Research Article

Structures and Kinematics of the Huanghua Depression in Bohai Bay Basin, East China: Implications for the Formation Mechanism of a Transtensional Basin

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The Bohai Bay Basin in East Asia is a rift basin created by Cenozoic subduction of the oceanic Pacific plate beneath the Asia continent. Many prior studies suggest that the basin was initially formed in the Paleocene with the development of several NNE-trending extensional grabens, but subsequently impacted by right-lateral shear along these existing NNE-trending structures in the middle Eocene, transforming the Bohai Bay Basin into a transtensional basin and producing EW-trending grabens in the Bozhong and the northeastern Huanghua depressions. However, how this transformation occurred remains to be fully understood. Based on seismic and drilling data, we herein investigated the fault structures, basin architecture, and evolutionary stages of the Huanghua Depression in the central-west Bohai Bay Basin to examine the strain partitioning and evolution mechanism during the Paleogene syn-rifting stage. The results reveal that the Huanghua Depression is composed of three structurally distinctive zones, namely, a dextral transtensional, a NW-SE extensional, and a N-S extensional zones from southwest to northeast, which are separated from each other by two transfer zones. The NW-SE extensional zone is interpreted as a horsetail structure on the northern termination of the dextral transtensional zone. This dextral transtensional zone and the Tan-Lu Fault zone to the east served as strike-slip boundaries within which EW-trending depressions such as the northeastern Huanghua and Bozhong depressions formed in the middle Eocene.

1. Introduction

During subduction of the oceanic Pacific Plate along the continental margin of East Asia, a number of Cenozoic extensional basins developed from the Sea of Okhotsk in the north to Vietnam in the south [1–5]. The Bohai Bay Basin in East China is one of the largest among them and preserves a nearly complete package of Cenozoic successions. Therefore, it provides an ideal place for studying processes and mechanisms of back-arc crustal stretching associated with Pacific subduction [6–24].

The Bohai Bay Basin initially formed in the early Paleocene by NWW-SEE-orientated extension, leading to the occurrence of several NNE-orientated elongated grabens [25, 26]. A change of subduction direction of the Pacific oceanic plate from NNW to WNW in the middle Eocene significantly impacted the tectonics of the Bohai Bay Basin [1, 26, 27], initiating dextral strike-slip deformation along these preexisting NNE-trending grabens and generating EW-trending pull-apart or transtensional subbasins in the center of the Bohai Bay Basin [1, 12, 26, 28, 29]. This two-phase rifting of the Bohai Bay Basin indicates a close
relationship between oceanic subduction and associated upper-crustal extension in the back-arc setting [4, 30].

Despite the above consensus, a key problem remains unsolved concerning the tectonic evolution of the second phase of the Bohai Bay Basin, that is, the western boundary of the pull-apart/transtensional system is not yet defined. The Eastern Taihang Shan Fault was previously regarded as the western dextral boundary [31]. However, studies based on recent seismic data indicate that the Eastern Taihang Shan Fault is a normal fault with minimal strike-slip component [15, 26]. The interior of the Jizhong Depression in the western Bohai Bay Basin is characterized by an S-shaped transtensional system since the middle Eocene, which is independent with adjacent large bordering faults, and thus does not belong to the pull-apart/transtensional system in the central-east Bohai Bay Basin [26, 32] (Figure 1a). In brief summary, there lacks a comprehensive model to account for the Paleogene tectonic deformation of the Bohai Bay Basin, hindering a further understanding of the Cenozoic tectonics of East Asia.

In addition to the Tan-Lu Fault zone in the east, two other NNE-orientated large-scale dextral fault zones have been identified within the Bohai Bay Basin [33] and are potential candidates for the western boundary of the dextral transtensional system of the entire central-east Bohai Bay Basin. From west to east, they are the Baxian-Sulu-Handan Fault Zone in the eastern Jizhong Depression and the Huanghua-Dongming Fault Zone in the central Huanghua Depression (Figure 1b). Thus, the structural deformation of the NE-orientated Huanghua Depression likely plays a key role in understanding the tectonic evolution of the Bohai Bay Basin. However, only a few studies have been carried out in the Huanghua Depression at present [34–42], and its geometric and kinematic characteristics remain poorly understood.

