bohai Bay Basin is a superimposed Mesozoic-Cenozoic basin developed on a Paleozoic basement (Hou et al., 1998; Li and Wang, 1998; Li et al., 2015; Lin, 2006). The Dongying Depression is located in the eastern part of the Bohai Bay Basin (Fig. 1). The Bohai Bay Basin has undergone multiple phases of tectonic movement under the combined influence of peripheral plate interactions, mantle dynamics, and deep-seated faults since the Mesozoic period (Hou et al., 1998; Li et al., 2015; Liu and He, 2019; Lu et al., 2006; Ma and Yang, 1993; Yu, 2007). The subduction of the Paleo-Pacific Plate imposed north-northwest–directed compressional stress on the regional crust, leading to the formation of northeast (NE)-trending sinistral transpressional strike-slip faults (Xiang and Gang, 2019; Yang et al., 2016; Zhang and Dong, 2019). Tectonic adjustment in the subduction direction of the Pacific Plate led to a right-lateral transtensional activity along NE-trending faults within the basin since the early Cenozoic period, and the transition from a compressional to an extensional regime formed the present-day structural framework (Hou et al., 1998; Li and Wang, 1998; Li et al., 2015; Yang et al., 2016; Yu, 2007; Zhou et al., 2003). The Bohai Bay Basin has experienced three main evolutionary processes: the initial rifting stage during the period from Late Jurassic to Early Cretaceous, the fault-controlled subsidence stage in the Paleocene period, and the post-rift sagging stage in the Neogene period (Yu, 2007; Zhou et al., 2003). During the early Paleogene, the Jiyang Depression was affected by sinistral northwest (NW)-trending strike-slip faults and developed a series of NE to north-northeast (NNE)-trending normal faults (Xia et al., 2007; Yu, 2007).

As shown in its stratigraphy (Fig. 2), the Dongying Depression can be divided into four structural layers: the pre-rifting structural layer, syn-rifting structural layer, strike-slip rifting layer, and post-rifting subsidence structural layer. The pre-rifting structural layer is formed with Triassic-Jurassic terrestrial sequences and thick volcanic Cretaceous (up to 2000 m). It exhibits an intensive unconformity contact relationship with the overlying sedimentary layers (Tian et al., 2025). The syn-rifting structural layer is comprised of the Kongdian and Shahejie formations (E_1k_2-E_2s_4). The Kongdian Formation represents a small and isolated lacustrine infilling formed during the early Paleocene period (Bai, 2019; Gao et al., 2025a,b; Zhang, 2025; Zhang et al., 2025). The second member of the Kongdian Formation (E_1k_2) marks the development of the incipient rift, consisting of volcanic rocks interbedded with mudstones and sandstones that reflect syn-volcanic activities. Meanwhile, the underlying first member of the Kongdian Formation (E_1k_1) is dominated by reddish conglomerates and fine-grain clastic rocks indicative of high-energy alluvial-to-fluvial environments. The overlying Shahejie Formation (E_2s) is subdivided into four members. Its fourth member (E_2s_4) is composed mainly of dark mudstones, representing deep lacustrine-to-saline lake settings. Its third member E_2s_3 features interbedded mudstones and sandstones, and the second member E_2s_2 includes carbonates, sandstones, and shales, which suggest frequent environmental fluctuations. The first member of the Shahejie Formation (E_2s_1) is primarily made up of mudstones with interbedded siltstones. This interval constitutes the principal hydrocarbon generation and accumulation system in depression (Gao et al., 2025a,b; Wang et al., 2025, 2025; X. Wang et al., 2025; Xu et al., 2025; Zhang et al., 2014).

The strike-slip rifting structural layer of the Dongying Formation (E_3d) is composed of three members. The lower part is rich in mudstones and siltstones, while the upper part contains frequent sandstone interbeds. The tectonic regime transitioned into lateral shearing during Dongying Formation, which led to the development of echelon faults and localized depocenters (Xu et al., 2025; Zhang et al., 2012).The post-rifting thermal subsidence structural layer was formed with the Guantao and Minghuazhen formations (N_1g-N_2m). After the cessation of active rifting, the Neogene strata became representative of a phase of thermal subsidence and

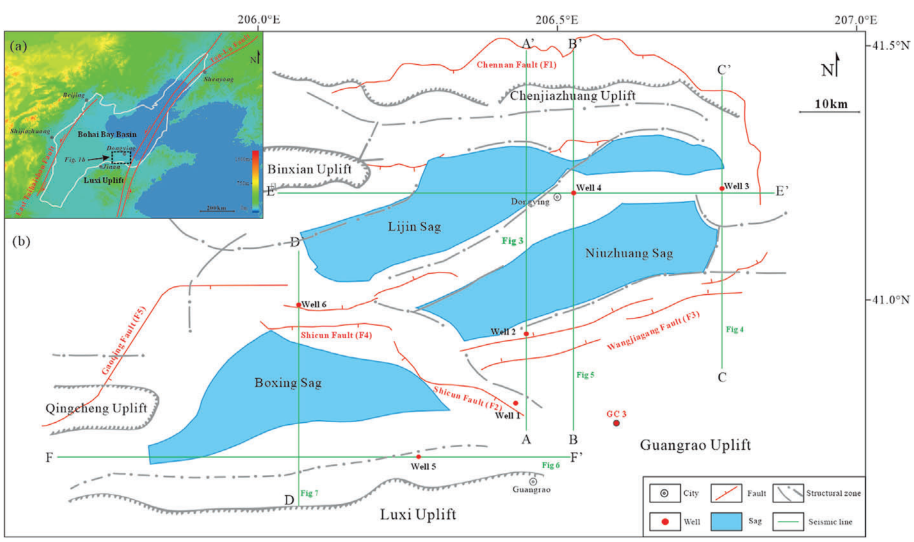

Fig. 1. Schematic map of the Dongying Depression in the eastern Bohai Bay Basin.

