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Origin of the Bohai Sea Basin, North China Craton, and implications for bidirectional back-arc extension in the East Asian continental margin

Alan Liu Chen[1] **and Xuanhua Chen**[2]

[1]Northview High School, Johns Creek, GA 30097, USA
[2]SinoProbe Laboratory, Chinese Academy of Geological Sciences, Beijing 100037, China

Correspondence: Xuanhua Chen (xhchen@cags.ac.cn)

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Abstract. The Bohai Sea Basin in eastern China is located in a back-arc extensional regime due to northwestward subduction of the Philippine Sea Plate and westward subduction of the Pacific Plate underneath the Eurasian Plate. The Bohai Sea Basin and surrounding region experience frequent earthquakes. Previous recognition of the origin of the Bohai Sea Basin was limited by the understanding of the back-arc extensional mode perpendicular to the subduction zone in the eastern Asian continental margin. In this paper, a new model for the genesis of the Bohai Sea Basin is proposed based on the construction of a major fault system and investigation of several main boundaries enclosing the Bohai Sea Basin. We have made field investigations and analyses of tectonic landforms and boundary faults on the northwest coast of the Bohai Sea and eastern and western margins of the Liaodong Peninsula, which revealed left-lateral strike-slip faults along the northwest coast of the Liaodong Bay and western margin of the Liaodong Peninsula. Then, we conducted a geological comparison of the Liaodong and Jiaodong Blocks and surrounding areas, as well as a structural interpretation of an aeromagnetic anomaly map of this region. We propose a right-lateral strike-slip fault between the eastern margin of the Liaodong Block and northwestern margin of the Jiaodong Block. This mode of movement may have resulted from the NE stretching, which is parallel to the subduction zone in the northwestern Pacific margin. Therefore, we suggest that the formation of the Bohai Sea Basin resulted from trench-parallel and trench-perpendicular extension. We speculate that the two-direction extension perpendicular and parallel to the subduction zone should be the basic pattern of the back-arc extension with a spherical geometric effect.

1 Introduction

The Bohai Sea is located in the eastern part of the North China Craton (NCC; Fig. 1; X. H. Chen et al., 2022). Traditionally, the Bohai Sea Basin is interpreted as a Cenozoic basin bounded by the Jiaodong Peninsula, North China Plain, Yanshan Mountains, Liaohe Bay Plain, and Liaodong Peninsula (Wang et al., 2016), included in the Bohai Bay Basin (BBB). The BBB consists of the North China Plain (also known as the North China Basin), Bohai Sea Basin, and lower Liaohe Plain, with an area of ca. 200 000 km^2 (Fig. 3; Hou et al., 1998). It is always considered to be an intracontinental extensional rift basin in a back-arc setting, resulting from the westward subduction of the Pacific Plate underneath the Eurasian Plate in the late Mesozoic and Cenozoic (Allen et al., 1997; Liang et al., 2016). The BBB and surrounding region also constitute one of the regions with strong earthquake activities in East Asia (Xiao et al., 2004; Yin et al., 2015; Chen et al., 2020; Fig. 2). The remarkable feature of the BBB is the thinned crust and lithosphere with a high geothermal gradient due to craton destruction and mantle uplifting (Guo et al., 2005; Li et al., 2012; Zhu and Xu, 2019; Zhu et al., 2020; Zhou et al., 2022). Although the water depth in the Bohai Sea is only an average of 18 m, Cenozoic sediments are widely distributed in the BBB and Bohai Sea Basin, with total thicknesses of over 8000 and 11 000 m, respectively, making them an important source rock series of oil and gas (Xiao et al., 2004; Wang et al., 2016).

Regarding the origin of the Bohai Sea Basin and BBB, there is still significant controversy. The main viewpoints proposed by previous studies are the following. The BBB is (1) a back-arc intraplate rift basin with lithospheric extension (Guo et al., 2005; Li et al., 2012; Liu et al., 2018; Zhou et al., 2022), (2) a pull-apart basin resulting from right-lateral strike slipping along the Tan–Lu and Taihang Shan faults due to subduction of the Pacific Plate in the Cenozoic (Hou et al., 1998; Xu et al., 2014; Hu et al., 2022; Liu and Wu, 2022), (3) the result of an active mantle plume with a diameter of ca. 600–800 km (Xiao et al., 2004), or (4) a superimposed effect of multiple-phase extensions and strike-slip deformations (Allen et al., 1997; Liu and Wu, 2022). The formation and evolution of the BBB reflect superimposed effects of multiple episodes of back-arc extensional and strike-slip deformation (Liu and Wu, 2022). Historically, the BBB has experienced many strong earthquakes, including the 1597 $M > 7$, 1679 M 8.0 Sanhe, 1830 M 7.5 Cixian, 1888 M 7.5, 1966 M 7.2 Xingtai, 1969 M 7.4 Bohai Bay, 1975 M 7.3 Haicheng, 1976 M 7.8 Tangshan, and 1976 M 7.4 Luanxian earthquakes (Fig. 2; Deng et al., 1976; Yin et al., 2015; Chen et al., 2020). The present GPS velocity field and focal mechanism solution of the 1975 M 7.3 Haicheng earthquake shows NNW–SSE-stretching stress in the Liaodong Bay and surrounding area (Deng et al., 1976; Wang et al., 2014; Zhao et al., 2015).

Some unresolved key scientific issues on the genesis of the Bohai Sea Basin and BBB are posed as the following questions: (1) did the activity of the Tan–Lu fault or other tectonic factors control the formation of the Bohai Sea Basin? (2) Has the Tan–Lu fault extended northward through the Bohai Sea region, or has the formation of the Bohai Sea Basin disturbed the Tan–Lu fault, causing a discontinuous gap of the Tan–Lu fault in the Bohai Sea region? In this paper, we propose a new model for the tectonic origin of the Bohai Sea Basin based on detailed analyses of boundary geometry and fault systems in the Bohai Sea region and BBB, as well as geological correlation of the Jiaodong and Liaodong peninsulas and surrounding area (Figs. 3 and 4).

2 Regional geological background

2.1 Geological overview of the Jiaodong, Liaodong, and Jidong Blocks

The Bohai Sea is surrounded by the Jiaodong Peninsula in the southeast, the Liaodong Peninsula in the northeast, the Jidong Block and Yanshan fold–thrust belt in the northwest, the North China Plain in the south, and the Liaohe Bay Plain in the north (Figs. 3 and 4). The structural relationship between the Jiaodong and Liaodong peninsulas is the key issue to solving geological problems of the Bohai Sea region.