This study concentrates on fault structures, basin architecture, and the evolution of the Huanghua Depression in the central Bohai Bay Basin. We use a newly obtained 3D seismic data volume covering an area of 7654 km2 within the Huanghua Depression (Figure 1) to generate isopach maps of the Paleogene strata and establish geological profiles. By calculating the coherent properties of the 3D seismic data volume, we identified lateral discontinuities in the strata including fractures, faults, and lithologic boundaries. These analyses, together with published results of adjacent depressions, provide constraints for the geometric and kinematic features of the Paleogene dextral transtensional system of the central-east Bohai Bay Basin and also have implications for tectonic interactions between subducting west Pacific Plate and its back-arc regions.

2. Geological Setting

2.1. Structure and Stratigraphy of the Bohai Bay Basin. The Cenozoic Bohai Bay Basin was developed along the eastern North China Craton. It encompasses an area of about 200,000 km2 on land and at sea, with up to 10 km of Cenozoic terrestrial deposits (Figure 1). The initial opening of the basin was probably triggered by the roll-back of the subducting Pacific Plate at the beginning of the Cenozoic and was characterized by reactivation of preexisting weaknesses from Mesozoic tectonism [1, 43–49]. It underwent a syn-rifting stage in the Paleogene and a postrifting thermal-subsidence stage during the Neogene through the present [33, 50]. As a result, the Bohai Bay Basin contained six isolated rift basins in the Paleogene, namely, the Jizhong, Linqing, Huanghua, Jiyang, Bozhong, and Liaohe depressions from west to east, and became a unified thermal subsidence basin in the Neogene to Quaternary (Figure 1).

Initiation of rifting in the Paleogene was diachronous across the basin. It initially took place along several grabens bounded by NNE-trending faults during the early Paleogene to the early Eocene, including the Jizhong, Linqing, Southwest Huanghua, and the North Liaohe depressions, and the E-W-orientated Jiyang Depression also formed during this time period [11, 12, 51–54]. The Kongdian Formation (Ek) and the fourth member of Shahejie Formation (Es4) accumulated during this first phase of rifting (Figure 2).

The second phase of rifting took place in the middle Eocene through the Oligocene. It was characterized by the occurrence of dextral transtensional deformation along pre-existing NNE-trending structures and the opening of the Northeast Huanghua and Bozhong depressions, which were bound by E-W-trending faults [12, 22, 26]. Strata from the third to the first members of Shahejie Formation (Es3, Es2, and Es1) to the Dongying Formation (Ed) accumulated during this phase (Figure 2).

The Paleogene strata of both rifting phases 1 and 2 are largely composed of lacustrine and/or deltaic mudstones, shales, and sandstones, and sandstones and conglomerates were deposited in alluvial environment. The overlying Neo- gene and Quaternary strata are mainly composed of alluvial sandstones and conglomerates. Basalts interbedded are commonly seen within the Paleogene syn-rifting sequences and provide age constraints on the Paleogene stratigraphic units [55].

2.2. Subdivisions of the Huanghua Depression. Bounded by the SE-dipping Cangdong Fault (composed of F1, F2, and F9 in Figure 3) and the NW-dipping Chengxi Fault (F3) to the northeast and the southwest, respectively, the Huanghua Depression is overall NE-orientated. It extends nearly 250 km along a NE direction and spans about 50 km in width along a NW direction (Figure 3). Structurally, the Huanghua Depression is composed of three types of subunits: sags that experienced relatively high subsidence with thick syn-rifting sequences, rises featuring little subsidence or even uplift with rock denudation, and slopes characterized by gently sloped regions between them.