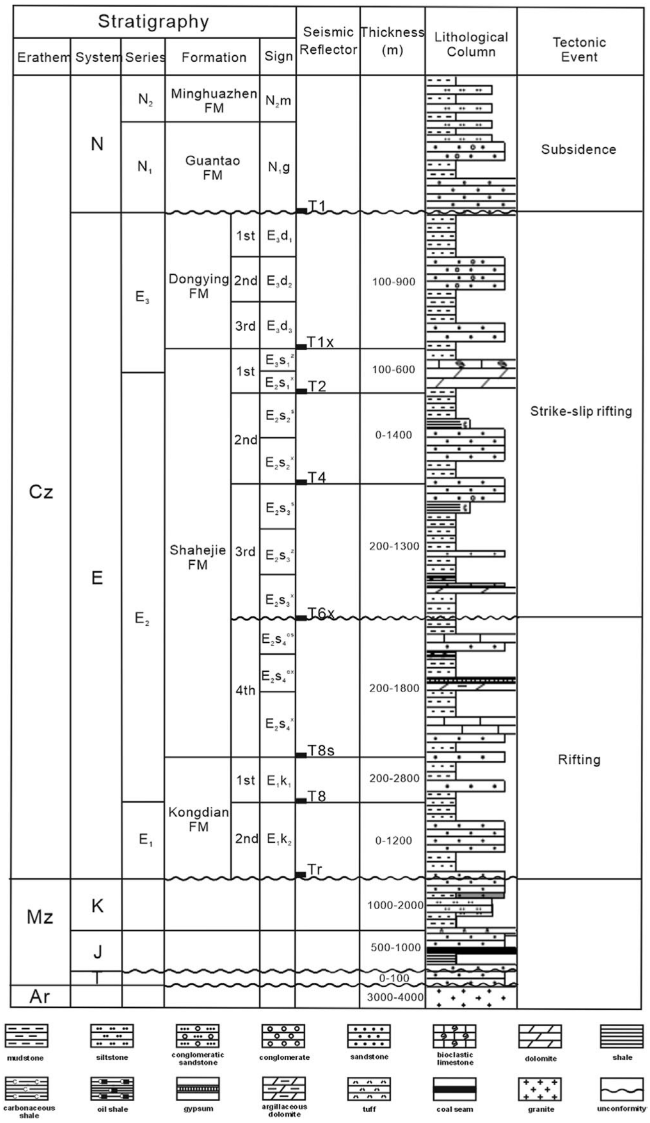

Fig. 2. Comprehensive stratigraphic map the of Dongying Depression in Bohai Bay Basin.

progressive basin infilling. The Guantao Formation (N_1g) is dominated by fluvial sandstones and mudstones. The Minghuazhen Formation (N_2m) consists mainly of reddish sandy mudstones and silts deposited in alluvial to lacustrine environment (Zhang et al., 2014).

3. Structural geometry features

In this study, four major unconformities were identified on the basis of the lateral termination of seismic events: the distinct unconformity between the second member of the Cenozoic Kongdian Formation (E_1k_2) and the underlying pre-Mesozoic strata (Fig. 3, Tr), the unconformity between the fourth and third members of the Shahejie Formation (E_2s_4 and E_2s_3; Fig. 3, T6x), the regional unconformity between the third and second members of the Shahejie Formation (E_2s_3 and E_2s_2; Fig. 3, T2), and the unconformity between the Neogene-Quaternary strata (N + Q) and the Tertiary Dongying Formation (E_3d; Fig. 3, T1).

3.1. Structural geometry from seismic profiles

Three-dimensional seismic interpretations revealed that the basin-controlled faults in the Dongying Depression are well developed, including the Chennan, Qingxi, Binnan, and Binbei faults (Figs. 1 and 4–6, respectively; Table 1). Among these faults, the Chennan Fault, the major boundary fault, extends approximately 40 km and can be divided into three segments based on strike: an east-west (E-W)–trending western segment, a southwest-trending middle segment, and an approximately north-south (N–S)–trending eastern segment. The south-dipping western segment exhibits a complex chair-like structure, while the middle segment displays a simpler shovel-shaped structure. In the footwall, a syn-sedimentary growth horizon characterized by stratigraphic thickening developed upward along the fault. This fault formed a series of reverse faults forming Y-shaped and negative flower structures (Fig. 4).

The Wangjiagang Fault, located in the eastern part of the study area, consists of northern and southern segments. The northern segment mainly comprises the NNE-trending Yanli fault system, while the southern segment is dominated by relatively large-scale northeast-east–trending faults. These two fault segments form the NW-dipping fault zone that serves as the southeastern boundary of the Niujuang Depression. Seismic sections reveal a relatively small-scale negative flower structure developed from the third member of the Shahejie Formation to the Dongying Formation. Similar to the Chennan Fault, this fault might have experienced right-lateral strike-slip activity during the period from Late Eocene to Oligocene (Fig. 5). The Shicun Fault, approximately 40 km long, is located on the southern slope of the Dongying Depression, making it the main controlling fault of the Boxing Depression. E-W

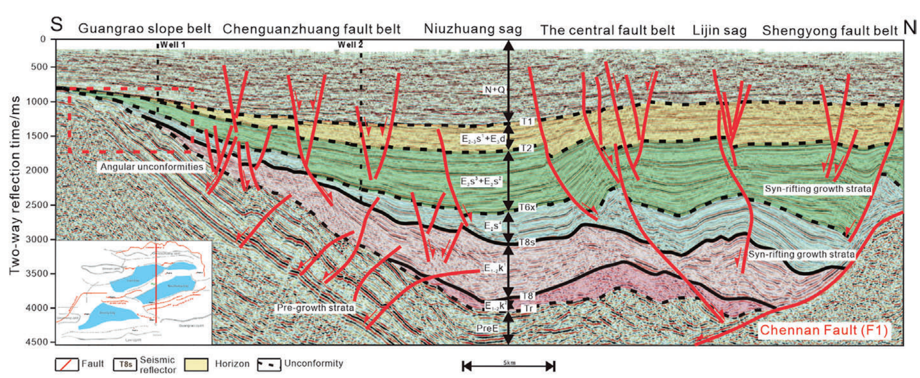

Fig. 3. Regional seismic section in the central part of the Dongying Depression: structural response of the unconformity and syn-rift sedimentary layers (see location in Fig. 1 A–A′).

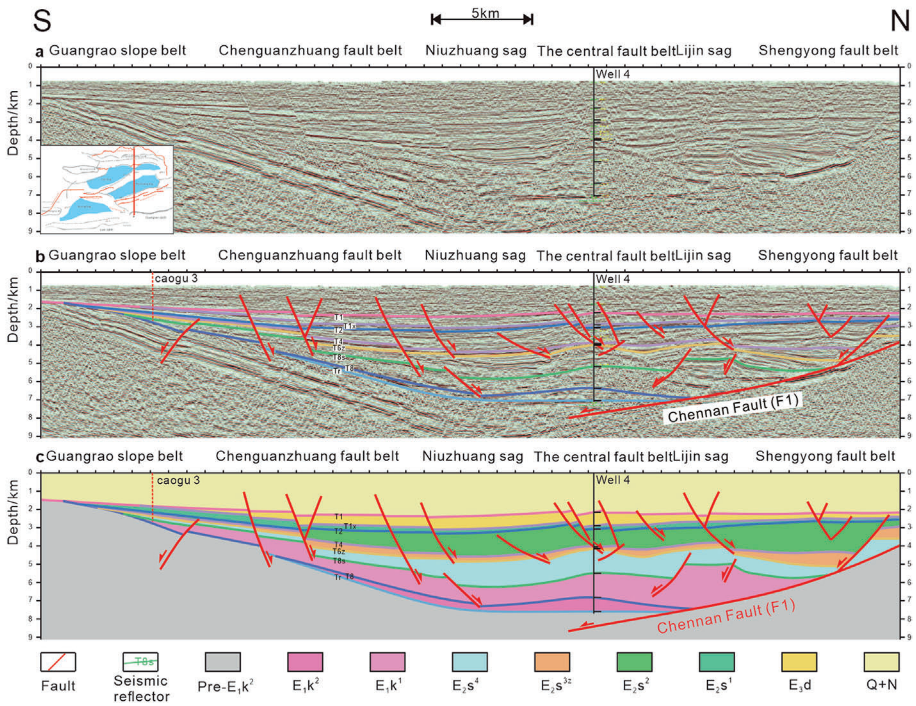

Fig. 4. Seismic interpretation of the S–N–trending profile in the eastern part of the Dongying Depression (see location in Fig. 1 B–B′).