The Jiaodong Block is located in the central part of the eastern coast of China. It is mainly composed of three major tectonic units: the Jiaobei Terrane in the north, Jiaolai Basin in the central area, and Sulu Orogen in the south (Figs. 3 and 4). The Jiaobei Terrane is the most southern part of the NCC, mainly composed of Archean TTG rocks, i.e., tonalites, trondhjemites, and granodiorites; gneisses, such as biotite gneisses and plagioclase amphibolites; and Archean to Paleozoic metamorphic rocks. Intrusive rocks include Triassic granites (225–200 Ma; Koua et al., 2022), Jurassic composite Linglong pluton (170–145 Ma; Yang et al., 2017), and two-stage Early Cretaceous granites (130–126 and 121–116 Ma; Koua et al., 2022; Dong et al., 2023). The Jiaobei Terrane experienced rapid exhumation in 120–95 Ma (Q. B. Zhang et al., 2022), with development of extensional structures, such as the Linglong extensional dome (Figs. 3 and 4; Zhu et al., 2020; Yan et al., 2021) and metamorphic core complex (MCC; Charles et al., 2013), as well as supersized Jiaodong-type or decratonization-type gold deposits in the late period of the Early Cretaceous (Deng et al., 2020; Zhu et al., 2020, 2024; Yang et al., 2021; Q. B. Zhang et al., 2022). The Sulu Orogen is located on the southeast side of the Wulian–Qingdao–Yantai fault zone (WQYF), characterized by the occurrence of high- to ultrahigh-pressure metamorphic rocks. It is considered to be the eastern segment of the Triassic collisional suture zone between the NCC and South China Block (Yin and Nie, 1993; Zhu et al., 2020; Ma et al., 2021; Dong et al., 2023; H. P. Li et al., 2023; Qiu et al., 2023), coeval with the South China–Indochina collision (Faure et al., 2014).

The Jiaolai Basin is located between the Jiaobei Terrane and Sulu Orogen, as a graben basin formed in the late Early Cretaceous. It had a high elevation of ≥ 2.0 km in the Late Cretaceous (ca. 80 Ma), which was a part of the coast mountains on the eastern margin of the Asian continent (Zhang et al., 2016). Cenozoic basalts outcrop in the Penglai area, eastern Jiaodong Peninsula (Figs. 3 and 4).

The Liaodong Block is located in the northeast of the NCC. It is bordered by the North Yellow Sea Fault (NYSF) with the northern Yellow Sea Basin (Tian et al., 2007). It is mainly composed of Archean TTG rocks, Paleoproterozoic Liaohe Group metamorphic rocks, Mesoproterozoic to Paleozoic metamorphic sedimentary rocks, and Mesozoic to Cenozoic sedimentary and magmatic rocks. It is dominated by a large number of granites with ages of Triassic (231–200 Ma), Jurassic (183–152 Ma), and Cretaceous (139–117 Ma) (Figs. 3 and 4; Yan et al., 2021; Zeng et al., 2022; Zhu et al., 2024). It experienced Yanshanian intracontinental compressional deformation initiated at ca. 171 Ma in the Middle Jurassic (Ren et al., 2023), with a Late Jurassic continental arc formed due to the paleo-Pacific subduction (Zeng et al., 2022; Qiu et al., 2023). Granitoid plutons intruded with ages ranging from 130 to 126 Ma, indicating asthenosphere upwelling-related craton destruction in the Early Cretaceous (Wu et al., 2021; Yang et al., 2021; Wang et al., 2022). Simul-

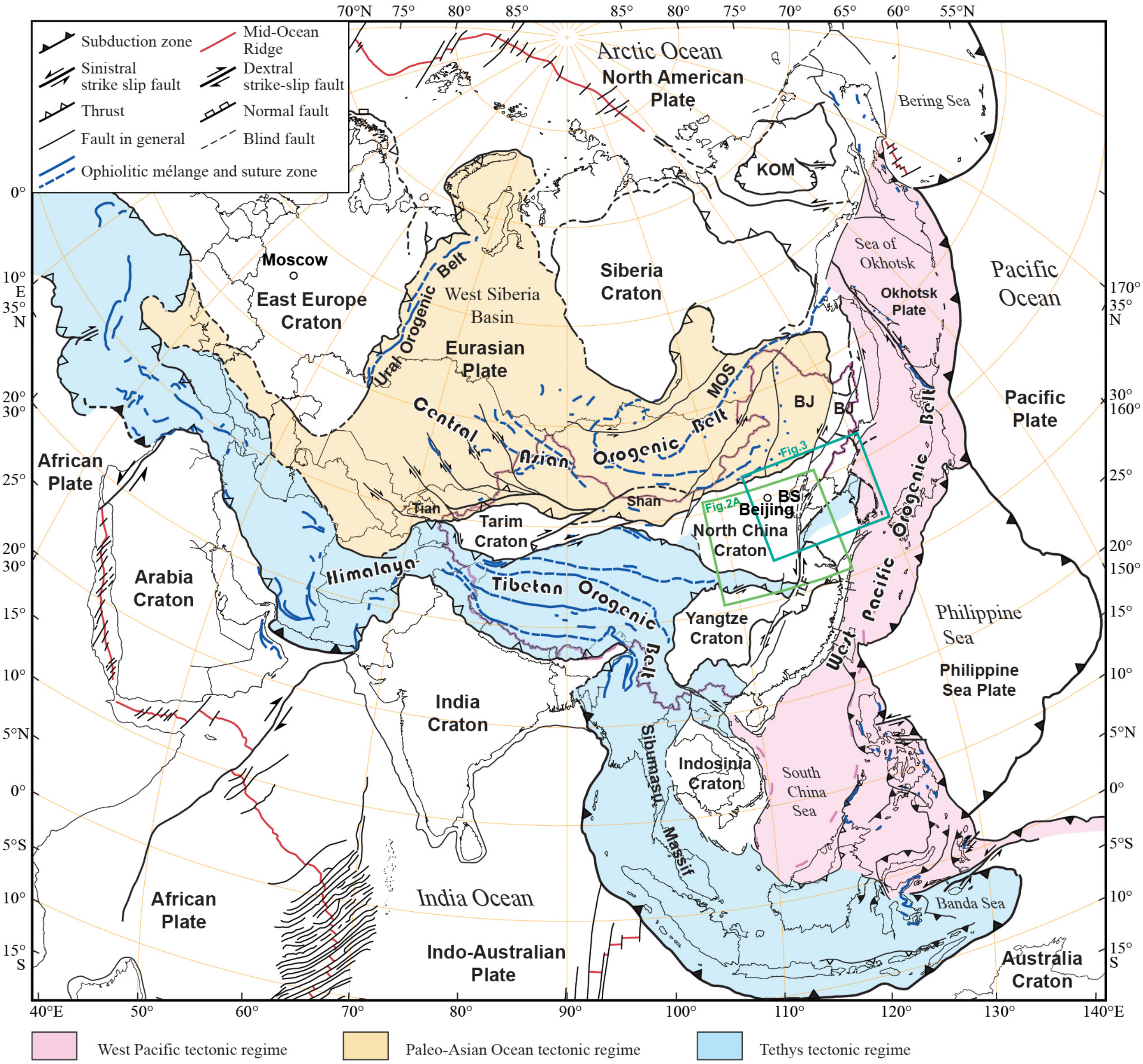

Figure 1. Simplified tectonic map of Asia, showing the location of the Bohai Sea in eastern China. Modified from X. H. Chen et al. (2022). BS, Bohai Sea. KOM, Kolyma–Omolon superterrane (Ar-P). BJ, Bureya–Jiamusi superterrane (Ar-J). TLF, Tan–Lu fault. Locations of Figs. 2a and 3 are also shown.