Five rises have been identified in the Huanghua Depression. They include the Dongguang, Xuhe, Kongdian, Yangsanmu, and Gangxi-Shengqingzhuhang rises from southwest to northeast. The NW-orientated Dongguang (DG) rise is located between the southern parts of the S. Cangdong (F1) and Xuxi (F3) faults. The NE-orientated Xuhe (XH) rise is located in the footwall of the NW-dipping Xuxi Fault (F3) and may form by normal faulting of F3 during the Paleogene.
The Kongdian (KD) rise is NE-trending and located along the central axis of the depression. It possibly formed as the result of the geometric change of the Cangdong fault (F1) from planar to listric [35] or the influence of transtensional movement of the two bordering faults (F1 and F4) of the Huanghua Depression [56]. The Yangsanmu (YSM) and the Gangxi-Shenqingzhuang (GX-SQZ) rises are located in the central Huanghua Depression, separating a NE-trending fault system to the southwest and a NEE-trending one to the northeast. Among these rises are sags with relatively thick Cenozoic deposits (Figure 3). The Wuqiao (WQ) Sag is located at the southwestern end of the Huanghua Depression. It is isolated from the main body of the Huanghua Depression by the DG Rise and contains about 1500 m of Paleogene strata at its depocenter. The NE-trending Cangdong (CD) and Changzhuang (CZ) Sags are located to the west and east of the Kongdian Rise, respectively, and have a maximum Paleogene thickness of about 4000-5000 m. They were once linked together to form a single depression during deposition of...
| Epoch      | Formation (member) | Code | Age (Ma)       | Units in HH D. | Lithology | Evolutionary stages |
|------------|--------------------|------|----------------|----------------|-----------|---------------------|
| Quaternary | Pingyuan           |      |                |                |           |                     |
| Pliocene   | Minhuazhen         |      |                |                |           |                     |
| Miocene    |                     |      |                |                |           |                     |
|            | Guantao            | N-Q  | 24.6-present   |                |           | Post-rifting        |
|            |                    |      |                |                |           |                     |
| Oligocene  | Dongyin            | Ed   | 32.8-24.6      |                |           | Syn-rifting phase-2 |
|            | Sha-1              | Es1  | 36.5-32.8      |                |           |                     |
|            | Sha-2              | Es2  | 38-36.5        |                |           |                     |
|            | Sha-3              | Es3  | 42-38          |                |           | Syn-rifting phase-1 |
|            | Sha-4              | Es4  | 50.4-42        |                |           |                     |
| Paleocene  | Kongdian           | Ek   | 65-50.4        |                |           |                     |
|            |                    |      |                |                |           |                     |
| Pre-cenozoic |                  |      |                |                |           |                     |

Figure 2: Stratigraphic column of the Bohai Bay Basin, modified from Mao et al. (2019); ages are cited from Feng et al. (2010).
the Ek Formation but were separated since deposition of the Es3 Formation when the KD Rise began to uplift [52, 56]. Three ENE-orientated sags are found in the northeastern part of the Huanghua Depression. From north to south, they are the Banqiao (BQ), Qibei (QB), and Qinan (QN) sags, with maximum Paleogene syn-rift strata up to ~5000 m, ~4000 m, and ~3000 m, respectively. The Qikou (QK) Sag to the east of the Huanghua Depression is bounded by EW-trending faults and is the largest and deepest sag in the Huanghua Depression, with 5000-6000 m of syn-rifting strata deposited in the Paleogene. The Beitang (BT) Sag is separated from the Qikou Sag by F8 and bounded by F7 to the northwest.

3. Structural Architectures of the Huanghua Depression

Here, we present horizontal slices of the coherence data volume (Figure 4) and the seismic data volume (Figure 5) with a depth of 1800 ms to examine the fault patterns of the Huanghua Depression. Three unique fault zones are
identified and include a dextral transtensional zone, a NW-SE extensional zone, and a N-S extensional zone, from west to east (zone a, c, f in Figure 6, respectively). They are separated by two transfer zones (zone b and d–e in Figure 6).

3.1. Dextral Transtensional Zone. The dextral transtensional zone (zone a in Figure 6) is located in the southwest Huanghua Depression, extending from the WQ Sag to the southwest through the KD Rise to the northeast (Figure 3). The boundary faults of this zone include the southern segment of Cangdong Fault (F1) and the Xuxi Fault (F3) to the northwest and southeast, respectively. Fault patterns interpreted from horizontal slices of 3D seismic data (Figure 6) suggest that this zone is characterized by a group of widely distributed, left-step, en echelon normal faults. The azimuths of these faults are generally $\sim 72^\circ$, oblique to the whole fault group striking $\sim 38^\circ$.