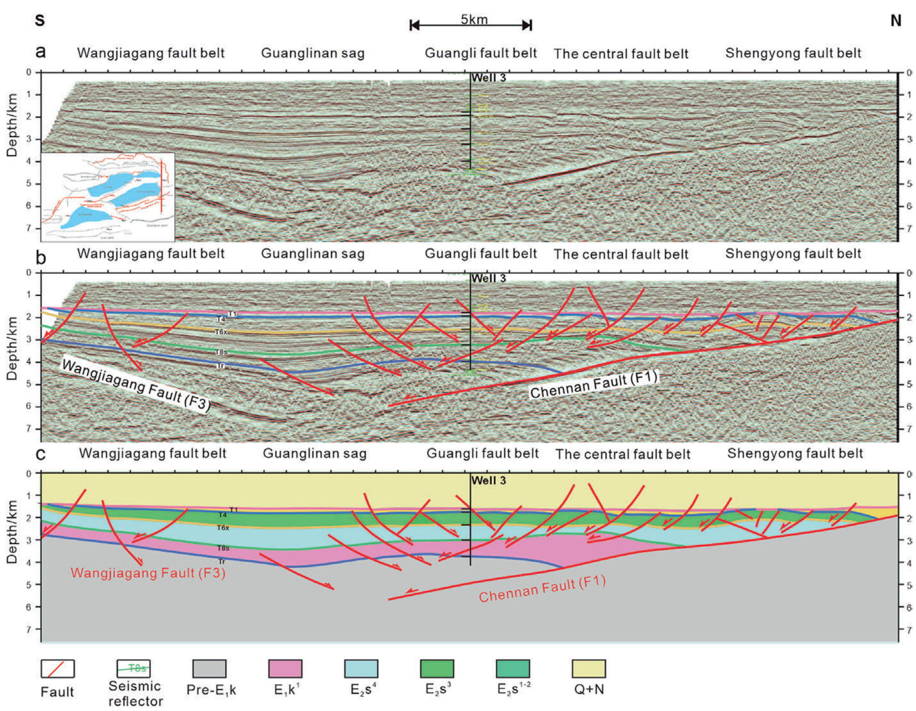

Fig. 5. Seismic interpretation of the S–N–trending profile in the eastern part of the Dongying Depression (see location in Fig. 1 C–C′).

seismic section profiles indicate that the Kongdian Formation thickens eastward toward the fault, reaching its maximum thickness near the fault zone (Figs. 6 and 7). The N–S–trending seismic profiles exhibit a typical shovel-shaped structure, whereas the E-W–trending seismic profiles indicate a thickening of the strata. In addition to controlling sedimentary architecture, these faults, particularly the Shicun Fault and associated southern faults, such as the Boxing and Jinjia Faults, play a critical role in guiding basaltic eruptions. Basalts are mainly emplaced along these southern fault zones, gradually thinning away from the faults.

3.2. *Planar features in the Paleocene Kongdian stage*

On the basis of the stratigraphic calibration with logging and three-dimensional seismic interpretation and structural mapping, the fault distribution and structural contour maps of the top and

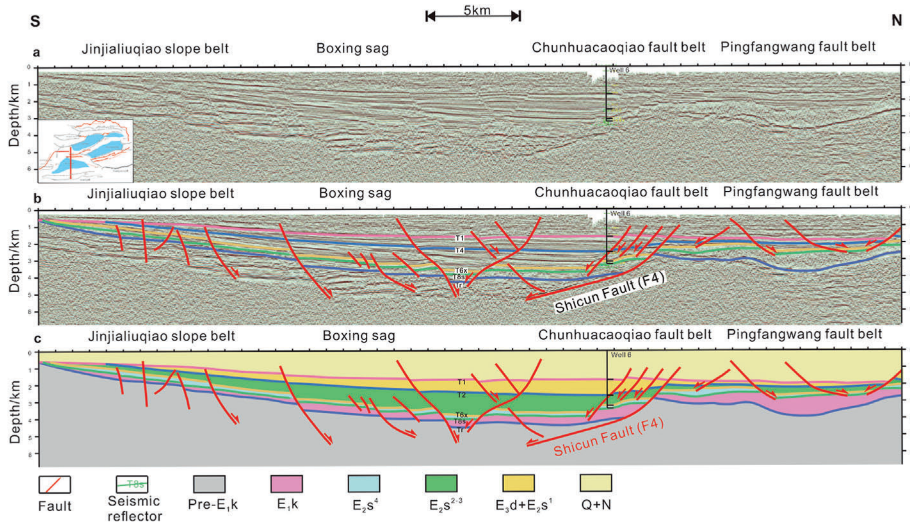

Fig. 6. Seismic interpretation of the S–N–trending profile in the eastern part of the Dongying Depression (see location in Fig. 1 D–D′).

Table 1
Statistical elements of the major faults in the Dongying Depression.

Fault	Strike	Dip	Dip angle(°)	Extension(km)
The Chennan Fault	NWW	SSW	30–40	41.8
The Shicun Fault	NW	SW	30–45	43
The Wangjiagang Falut	NE	NNW	50–60	30
The Pingnan Fault	NE	SE	40–60	20
The Gaoqing Fault	NE	SEE	40–60	42.5
The Boxing Fault	NEE	NNW	40–60	24.5
The Bamianhe Fault	NE	SE	50–60	35.5

bottom of the Kongdian Formation were constructed (Fig. 8). As the boundary basin-controlled master fault, the Chennan Fault has played a key role in the formation and evolution of the Dongying Depression. The fault distribution map of the first member of the Kongdian Formation shows greater fault intensity and diversity than the second member of the Kongdian Formation, displaying a series of discontinuous secondary faults, such as the north-northwest and near E-W–trending Shicun faults (Fig. 8a). The sedimentary area expanded, forming two centers separated by the Shicun Fault. The northern center shows greater sediment thickness (up to 2800 m), while the southern center is closely associated with zones where basaltic eruptions occurred along major southern faults.

The fault distribution map projected on the second member of the Kongdian Formation shows that faults are mainly oriented northwest and nearly E-W (Fig. 8b). The NE-trending Chennan Fault is likely a successor fault of Mesozoic tectonic activity and major basin-controlling fault during the sedimentary stage of the second member of the Kongdian Formation. Secondary faults are nearly parallel to the E-W trending Chennan Fault, reflecting a north-south extensional tectonic background. The sedimentary strata are primarily distributed in the central part of the Dongying Depression, with sporadic distribution in the southern part. The maximum sediment thickness near the sedimentary center reaches approximately 1200 m. The fault distribution and uplift-subsidence maps of the Paleocene Kongdian Formation show a regional stress transition from extension to strike slip, which marks the onset of the Paleogene basin development. The basaltic eruptions during the Kongdian period display a strong spatial association with major southern faults, particularly the Shicun, Boxing, and Jinjia faults. Their distribution indicates that magma emplacement was strongly controlled by these fault zones, with lava thickness decreasing progressively away from the faults. The variations in basalt thickness and lithology across the depression were influenced by paleotopography and the distance from the eruption centers.