taneously, extensional structures, such as the Liaonan MCC, developed in the late Early Cretaceous (Figs. 3 and 4; Lin et al., 2007, 2008; Charles et al., 2013; Lin and Wei, 2020; Zhu et al., 2020; Yan et al., 2021; Qiu et al., 2023; Ren et al., 2023), accompanied by the occurrence of Cu, Mo, and decratonization-type gold deposits (Wu et al., 2021; Yan et al., 2021; Yang et al., 2021; Zhu et al., 2024). Typical gold deposits in the Wulong–Sidaogou and Xinfang regions, Liaodong Peninsula, have metallogenic ages of ca. 120 Ma (P. Zhang et al., 2022).

The Jidong Block and Yanshan fold–thrust belt are located in the northern NCC and northwest coast of the Bohai Sea (Figs. 3 and 4). The Archean basement rocks outcropping here are mainly gray gneisses and TTG rocks, as well as supracrustal rock series in granulite facies metamorphism (Zhu et al., 2020). The Jidong Block experienced the development of the late Paleoproterozoic to Mesoproterozoic Yanliao Rift System (Zhu et al., 2020) and intracontinental Yanshanian compression in the late Middle Jurassic to Early Cretaceous (Dong et al., 2015; Yang et al., 2020; Qiu et

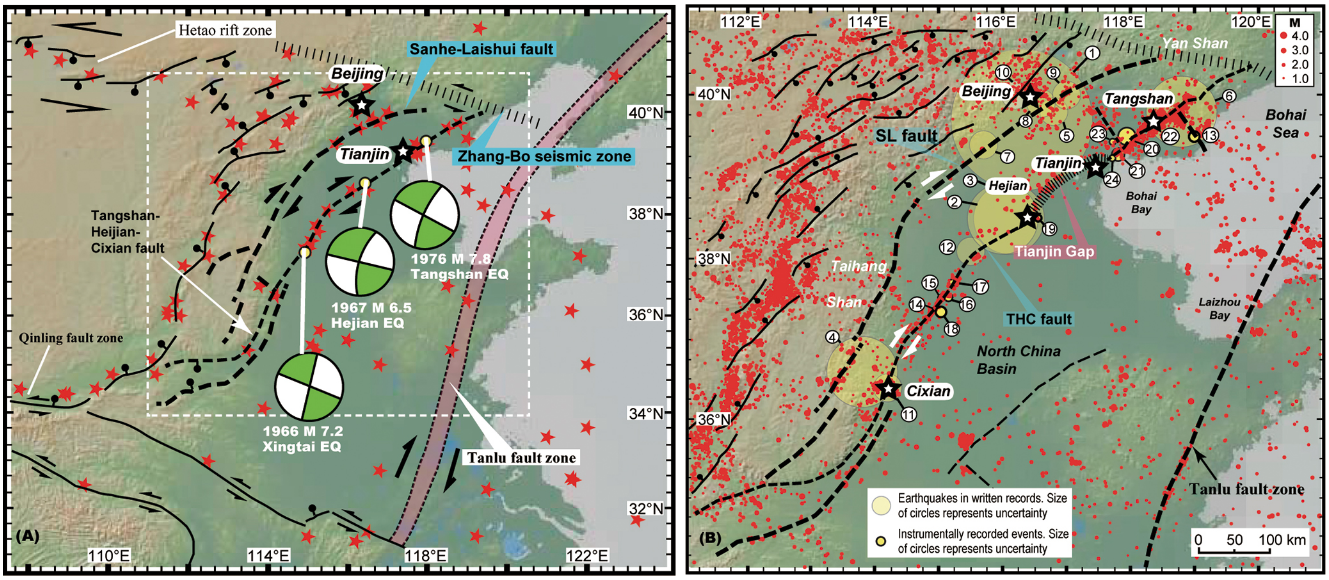

Figure 2. (a) Pre-instrumentation historical earthquakes (EQs) with $M \geq 6$ across northern China and focal mechanisms of the 1966 CE Xingtai, 1967 Hejian, and 1976 Tangshan earthquakes (mainly right-lateral strike slipping along the THC; after Yin et al., 2015). **(b)** $M \geq 6$ earthquakes from 1000 CE to the present in the North China Basin against a background of microseismicities between 2009 and 2013 (after Yin et al., 2015). THC – Tangshan–Hejian–Cixian fault; SL – Sanhe–Lushui fault. For earthquakes that occurred in the same year, they are labeled sequentially, such as 1966-1, 1966-2, 1976-1, and 1976-2. Earthquakes: (1) 1057 CE S. Beijing earthquake (*M* 6.8); (2) 1068 CE Hejian earthquake I (*M* 6.5); (3) 1144 CE Hejian earthquake II (*M* 6.0); (4) 1314 CE Shexian earthquake (*M* 6.0); (5) 1536 CE Tongxian earthquake (*M* 6.0); (6) 1624 CE Luanxian earthquake (*M* 7.0); (7) 1658 CE Laishui earthquake (*M* 6.0); (8) 1665 CE W. Tongxian earthquake (*M* 6.5); (9) 1679 CE Sanhe earthquake (*M* 8.0); (10) 1730 CE W. Beijing earthquake (*M* 6.5); (11) 1830 CE Cixian earthquake (*M* 7.5); (12) 1882 CE Shenxian earthquake (*M* 6.0); (13) 1945 CE Luanhe earthquake (*M* 6.3); (14) 1966-1 (CE) Xingtai earthquake (*M* 6.8); (15) 1966-2 (CE) Xingtai earthquake (*M* 6.7); (16) 1966-3 (CE) Xingtai earthquake (*M* 7.2); (17) 1966-4 (CE) Xingtai earthquake (*M* 6.2); (18) 1966-5 (CE) Xingtai earthquake (*M* 6.0); (19) 1967 CE Hejian earthquake (*M* 6.5); (20) 1976-1 (CE) Tangshan earthquake (*M* 7.8); (21) 1976-2 (CE) Changli earthquake (*M* 6.2); (22) 1976-3 (CE) Luanxian earthquake (*M* 7.4); (23) 1976-4 (CE) Ninghe earthquake (*M* 6.9); (24) 1977 CE Tanggu earthquake (*M* 6.2) (from Yin et al., 2015).

al., 2023). Post-orogenic extension occurred in the late Early Cretaceous (135–100 Ma), represented by the Yunmengshan and Yiwulvshan MCCs, as well as the Kalaqin and Fangshan extensional domes (Lin et al., 2008; Charles et al., 2013; Liu et al., 2017; Lin and Wei, 2020; Yang et al., 2020; Zhu et al., 2020; Sun et al., 2022).