The S. Cangdong Fault (F1) on Seismic Profile A (Figure 7) is a planar boundary normal fault dipping SSE. It becomes a listric normal fault about 20 km to the north on Seismic Profile B, with the fault plane rapidly flattening at a depth of between 4500 ms and 5000 ms (Figure 8). The Xuxi Fault (F3) is not revealed by Seismic Profile A but observable on Profile B where it shows a listric geometry (Figure 8). Seven stratigraphic units have been recognized in drill cores
in this zone. These units include, in stratigraphic order, the Carboniferous–Permian (C-P), the Mesozoic (Mz), the Kongdian (Ek), Sha-3 (Es3), Sha-1 (Es1), Dongyin (Ed), and the Neogene-Quaternary (N-Q). The Ek Formation shows a relatively uniform thickness (800-1000 ms) along the NNW-SSE direction (Figures 7 and 8). However, the Es3, Es2, and Ed formations are all thin towards the Kongdian Rise, with a maximum thickness of about 1500 ms in the sags but missing at the top of the rise (Figure 8).

Compared with Profile A (Figure 7), Profile B (Figure 8) shows some distinct features including the upward doming of the Kongdian Rise, the wedge-shaped Es3, Es2, and Ed formations, and the listric geometry of the boundary faults (F1 and F3). Previous studies suggested that the change from planar to listric geometries of the Cangdong and Xuxi faults controlled the formation of the Kongdian Rise since the deposition of Es3 [35]. The left-step en echelon faults in the core of the Kongdian Rise represent a negative-flower structure (Figures 7 and 8), indicative of dextral transtensional shear in this zone. In contrast, the northwestern and southeastern boundary faults (F1 and F3) of this zone were characterized by prolonged normal faulting with minimal strike-slip motion.

3.2. NW-SE Extensional Zone. This zone (zone c in Figure 6) comprises the central segment of the Huanghua Depression
and includes three SW-NE orientated sags, namely, the Banqiao, Qibe, and Qinan Sags. The boundary faults of those sags are the N. Cangdong (F2), Binhai-Gangdong (F5), and Nandagang (F6) faults, respectively. They extend 30 to 50 km laterally along the direction of $\approx 33^\circ$ (Figure 3). However, interpretation of horizontal slices indicates that the secondary faults within this zone generally strike 60-80°, oblique to or braided along the main faults (Figures 4–6). The listric N. Cangdong Fault (F2) changed rapidly from steep south-dipping to nearly horizontal geometry at a depth of 4000-6000 ms. The Binhai-Gangdong (F5) and Nandagang (F6) faults are connected with the N. Cangdong Fault (F2) at depth (Figure 9). Flower structures are observed at the tips of these boundary faults (Figure 9). The Ek Formation is missing in this zone, suggesting later rifting than the dextral transtensional zone (Figure 9).

3.3. N-S Extensional Zone. The N-S extensional zone including the Beitang and Qikou sags is located in the northeastern Huanghua Depression. EW-trending faults and grabens extend eastward into the Bozhong Depression (Figure 1). Similar to the NW-SE extensional zone, the Ek Formation is absent in this zone, whereas the overlying Es3 formation to Quaternary deposits are comparable (Figure 10). The Es3 member has a nearly uniform thickness across the Haihechanglu Fault (F8), whereas the Es1 and Ed formations are present ...
much thicker in the hanging wall than in the footwall (Figure 10). These observations suggest that the Haihechangu Fault (F8) were likely initiated after deposition of Es1. Before that time, the Beitang and Qikou sags were linked together as a uniform sag under the control of the Chadianxinhe Fault (F7).

3.4. Transfer Zones. Transfer zones are usually observed within rift basins, showing a range of geometries from discrete fault zones to wide warping zones [57]. Two N-S to NNW-SSE trending transfer zones have been identified within the 3D seismic slices in this study and are named the W. Transfer Zone and the E. Transfer Zone, respectively (Figure 3).
Figure 9: Seismic Profile C and its interpretation, with location given in Figure 3.

Figure 10: Seismic Profile D and its interpretation, with location given in Figure 3.