3.3. Structural kinematic analysis

To restore the structural kinematic processes (Figs. 9–12), four interpreted seismic profiles were selected to carry out balanced three-dimensional reconstruction using the MOVE software (Table 2).

3.3.1. Quantitative kinematic analysis

On a temporal scale, the average extensions in the eastern part of the study area during the stages from rifting to regional extension were 3.0, 4.8, 2.5, and 3.6 km, corresponding to extension ratios of 4.8%, 7.3%, 3.2%, and 4.9%, respectively. The estimated extension rates were approximately 0.007, 0.0081, 0.003, and 0.002 Ma^{-1}. In the western part of the study area, the corresponding average extensions were 1.4, 1.9, 2.0, and 1.8 km, with extension ratios of 2.4%, 3.0%, 3.2%, and 2.8%, respectively, and extension rates of approximately 0.0035, 0.0033, 0.003, and 0.0012 Ma^{-1}, respectively.

On a spatial scale, the average extensions along the four seismic profiles were 2.8 and 8.8 km from west to east, and 7.1 and 13.7 km from south to north, with corresponding extension rates of 7.8%, 19.6%, 11.4%, and 20.2%, respectively. The extension in the easternmost area reached 8.8 km, with a rate of 19.6%, while the extension in the western part of the central area was only 2.8 km, with a rate of 7.8%, indicating that extensional deformation is

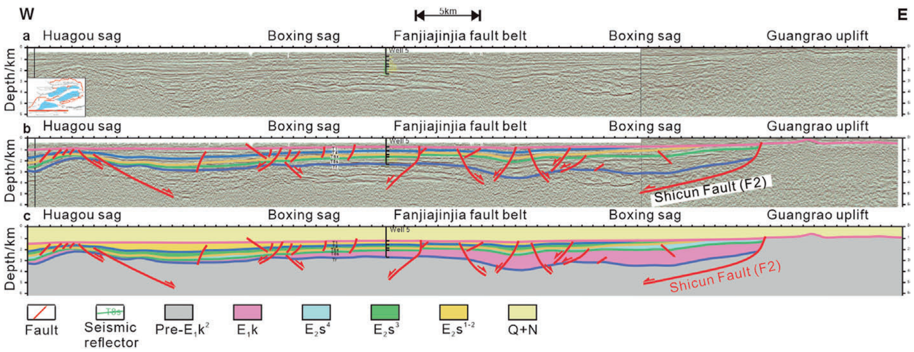

Fig. 7. Seismic interpretation of the E-W–trending profile in the western part of the Dongying Depression (see location in Fig. 1 F–F′).

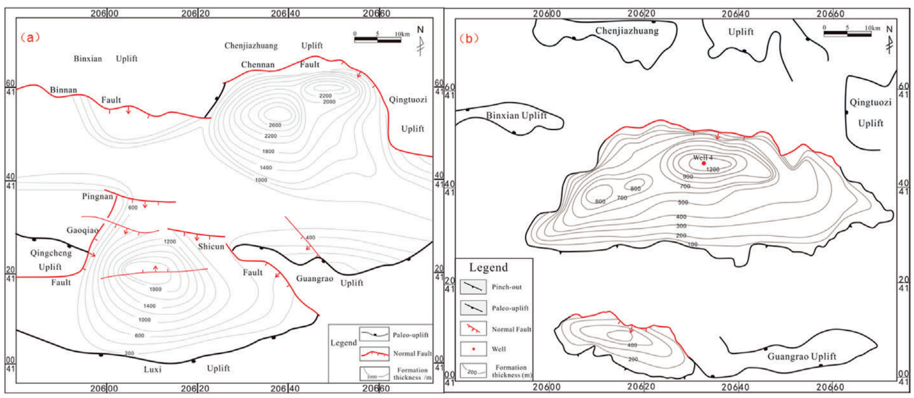

Fig. 8. Distribution of faults in the first (a) and second members (b) of the Kongdian Formation in the Dongying Depression.

strongest in the eastern part of the depression. In addition, significant differences exist between the southern and northern parts of the Dongying Depression. The average extension in the south was 13.7 km, with a rate of 20.2%, whereas that in the north was 7.1 km, with a rate of 11.4%.

On a temporal scale, the extension from the second member of the Kongdian Formation to the lower part of the Shahejie Formation was 4.9 km, with an extension rate of 11.7%, and that from the upper part of the Shahejie Formation to the Dongying Formation was 1.0 km, with a rate of 2.1%. Overall, the extension rate showed a decreasing trend over time, indicating a gradual weakening of structural activity. The Kongdian Formation was deposited from the Paleocene to the early Eocene, a period when the basin transitioned from compression to extension and entered the rift evolution stage. This was the phase of the most intense structural activity in the study area, and its high extension rate significantly influenced both the sedimentary and structural characteristics of the Kongdian Formation.

By contrast, the extension in the eastern was larger than that in the western part of the faulted basin, which may be related to the different geological configuration and lithologic property distribution on sedimentary facies.

3.3.2. Structural kinematic processes

The balanced reconstruction (Figs. 9–12) revealed that the Dongying Depression might have experienced the following evolutionary stages: (1) structural transition stage from the late Cretaceous period to the early Paleocene period. This stage is characterized by a transition in regional structural stress from compression to extension, and the basin entered an initial extensional structural setting. During the early Kongdian Formation, the basin might have briefly undergone a phase of thermal subsidence. (2) During the extension stage from the Paleocene Upper Kongdian Formation to the Oligocene Lower Shahejie Formation, boundary faults gradually developed, the depression center migrated northward and eastward, and the sedimentary centers were adjusted, leading to a significant increase in basin extension (Figs. 9–12). (3) The extension-strike-slip transition stage from the Oligocene Middle Shahejie Formation to the Miocene Dongying sedimentary period is marked the development of a series of secondary strike slip faults in the depression. Structural activity was no longer mainly concentrated along the boundary faults, and the differential deformation in the basin intensified. (4) During the regional thermal subsidence and strike-slip stage from the Neogene to the Quaternary period, structural activity gradually diminished, and the basin entered a phase dominated by regional thermal subsidence overlain by localized strike-slip structural activity. Balanced reconstructions indicate that the extension in the study area was primarily formed from the Paleocene to the Middle Eocene, while the composite strike-slip and extensional rift system mainly developed from the Middle Eocene to the Oligocene.