The Jiaobei Terrane, Liaodong Block, and Jidong Block are all parts of the NCC, composed of Archean metamorphic rocks and Proterozoic greenstone belts. They suffered similar geological evolution processes in the Phanerozoic. They are all located in the back-arc setting of the subducted western paleo-Pacific Plate, i.e., the Izanagi Plate. They underwent intracontinental Yanshanian compression in the late Middle Jurassic to early Early Cretaceous and extensional faulting in the late Early Cretaceous, with extensive crustal melting in the Mesozoic (Dong et al., 2015; Yang et al., 2017; Clinkscales and Kapp, 2019; Zhu et al., 2020; Yan et al., 2021; X. H. Chen et al., 2022; Sun et al., 2022; Dong et al., 2023; Qiu et al., 2023).

2.2 Fault system of the Bohai Sea Basin, northern Yellow Sea Basin, and surrounding areas

The Bohai Sea is divided into the main sea and three bays: the Bohai Bay in the west, Laizhou Bay in the south, and Liaodong Bay in the north (Figs. 3 and 4). As a part of the BBB, the Bohai Sea Basin and surrounding region constitute an important petroliferous basin and one of the oil and gas production bases in China, with extremely complex and diverse fault systems. The Liaodong Bay region and western North China Plain are dominated by NNE–SSW-trending normal faults and extensional right-lateral strike-slip faults, while the Laizhou Bay region and eastern North China Plain are dominated by nearly E–W- and NNE–SSW-trending normal faults (Figs. 3 and 4; Allen et al., 1997; Ren et al., 2002; Li et al., 2012; Hu et al., 2022; Yuan et al., 2022).

Previous studies have suggested two-phase rifting of the BBB in the Cenozoic, controlled by the enhanced back-arc extension due to eastward roll-back of the subducted Pacific Plate (Liu et al., 2017; Allen et al., 1997; Hu et al., 2022). The first phase is the development of elongate half-grabens in the Paleocene to early Eocene, with deposition of the Kong-