Figure 11: Diagram showing axis-orthogonal extension of the dextral transtensional, the NW-SE extensional, and the N-S extensional zones of the Huanghua Depression, indicating a sense of dextral shear of both transfer zones.
The W. Transfer Zone separates the dextral transtensional zone to the west from the NW-SE extensional zone to the east (Figure 6) and is composed of the Gangxi-Shenqingzhuang Rise (GX-SQZ) and the Yangsanmu Rise (YSM). It is an S-shaped discrete fault zone consisting of numerous conjugated small faults with lengths of 5–10 km and strikes of 50-80°, 110-120°, and 150-180°, showing a fault pattern different from adjacent extensional zones.

The E. Transfer Zone is located between the Banqiao, Qibei, and Qinan sags to the west and the Beitang and Qikou sags to the east, separating the NW-SE extensional zone from the N-S extensional zone (Figure 3). Unlike the W. Transfer Zone, no prominent rises have been found within this zone.

The northern segment of the transfer zone (e in Figure 6) is characterized by conjugate small faults that extend horizontally for 4-5 km, and strike ~170-180° and 50-80°. The southern segment (d in Figure 6) is dominated by some NNE-striking larger faults and numerous east-striking en echelon secondary faults.

In profiles B, C, and D, the dextral transtensional, the NW-SE extensional, and the N-S extensional zones were stretched horizontally for ~4.7 km, ~15.3 km, and ~19 km, respectively, during the deposition of Es3 to Ed formations. This suggests dextral shear of both transfer zones assuming a continuous western boundary of the Huanghua Depression (Figure 11).
4. Discussion

4.1. Evolutionary Stages. Our above analysis reveals that the Huanghua Depression underwent three evolutionary stages during the Paleogene and are illustrated by isopach maps (Figure 12).

4.1.1. 65-50.4 Ma during the Deposition of the Ek Formation. Rifting activity started in the southwestern Huanghua Depression in the early Eocene, with the S. Cangdong Fault (F1) and Xu Xi Fault (F3) and synkinematic strata deposited in their hanging walls. The Huanghua Depression in this stage was NNE-oriented, with a length of ~100 km and a width of ~30 km. The Ek formation is the lowest Cenozoic unit with a thickness of 1000-3500 m, and is disconformably overlain by the Es3 formation. The absence of the Es4 formation indicates that normal faulting of the boundary S. Cangdong and the Xuxi faults almost stopped after the deposition of the Ed formation. Affected by NWW-SEE-oriented extension, this stage of rifting basically occurred along preexisting NNE-trending faults [1, 12, 32]. The central and northeastern Huanghua Depression was lack of such faults and thus no rifting occurred in this region.

4.1.2. 42-32.8 Ma during the Deposition of Es3 and Es2 Formations. The Huanghua Depression experienced a significant reorganization since deposition of the Es3 formation in the middle Eocene. A number of boundary faults formed in the central and northeastern Huanghua Depression, including the N. Cangdong (F2), Chadianxinhe (F7), Binghai-Gangdong (F5), and Nandagang (F6) faults. This manifests a fast expansion of the rift basin towards the northeast. During this period, the depocenter was located around the Qikou Sag, accumulating a maximum thickness of about 3400 m. At the same time, the boundary faults changed from planar to listric geometries (Figures 7–10), resulting in uplift of the Kongdian Rise [35]. Along with the initiation of those boundary faults, three structurally and kinematically unique zones developed within the Huanghua Depression, i.e., a dextral transtensional, a NW-SE extensional, and a N-S extensional zones. We suggest that the two transfer zones were initiated simultaneously since deposition of the Es3 formation, separating the above three rifting zones. Es2 formation was completely missing in the Huanghua Depression, suggesting that normal faulting weakened and even stopped after deposition of the Es3 formation.

4.1.3. 32.8-24.6 Ma during the Deposition of Es1 and Ed Formations. The structural deformation in this stage was largely inherited from the previous stage of the Huanghua Depression. The depocenter was located around the Qikou Sag, with a thickness up to 2000 m for both the units. Several faults were newly initiated during this stage, such as the M. Cangdong Fault (F9) and the Haihe-Changlu Fault (F8).