During these structural phases, fault activity and stratigraphic deposition are closely related. Syn-sedimentary fault growth strata are direct evidence of fault activity periods. The seismic reflection data indicate that the Chennan Fault remained active from the Mesozoic to the Cenozoic, with clearly identifiable

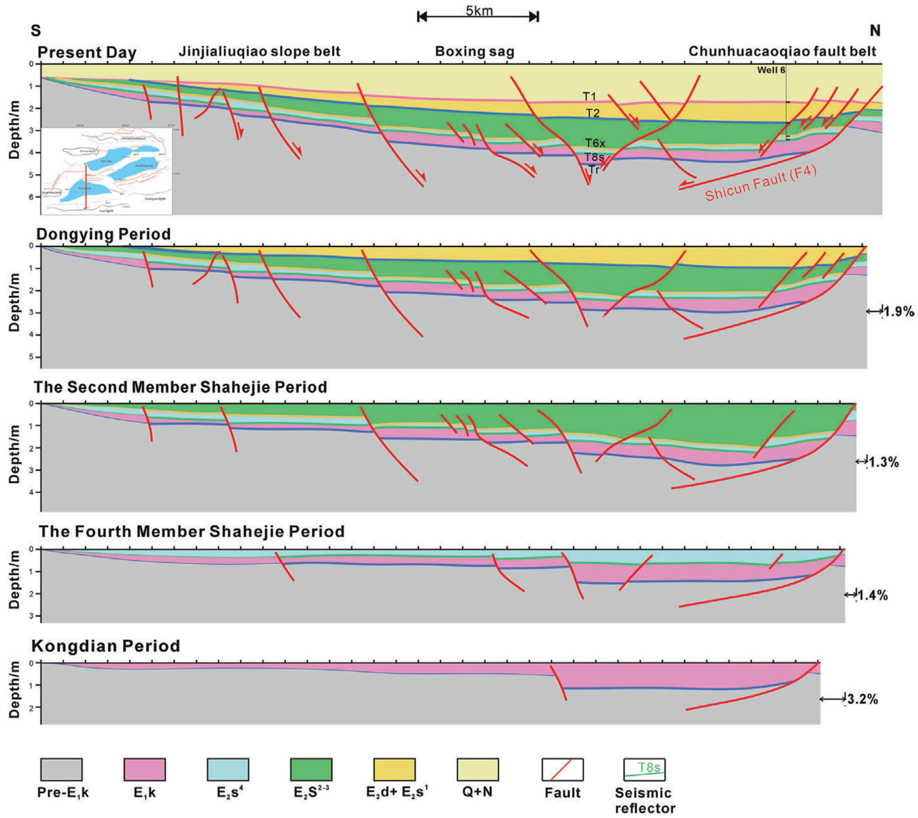

Fig. 9. Balanced structural reconstruction and evolutionary seismic profile in the eastern part of the Dongying Depression (see location in Fig. 1 B–B′).

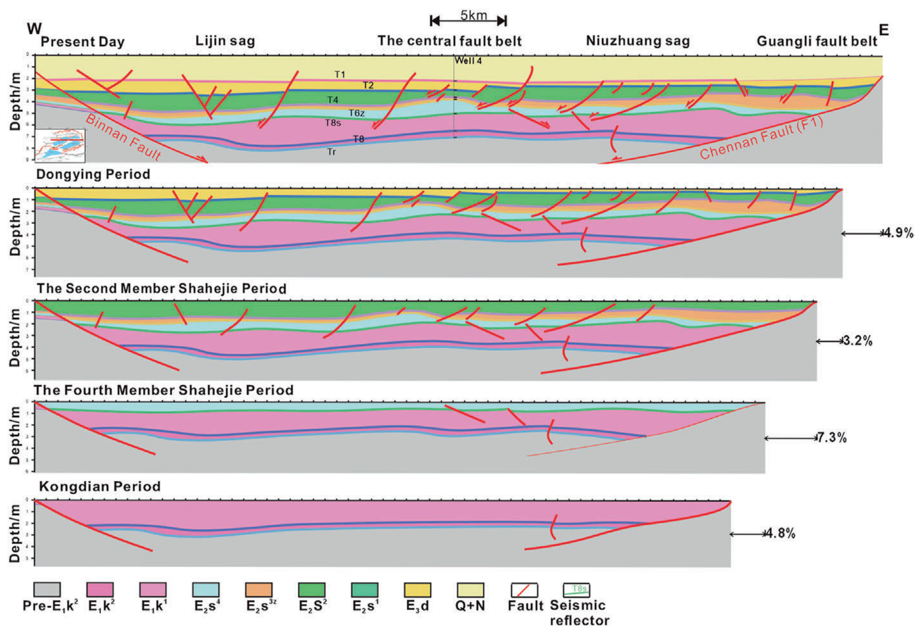

Fig. 10. Structural balanced restoration and evolutionary seismic profile in the western part of the Dongying Depression (see location in Fig. 1 D–D′).

growth strata in its hanging wall that exhibit characteristic wedge-shaped thinning. Specifically, the syn-sedimentary growth strata associated with the same fault can be identified in the Paleocene Kongdian Formation and the overlying fourth member of the Eocene Shahejie Formation (E_2s_4). Eismic profiles show strong amplitude and chaotic reflection zones at the base of the second member of the Kongdian Formation. These anomalies correspond to basaltic flows and volcanic edifices. They are commonly located adjacent to major normal faults. Locally, the syn-rift strata in the footwall show noticeable thickening. These observations indicate that volcanism is closely associated with fault-controlled accommodation development. However, the strata beneath the Kongdian Formation show relatively stable thicknesses and can be interpreted as pre-growth strata. In addition, other sets of growth strata

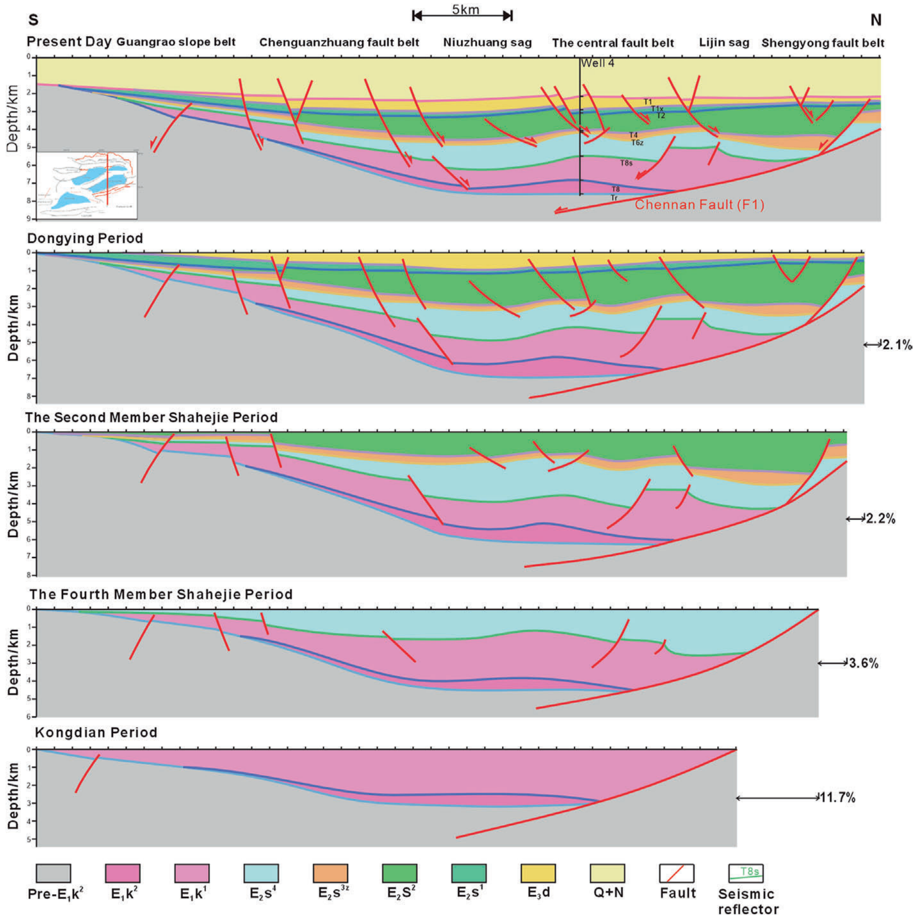

Fig. 11. Balanced structural restoration and evolutionary seismic profile in the northwest part of Dongying Depression (see location in Fig. 1 E–E′).