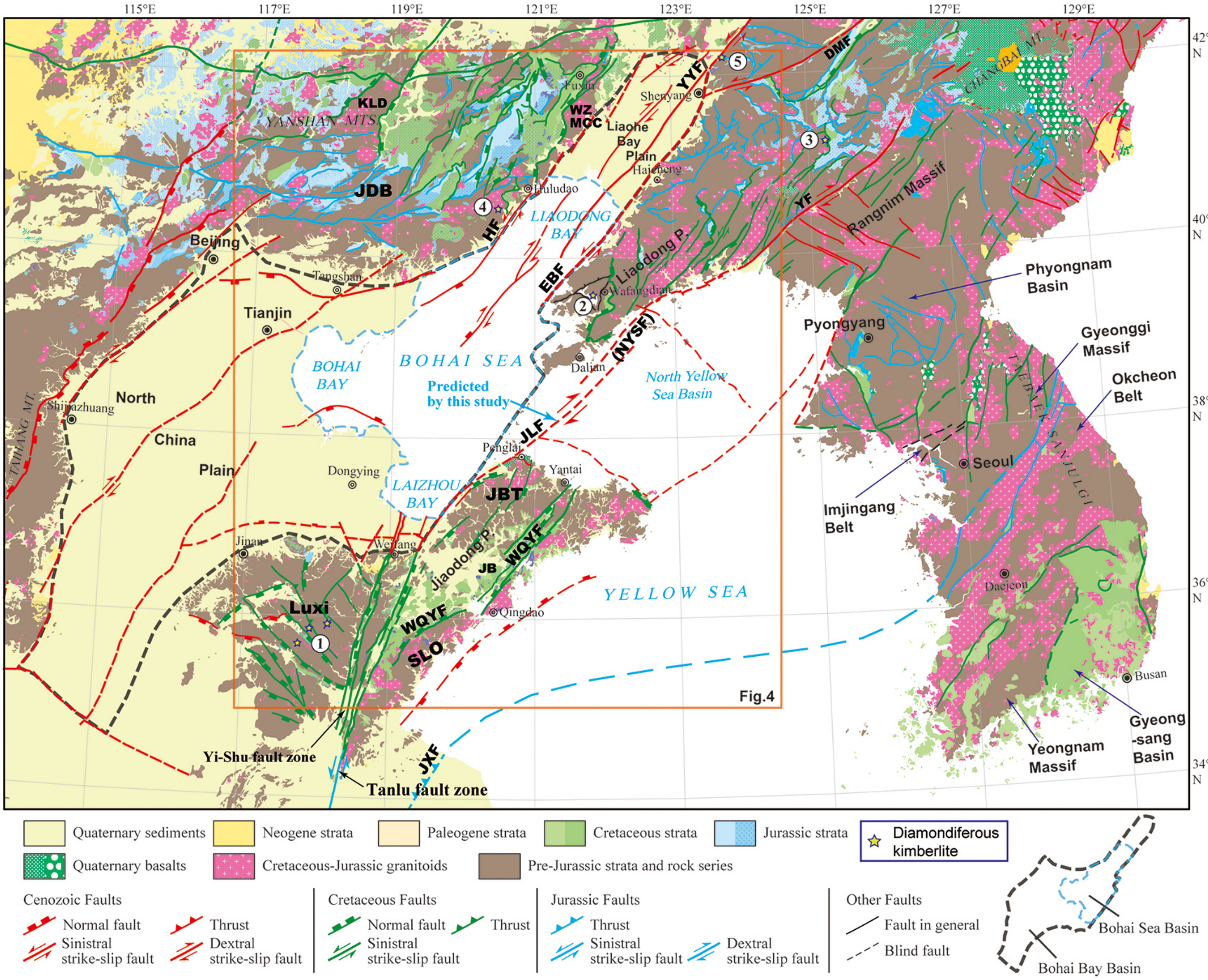

Figure 3. Sketched structural geological map of the Bohai Bay Basin and surrounding region (modified from Allen et al., 1997; China Geological Survey, 2004; Ren et al., 2013; Yin et al., 2015; Kim et al., 2018; Zhai et al., 2019; Yang et al., 2020; Lin et al., 2021; Ren et al., 2023; and Zhu et al., 2024). The Tan–Lu and Yi–Shu fault zones share a common segment of the western boundary of the Sulu Orogen. Diamondiferous kimberlites are from Liu et al. (2019). JDB, Jidong Block. JBT, Jiaobei Terrane. JB, Jiaolai Basin. SLO, Sulu Orogen. WZMCC, Waziyu (also named Yiwulvshan) MCC (Sun et al., 2022). KLD, Kalaqin Dome (Yang et al., 2020). HF, Honglazi fault. EBF, eastern Bohai fault. JLF: Jiao–Liao fault as the boundary faults of the Jiaodong and Liaodong peninsulas predicted in this study. NYSF, North Yellow Sea Fault (Tian et al., 2007). YYF, Yilan–Yitong fault. DMF, Dun–Mi fault. YF, Yalvjiang fault. WQYF, Wulian–Qingdao–Yantai fault. JXF, Jiashan–Xiangshui fault. Diamondiferous kimberlites: 1, Mengyin; 2, Wafangdian; 3, Huanren; 4, Huludao; 5, Tieling.

dian and lower Shahejie Formations (Allen et al., 1997). The second is the development of a dextral transtensional pull-apart basin in the middle Eocene to early Oligocene, with a transition that occurred at ca. 45–43 Ma in the middle Eocene (Allen et al., 1997; X. P. Chen et al., 2022). Then, the BBB entered the post-rifting development stage in the Neogene and Quaternary (Allen et al., 1997; X. P. Chen et al., 2022). The superimposed strike-slip faulting on an extensional stress field controlled the formation and evolution of the dextral transtensional BBB fault system in the Cenozoic (Liu et al., 2018; Hu et al., 2022).

The northern Yellow Sea Basin is located to the east of the Liaodong Peninsula and northeast of the Jiaodong Peninsula, adjacent to the Bohai Sea (Figs. 3 and 4). It has a boundary fault, i.e., the North Yellow Sea Fault in its northwest (Tian et al., 2007). It is characterized by normal faults trending in the NE to NNE, ENE to EW, and NW to NNW directions in the Neogene and Quaternary (Shen et al., 2013).