4.2. Kinematic Model of the Huanghua Depression. Horse-tail structures are usually observed at the tip of the strike-slip faults. The obliquely arranged faults usually develop along the termination of a strike-slip fault to adjust the change of lateral offset [58, 59]. The Cenozoic deformation within the Huanghua Depression, which is composed of a dextral transtensional zone, the W. transfer zone, and the NW-SE extensional zone, is similar to the dextral strike-slip systems within horsetail structures (Figure 13). Specifically, the dextral transtensional zone is characterized by a large dextral shear zone characterized by numerous left-stepping en echelon normal faults in the shallow crust. The NW-SE extensional zone served as the horsetail structure of this dextral shear zone to accommodate the gradual disappearance of lateral offset. However, these two zones are not directly connected but separated by a transfer zone (W. Transfer zone) composed of local rises and fault arrays. This dextral shear system emerged since deposition of the Es3 formation at ca. 42 Ma suggested an initiation of dextral deformation in the Huanghua Depression.

4.3. Implications for Transtensional Basin. The West Pacific oceanic plate changed its subduction direction from NNW
to NWW at ca. 42 Ma, from a roughly orthogonal to an oblique subduction with respect to East Asia. As a result, dextral deformation initially occurred along several NNE-trending zones of the Bohai Bay Basin and transformed the basin into a complex transtensional basin. SSW-NNE-orientated dextral deformation formed in the Jizhong Depression [26], along the Tan-Lu Fault in the Liaohe Depression [28], and also in the Huanghua Depression (this study). The Bozhong Depression, which was bounded by EW-trending faults, developed concurrently with this dextral system (Figure 14) [23, 29, 30, 60]. Allen et al. (1997) suggested that the Bozhong Depression was similar to a pull-apart or a transtensional basin created within an extensional overlap by continued dextral transtension to the west and the east. This study further developed the model with new insights from the Huanghua Depression (Figure 15). We propose that the Huanghua, Bozhong, and Liaohe depressions together formed a dextral transtensional system. The east transtensional boundary was the Tan-Lu Fault along the Liaohe Depression. The west boundary was represented by the dextral transtensional and the NW-SE extensional zones of the Huanghua Depression, which resembled a dextral strike-slip system with horse-tail structures. The N-S extensional zone of the Huanghua Depression and the whole Bozhong

Figure 14: Structural sketch map of the Bohai Bay Basin during the deposition of the Kongdian Formation and the Sha-4 Member from 65 Ma to 42.5 Ma (a) and during the deposition of Sha-3 Member from 42.5 Ma to 38 Ma (b), modified after Allen et al. (1997). Depression name: JZ-Jizhong D., LQ-Linqing D., HH-Huanghua D., BZ-Bozhong D., JY-Jiyang D., and LH-Liaohe D.

Figure 15: A dextral transtensional basin model of the Huanghua, Bozhong, and Liaohe depressions during the Kongdian Formation and the Sha-4 Member (a) and during the deposition of the Sha-3 Member (b). This model suggests since deposition of the Sha-3 Member in the middle Eocene, dextral shear translated the Huanghua and Liaohe depressions into dextral transtensional boundaries and opened the EW-trending northeast Huanghua and Bozhong depressions within the extensional overlap.
Depression are the extensional overlap (pull-apart basin) created by dextral transtensional shear of those two boundaries since deposition of the Es3 formation in the middle Eocene. The Jizhong Depression to the west evolved independently with this dextral system in the Paleogene [26].

5. Conclusions

Based on the analysis of seismic profiles, a coherence data volume, and stratigraphic isopach maps, we draw the following conclusions.

(1) The Huanghua Depression is geometrically composed of a dextral transtensional zone, a NW-SE extensional zone, and a N-S extensional zone from the southwest to the northeast, which are separated by two transfer zones.

(2) Initial rifting in the early Paleocene occurred mainly in the southwestern Huanghua Depression, whereas the second rift in the middle Eocene, which was characterized by dextral transtension, was widely distributed and formed the present configuration of the Huanghua Depression.

(3) The Huanghua, Bozhong, and Liaohe depressions formed a large dextral shear system bounded to the east by the Tan-Lu Fault and to the west by horse-tail-like structures within the Huanghua Depression in response to an oblique subduction of Pacific Plate in the middle Eocene.

Data Availability

All the data supporting the results of this study have been presented in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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