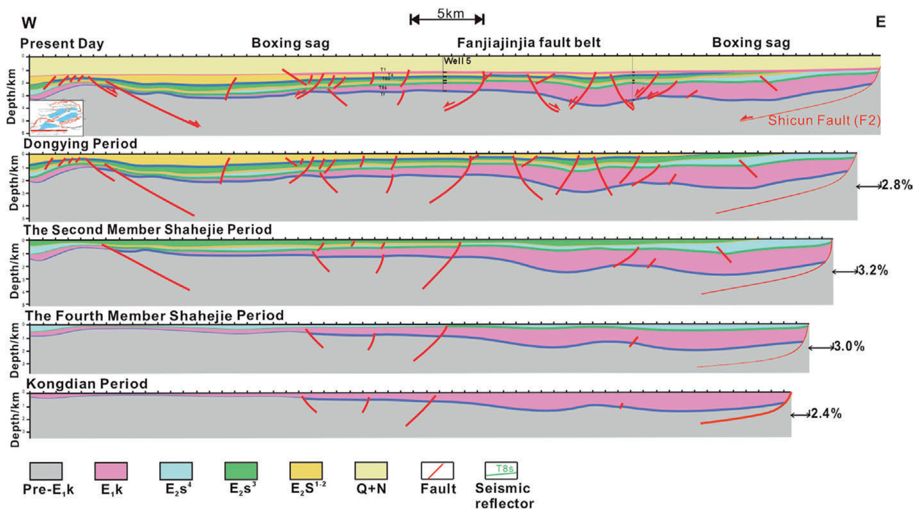

Fig. 12. Balanced structural restoration and evolutionary seismic profile in the southern part of the Dongying Depression (see location in Fig. 1 F–F′).

are confined to the third and fourth members of the Eocene Shahejie Formation (E_2s_4-E_2s_3) and the Oligocene Dongying Formation.

The radiometric dating results (see Section 4; $^{40}Ar/^{39}Ar$, approximately 57.58 ± 0.77 Ma) indicate that basaltic eruptions coincided with the onset of rapid extension during the early Kongdian Formation. This temporal overlap suggests that magmatism was not merely a passive response to lithospheric stretching but might have contributed to the localized thermal weakening of the crust, thereby facilitating fault propagation and plate-scale strain localization. Seismic observations that volcanic bodies are interbedded with syn-rift successions and commonly juxtaposed against active boundary faults further support a contemporaneous and genetically linked relationship between

Table 2
Quantitative statistics of the sections of the balanced structural restoration.

Section	Stages of tectonic	Extension(m)	Extensional Ratio(%)	Extensional Rate(%·Ma^{-1})
D-D′	Ng-Q	710	1.9	0.08
	Es_1-Ed	479	1.3	0.12
	Es_3–Es_2	505	1.4	0.16
	Ek-Es_4	1115	3.2	0.46
B–B′	Ng-Q	1043	2.1	0.09
	Es_1-Ed	1059	2.2	0.21
	Es_3–Es_2	1708	3.6	0.4
	Ek-Es_4	4941	11.7	1.7
F–F′	Ng-Q	1808	2.8	0.12
	Es_1-Ed	2001	3.2	0.3
	Es_3–Es_2	1865	3	0.33
	Ek-Es_4	1420	2.4	0.35
E-E′	Ng-Q	3581	4.9	0.2
	Es_1-Ed	2249	3.2	0.3
	Es_3–Es_2	4810	7.3	0.81
	Ek-Es_4	3040	4.8	0.7

volcanism and early rifting. These relations are corroborated by basalts identified in the first and second members of the Kongdian Formation (E_1k_2-E_1k_1), which demonstrate that magmatism occurred contemporaneously with syn-rift sedimentation. These structural activities provide a critical foundation for understanding the mechanisms of hydrocarbon accumulation and reservoir distribution. Therefore, structural kinematic analysis could establish a framework for interpreting the structural evolution of the Dongying Depression during the Kongdian sedimentary period.

4. Geochronological constraints based on basalt $^{40}Ar/^{39}Ar$ dating

4.1. Petrological characteristics

Studies of the basalts in the Dongying Depression of the Bohai Bay Basin have revealed that their distributions, origins, and evolutions are closely linked to the regional tectonic setting (Liu and Xie, 2003; Sun et al., 2024; Zhai et al., 2004). Regarding the distribution and genesis of the basalts, both their spatial extents and timings of emplacement exhibit clear structural control. On the basis of the spatial comparison, the emplacement of basalts aligns with the major fault zones and evolving depocenters, highlighting the strong control of fault activity on magma migration and eruption. This observation supports a genetic mechanism whereby regional extensional structures provide pathways for deep-seated magma during early rifting.

Furthermore, petrological characteristics reveal distinctive source regions and genesis mechanisms (Liu and Xie, 2003; Sun et al., 2024). Microscopic observations of basalt samples from the Kongdian Formation in Well Caogu 3 show that the rocks are primarily composed of coarse-grained basalt and vitric (glassy) basalt. The groundmass exhibits intersertal and intergranular textures, and the volcanic glass appears reddish-brown to black in color, with irregular morphology. Under cross-polarized light, the glass shows complete extinction and constitutes approximately 5% of the rock volume (Fig. 13c and d). In addition, the presence of calcite veins within the rock suggests the rapid cooling of magma in a tensile structural regime. Overall, these basalts are classified as alkaline volcanic rocks characterized by high densification and stable lithological properties (Fig. 13a and b).