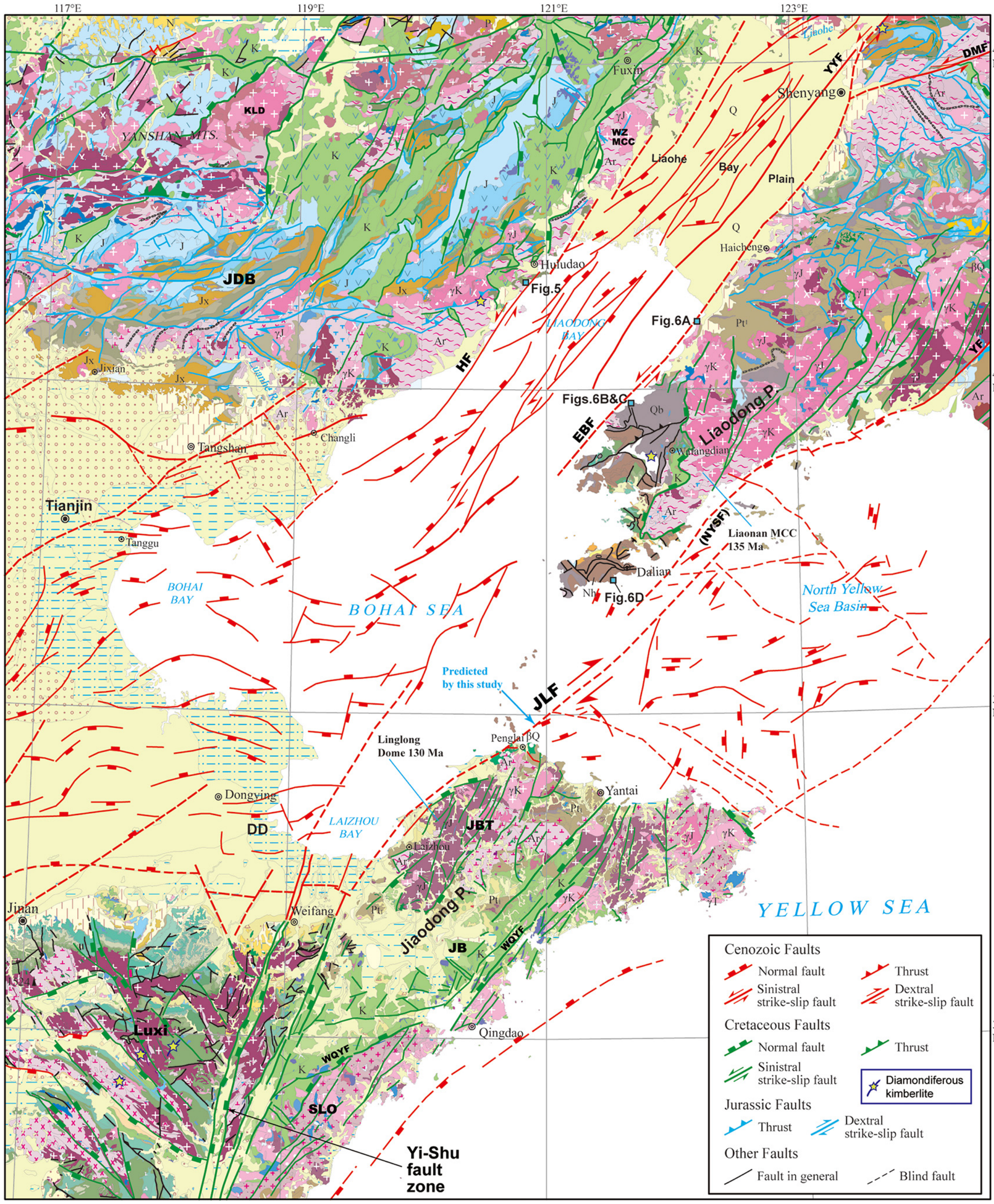

Figure 4. Detailed structural geological map of the Bohai Sea and surrounding region (modified from Allen et al., 1997; China Geological Survey, 2004; Ren et al., 2013; Yin et al., 2015; Wang et al., 2016; Yang et al., 2020; Ren et al., 2023, and Zhu et al., 2024), showing the distribution of the fault system and location of the field observation sites (see Figs. 5, 6, and 7). The Liaonan MCC and Linglong dome are from Charles et al. (2013), Zhu et al. (2020), Yan et al. (2021), and Ren et al. (2023). Diamondiferous kimberlites are from Liu et al. (2019). JDB, Jidong Block. JBT, Jiaobei Terrane. JB, Jiaolai Basin. SLO, Sulu Orogen. WZMCC, Waziyu (also named Yiwulvshan) MCC (Sun et al., 2022). KLD, Kalaqin Dome (Yang et al., 2020). HF, Honglazi fault. EBF, eastern Bohai fault. JLF: Jiao–Liao fault as the boundary faults of the Jiaodong and Liaodong peninsulas predicted in this study. NYSF, North Yellow Sea Fault (Tian et al., 2007). YYF, Yilan–Yitong fault. DMF, Dun–Mi fault. YF, Yalvjiang fault. WQYF, Wulian–Qingdao–Yantai fault. Strata systems: Q, Quaternary. N, Neogene. K, Cretaceous. Nh, Nanhua. Qb, Qingbaikou. Pt_3, upper Proterozoic. Jx, Jixian. Pt_1, lower Proterozoic. Ar, Archean. βQ, Quaternary basalts. Granitoids: γK, Cretaceous. γJ, Jurassic. γT, Triassic. γPt, Proterozoic. γAr, Archean.

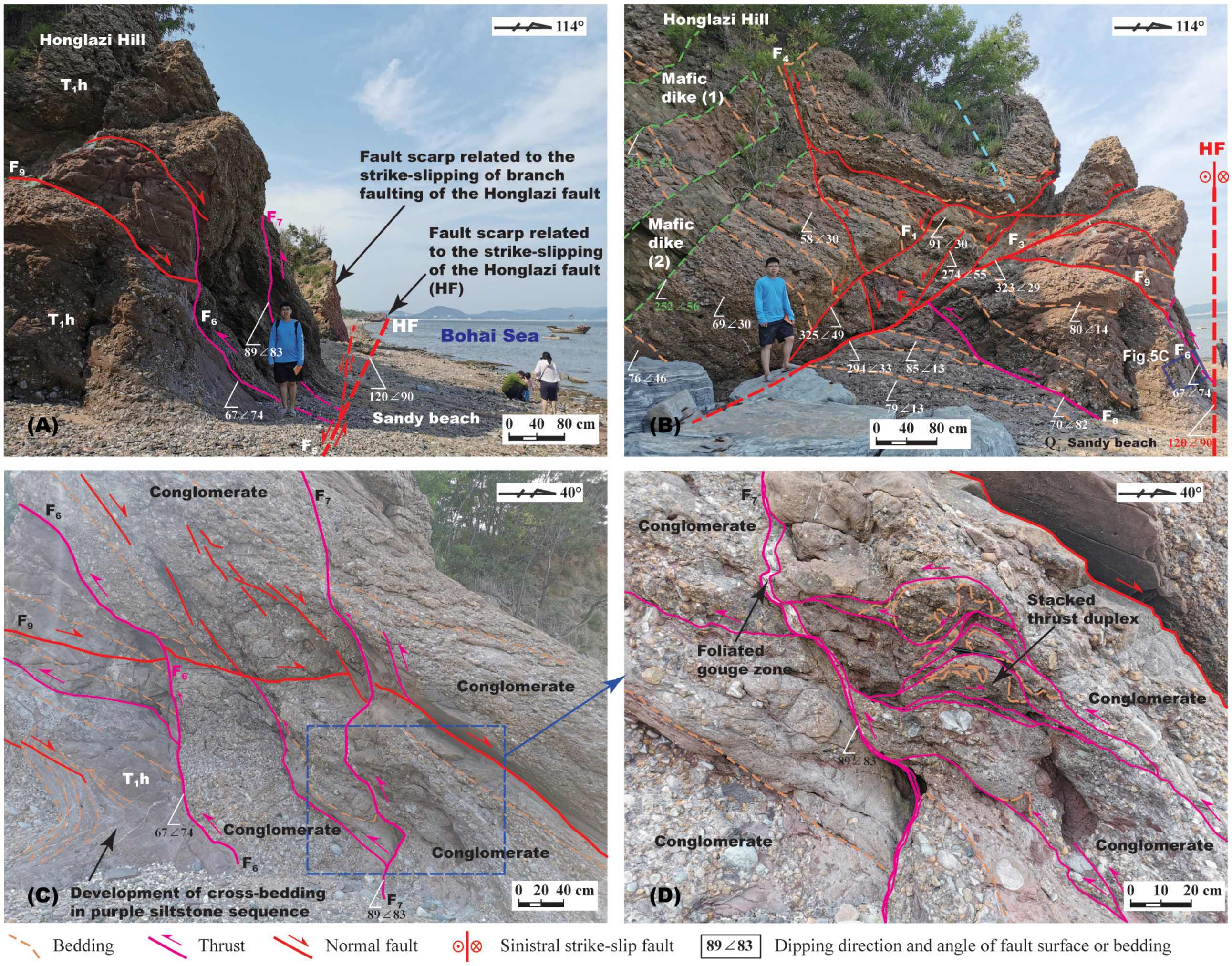

Figure 5. Structural analyses on the northwestern coast of the Bohai Sea. **(a)** The Honglazi fault (HF) with flower structure on the western coast of the Bohai Sea, formed in the Early Cretaceous. The flower structure is truncated by a normal fault system. **(b)** Development of the extensional normal fault system with intrusion of mafic dikes later than the HF and the flower structure. **(c)** The western half-thrust system of the flower structure related to the HF. **(d)** Duplex in the Lower Cretaceous related to the flower structure of the Honglazi fault. See panel **(b)** for location. T_1h, Hongla Formation of the Lower Triassic. Section view.

3 Field observation and structural analyses

3.1 Northwest coast of the Bohai Sea and the Liaodong Bay Basin

Near the Honglazi Bay, in the city of Huludao, the northwestern coast of the Liaodong Bay outcrops the Neoarchean gneisses, Mesoproterozoic Changcheng system, and Lower Triassic Hongla Formation (T_1h; Li et al., 2020), intruded by Jurassic and Early Cretaceous granitoids (Figs. 3 and 4; Ren et al., 2013). They form coast hills and cliffs with high relief of tens of meters to 100 m. The Hongla Formation is composed of purplish red cobble and sandy conglomerates, sandy mudstones, and sandstones from the bottom to the top. It is characterized by the development of cross-bedding of sandstones and siltstones (Li et al., 2020).

Field observations show several grayish-green mafic dikes intruding in clastic rock series of the Hongla Formation and a series of thrusts, extensional normal faults, and strike-slip faults that developed on the outcrop (Fig. 5a and 5b). The dikes are nearly parallel to the normal faults with en echelon arrangement (such as F_1 and F_2 in Fig. 5b). These normal faults and dikes are truncated by the normal faults formed at a later stage (such as F_3) and then cut by a detachment fault (F_4) that developed at the bottom of the conglomerate layer (Fig. 5b). The conglomerate layer above the detachment fault has suffered conformal folding, with its front tip (the western wing) inverted (Fig. 5b). A thin layer of fault gouge is also observed on the detachment plane. We interpret the mafic dikes as having formed during the lithosphere extension in the late Early Cretaceous, which is almost coeval with the detachment fault (the F_4). This is similar to the gravitational

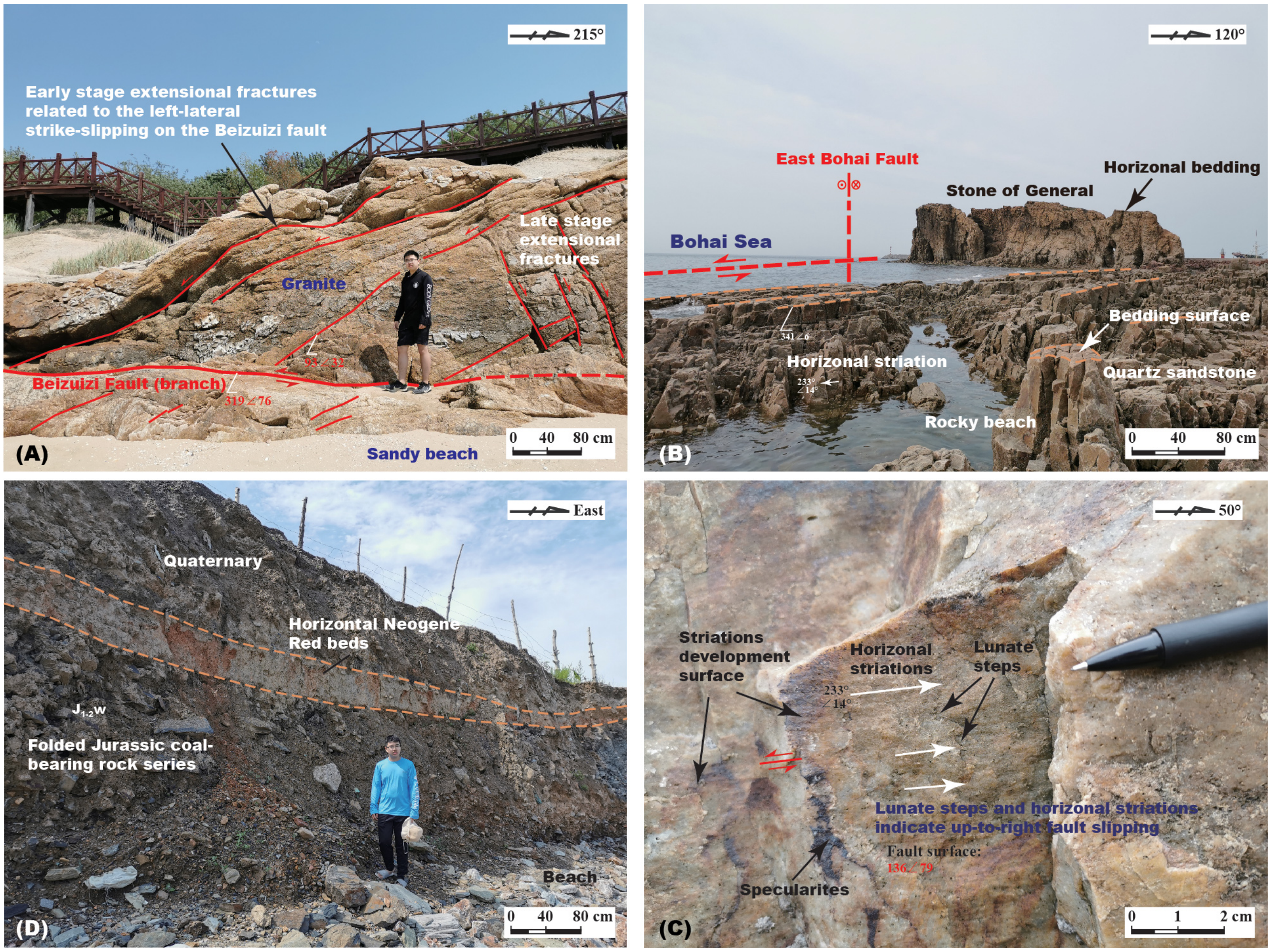

Figure 6. **(a)** The Beizuizi fault, a branch of the eastern Bohai fault, occurs on the northwestern coast of the Liaodong Peninsula, showing a left-lateral strike-slip movement similar to that on the Honglazi fault in Fig. 5. Section view. Both the Beizuizi and Honglazi faults are considered to be relic faults formed before the opening of the Bohai Sea. **(b)** Topographic feature on the western coast of the Liaodong Peninsula, showing geometric properties of the eastern Bohai fault. **(c)** Nearly horizontal striations indicate early-stage left-lateral strike-slip along the eastern Bohai fault on the western coast of the Liaodong Peninsula. Section view. **(d)** A coastal cliff occurs at the southernmost edge on the eastern coast of the Liaodong Peninsula, showing the vertical cutting of the horizontal Neogene red bed due to active normal faulting. Section view. J_{1-2}w, Lower–Middle Jurassic Wafangdian Formation.

collapse in a post-orogenic stage, with local thrusting developing in the detachment front.

The Honglazi fault (HF in Figs. 3, 5a and b) strikes N30° E, with a nearly vertical faulting plane. Thrusts such as the F_6, F_7, and F_8 faults in Fig. 5 constitute a flower structure related to the HF, indicating the HF has the feature of left-lateral strike slipping (as shown in Fig. 5a). At the outcrop scale, the occurrence of a stacked anticline in the Hongla Formation indicates imbricate thrusting in the fault system (Fig. 5d), also implying left-lateral slipping along the Honglazi fault. Early developed thrust faults, such as F_6 and F_7, have cut through the much earlier developed normal faults, such as F_9, and then were cut by the later normal faults, such as F_3 and F_4 (Fig. 5b and c).

Structural analyses revealed the following deformational and magmatic sequence in the Honglazi area: (1) regional extension and normal faulting, with mafic dike intrusion in the Lower Triassic Hongla Formation along extensional fractures, in late times of the Early Cretaceous; (2) left-lateral strike slipping along the Honglazi fault, accompanied by imbricate thrusts, flower structure, and stacked anticline, in early times of the Late Cretaceous; and (3) normal faulting along the Honglazi fault in the early Cenozoic. Resulting from the continuous extensional faulting and strike slipping in the Cenozoic, the Liaodong Bay area continued to receive fine-grained clay and siltstone sedimentation in the Liaohe River Delta and subsided to form the Liaohe Bay Basin and therein an abundance of wetlands.