In this study, $^{40}Ar/^{39}Ar$ dating analyses were performed on basalt samples from the Kongdian Formation, focusing primarily on black mica monominerals that exhibited minimal late-stage hydrothermal alteration. The samples were ultrasonically cleaned and then irradiated with neutrons in a nuclear reactor using the H8 irradiation channel, at a neutron flux density of approximately 6.0×10^{12} n/(cm^2·s). All analytical procedures were performed at the National Key Laboratory of Earth System and Resource Environment on the Tibetan Plateau, Institute of Tibetan Plateau Research of the Chinese Academy of Sciences. The samples were incrementally heated in an electron bombardment furnace and measured using an MM-1200B mass spectrometer. The raw data were corrected for mass discrimination, atmospheric argon, blanks, and interfering isotopes. Interfering isotope correction factors were determined through the analysis of irradiated K_2SO_4 and CaF_2 standards. The specific correction values applied were as follows: $(^{36}Ar/^{37}Ar_o)_{Ca} = 0.0002389$, $(^{40}Ar/^{39}Ar)_K = 0.004782$, and $(^{39}Ar/^{37}Ar_o)_{Ca} = 0.000806$, where ^{37}Ar-o refers to the ^{37}Ar value corrected for radioactive decay. A half-life of 35.1 days and a decay constant of 5.543×10^{-10}/a were used for ^{37}Ar (Liu and Liu, 2004; Wang and Zhu, 2005). The plateau and forward and inverse isochron ages were calculated using the Isoplot 3.0 software. All age uncertainties were reported at the 2σ level (95% confidence interval). For the detailed experimental procedures, refer to the relevant literature (Gao, 2012; Liu and Liu, 2004; Wang and Zhu, 2005; Xiang et al., 2013).

4.2. Basalt $^{40}Ar/^{39}Ar$ dating

Basalt samples from the Caogu 3 well in the Kongdian Formation of Dongying Depression were selected for $^{40}Ar/^{39}Ar$ dating. The results are presented in Table 3 and Fig. 14. The analytical results show that the apparent age remains relatively stable during the low-temperature stage (700°C-910 °C), ranging from 55.83 to 58.32 Ma. In the high-temperature stage (980°C-1250 °C), the apparent age gradually increased, reaching 93.25 ± 6.73 Ma at 1250 °C, indicating a potential influence of excess argon. At 1050 °C, the sample yielded a relatively stable plateau age of 57.58 ± 0.77 Ma, which corresponds to the release of most of the total ^{39}Ar. The significantly higher ages observed in the high-temperature interval (1130°C-1250 °C) may be attributed to excess argon or the effects of later thermal events.

On the basis of the analysis of the initial $^{40}Ar/^{36}Ar$ ratios, the proportion of radiogenic ^{40}Ar was relatively high (96.75%–99.76%) during the low-temperature stage (700°C-910 °C), indicating good closed-system behavior. By contrast, during the high-temperature stage (1050 °C−1250 °C), the proportion of ^{40}Ar gradually decreased to 77.14%, which may be attributed to the presence of excess argon or argon loss. Therefore, considering the plateau age distribution pattern, the main eruption age of the basalts from the Kongdian Formation in Well Caogu 3 is 57.58 ± 0.77 Ma. This suggests that the basalt formation occurred during the Paleocene

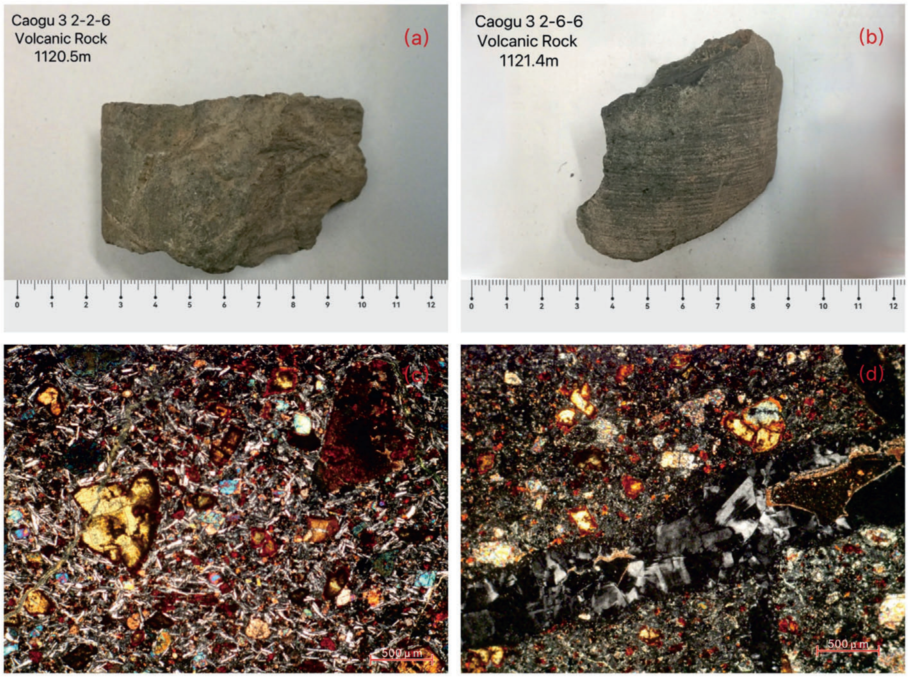

Fig. 13. Diagrams (a) and (b) and microscopic observations (c) and (d) of basalt samples from the Caogu 3 well to the Kongdian Formation.

Table 3
Stepwise $^{40}Ar/^{39}Ar$ dating results of the basalt sample.

Temp°C	$^{40}(r)/^{39}(k)$	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar(r)$ (%)	$^{39}Ar(k)$ (%)	Age (Ma)	±2s
700 °C	54.161	55.818	4.128	0.00724	96.75	20.75	58.06	0.76
750 °C	53.627	53.773	9.863	0.00439	99.04	26.38	57.49	0.71
800 °C	53.706	53.844	7.089	0.00327	99.25	16.61	57.58	0.69
850 °C	54.412	54.106	11.527	0.00355	99.76	8.38	58.32	1.12
910 °C	52.052	53.175	2.901	0.00492	97.69	7.94	55.83	1.38
980 °C	53.180	54.425	12.698	0.00923	96.84	9.04	57.02	1.33
1050 °C	59.446	63.424	20.558	0.02189	92.38	5.74	63.62	1.59
1130 °C	81.129	88.084	55.629	0.04924	88.52	2.75	86.28	4.56
1250 °C	87.847	112.937	11.939	0.09061	77.14	2.41	93.25	6.73

and was closely associated with the early rifting of the Dongying Depression.

The eruption age of the basalts in the Kongdian Formation is closely related to the structural evolution of the Dongying Depression. The geological background analysis results show that the Kongdian Formation was formed during the early rifting stage of the Dongying Depression in the Paleocene, which was influenced by regional extensional structures from the Late Cretaceous to the Paleocene. This structural setting triggered the ascent and eruption of deep-seated magma, resulting in basalt formation. The basalt distribution suggests that the Dongying Depression experienced intense mantle activity during this period, which is likely closely associated with the destruction of the North China Craton and subsequent expansion of the Bohai Bay Basin.

In addition, the elevated ages observed in the high-temperature phase may reflect the influence of later tectonothermal events. During the Neogene structural inversion of the Dongying Depression, regional geothermal activity might have caused the redistribution of argon isotopes in some basalt samples, thereby affecting the age data obtained from the high-temperature step. Similar phenomena have been reported in other volcanic studies on the Dongying Depression and Bohai Bay Basin, where structural adjustments and hydrothermal activities since the Neogene have likely disturbed the K–Ar isotopic systems of early basalts.

Taken together, the diagenetic age of the basalts from the Caogu 3 well in the Kongdian Formation is consistent with the early rifting stage of the Dongying Depression. The magmatic activity was primarily controlled by regional extensional structures during the Paleocene and might have been subsequently modified by later tectonothermal events.

5. Discussion

In the Dongying Depression of the Bohai Bay Basin, the geological evolution of the Paleocene Kongdian Formation records a close coupling between regional tectonic and magmatic activities. Through $^{40}Ar/^{39}Ar$ dating of basalts, this study constrained the timing of magmatic events during the Kongdian Formation, providing crucial insights into the structural setting of that period. The occurrence of magmatism is closely linked to variations in the regional structural stress field, reflecting the dynamic nature of structural evolution in the basin. Further seismic reflection phase and sediment provenance analyses revealed that magmatic activity not only influenced the topographic relief and sedimentary

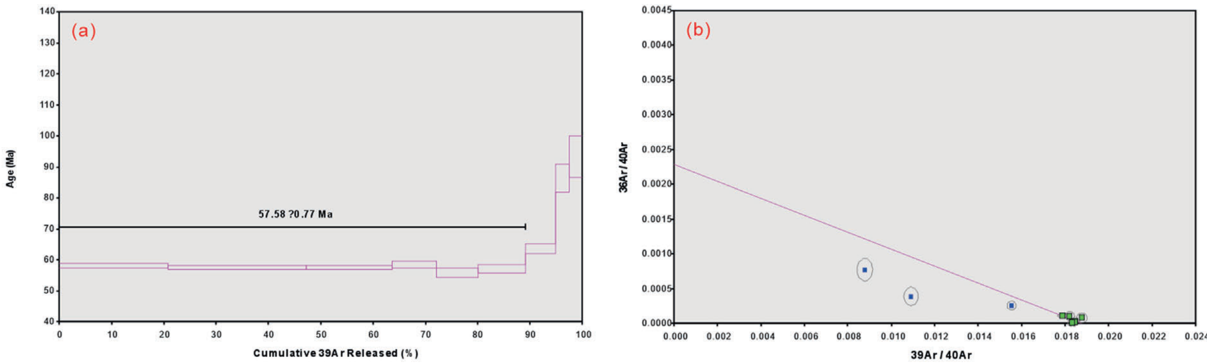

Fig. 14. Illustration of $^{40}Ar/^{39}Ar$ ping ages (a) and inverse isochron ages (b) of basalt samples from the Kongdian Formation to the Caogu 3 well.

patterns but also profoundly impacted the structural development of the basin. Therefore, integrating geochronological data with magmatic activity is essential to elucidate the mechanisms underlying the structural evolution during the Paleocene Kongdian Formation in the Bohai Bay Basin. The following section details the characteristics of the magmatism during this period and its relationship with the regional structural context.

5.1. Early Paleocene faulting and stratigraphic deposition in the Dongying Depression

The development of faults in the Paleocene Kongdian Formation in the Dongying Depression reflects complex extensional and shear processes during regional structural evolution. Fault activity played a critical controlling role during the sedimentary stage of the Kongdian Formation, especially in the early stage, not only shaping basin morphology but also significantly influencing stratigraphic distribution and the depositional environment. The analysis of the characteristics of the fault revealed that during Kongdian Formation deposition, NW-trending faults intersected with newly formed NE- and E-W–trending faults. This fault interaction led to rifting in the basin interior and controlled the tilting and fracturing of strata. Fault zones provide potential pathways for magma ascent, which suggests a spatial link between faulting and subsequent basaltic eruptions.

Fault activity exhibits a certain spatial distribution pattern. The formation of the southern Boxing Depression is mainly influenced by the Shicun, Gaocheng, and Boxing faults, while the northern depression is controlled primarily by the eastern segment of the Chennan Fault. The influence of fault activity extends beyond the development of structural zones to affect sediment distribution characteristics. The development of NE- and approximately E-W–trending faults enhances basin extension, controlling the distribution of sedimentary facies and the variations in sediment accumulation thickness.

Furthermore, the fault activity during the Kongdian Formation period, especially the strong activity of the NE- and approximately E-W–trending faults, caused rapid basin subsidence and extension. During this process, continuous movement of the fault zones provided pathways for later volcanic activity, particularly during the development of the Kongdian Formation basalts. Faulting significantly influenced the distribution and scale of volcanic rocks. Therefore, fault development is closely related to the depositional environment, further highlighting the dominant role of faulting in the structural evolution of the Bohai Bay Basin. Thus, the spatial distribution of faults not only controlled sedimentation and basin morphology but also established the structural framework that influenced the subsequent basalt emplacement (see Section 5.2).

5.2. Impact of early Paleocene Kongdian basalts on the Bohai Bay Basin

Building on the spatial control of faults discussed in Section 5.1, the development of Kongdian Formation basalts directly reflects the early structural evolution of the Bohai Bay Basin. The radiometric dating and stratigraphic observations indicated that basaltic eruptions occurred contemporaneously with the peak activities of the NE- and E-W–trending faults, demonstrating strong temporal coupling between faulting and volcanism. During this time, rifting within the basin provided pathways for deep magma, and localized thermal weakening from magma ascent might have facilitated further fault propagation and basin extension. The close correlation between fault activity and magma upwelling directly controlled the spatial distribution, thickness, and scale of basalt flows. The dating data show that the basalt eruption in the Kongdian Formation is closely related to the activities of the north-east– and near-E-W–oriented faults. These faults provide channels for magma and control stratigraphy, and basalt distribution. These observations indicate that volcanic activity is dynamically linked to fault evolution, reflecting ongoing structural adjustments during rifting. Basalt dating results provide a time frame for structural extension and key data for studying crustal evolution in the region. Fault-induced tensile action not only influences basalt eruption but also has profoundly impacts the later depositional environment (Liu and Xie, 2003; Sun et al., 2024).

Overall, the development of basalts in the Kongdian Formation is closely related to fault activity. The faults not only controlled basin subsidence but also provided conduits for magma ascent, demonstrating a close genetic link between tectonic extension and magmatic activity in the early rifting stage of the Dongying Depression. This spatiotemporal evidence clarifies the structural evolution of the Bohai Bay Basin and provides new perspectives on the relationship between volcanic activity and crustal movement.

6. Conclusion

The following conclusions can be drawn from the findings of this study: (1) In the Dongying Depression, regional faults are well developed, indicating a rapid expansion of the rifting basin during the first member of the Kongdian sedimentary stage, which formed a half-graben pattern characterized by faulting in the north and stratigraphic overlapping in the south. (2) The basalt $^{40}Ar/^{39}Ar$ dating of approximately 57.58 $\pm$ 0.77 Ma indicates that the Dongying Depression might have entered into an active rifting period accompanied by intense igneous eruption during the early Paleocene Kongdian sedimentary stage. (3) The balanced structural reconstruction demonstrated a stretching ratio of approximately 7.3%, which suggests a rapid rifting during the Paleocene Kongdian period. The spatiotemporal structure and sedimentary infilling of the Dongying Depression will provide a perspective foundation on potential deep hydrocarbon exploration.

CRediT authorship contribution statement

Chuanxin Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Jiaying Feng:** Software, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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