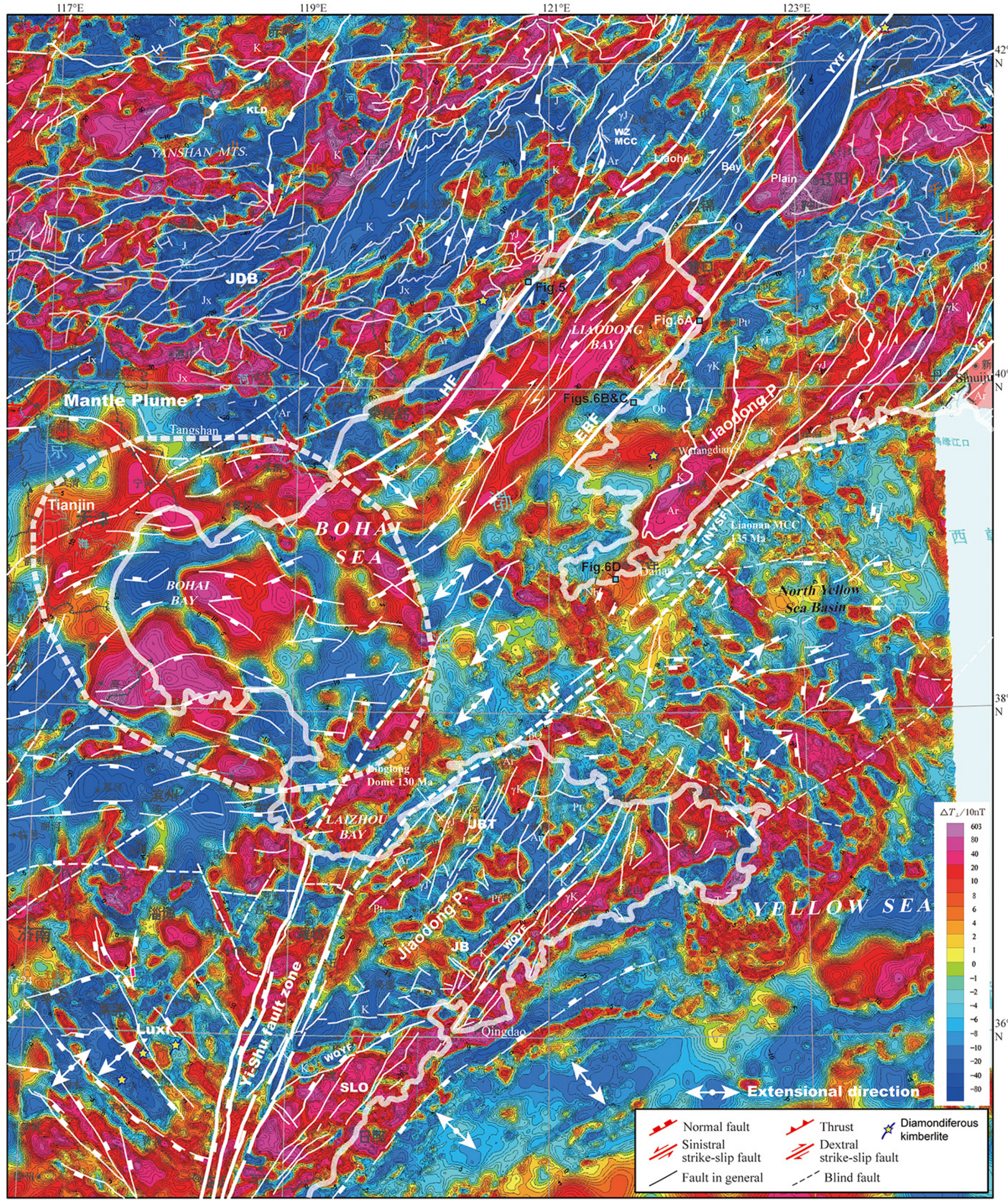

Figure 7. Polarized aeromagnetic anomaly map of the Bohai Sea Basin and surrounding region (modified from Xiong et al., 2015), superimposed with the distribution of fault systems and location of field observation points (see Figs. 5, 6, and 7). The dashed gray ellipse delineates the possible range of a mantle plume. See Fig. 4 for other explanations.

3.2 Northwest coast of the Liaodong Peninsula

In the Beizuizi area near the northeast coast of the Liaodong Bay, late Early Cretaceous granitoids, with an age of 127–120 Ma (Wang et al., 2023), intruded into the Paleoproterozoic Gaixian Group sequence (Figs. 3 and 4). A strike-slip fault developed in the granitoids, with a strike of N49° E and dip angle of 76°. We named it the Beizuizi fault, which could be a branch of the eastern Bohai fault (EBF in Figs. 3 and 4). Early-stage extensional fractures indicate left-lateral strike slipping along the Beizuizi fault (Fig. 6a), which is consistent with the movement direction of the Honglazi fault on the northwest coast of the Liaodong Bay. The fault truncated the two-stage extensional fractures in the granitoids (Fig. 6a), implying faulting later than ca. 120 Ma. The oriented arrangement of potassium feldspars in the granitoids forms sub-horizontal stretching lineation with an orientation of 100° and dip angle of 3°, indicating early-stage horizontal sinistral shearing along the Beizuizi fault during intrusion of Early Cretaceous granitoids. Fine-grained quartz veins developed on the fault plane, with the occurrence of bookshelf structures obliquely to the fault, implying transtensional dextral movement along the fault in a later relaxation stage. The arrangement of late-stage joints also reflects the right-lateral transtensional faulting along the Beizuizi fault (Fig. 6a). This kind of right-lateral transtensional activity could be inferred to have developed in the early Cenozoic, which is consistent with the widespread right-lateral strike-slip faulting in the Liaodong Bay and surrounding area in the early Cenozoic (Figs. 3 and 4; Allen et al., 1997; Hu et al., 2022).

Left-lateral strike-slip faulting is also found in the Jiangjunshi area on the central northwest coast of the Liaodong Peninsula. The Qingbaikou System (Qb) of the Neoproterozoic in this area is mainly composed of pure white quartz sandstones with medium- to coarse-grained texture, with nearly horizontal bedding (Fig. 6b). Multiple sets of joints developed perpendicular to the bedding of the Qingbaikou System. Striations on the joint surface indicate left-lateral movement striking N53° E (Fig. 6c, section view), consistent with the movement direction of the Beizuizi and Honglazi faults. Therefore, we speculate that there was also Late Cretaceous to early Cenozoic left-lateral strike-slip faulting on the southeast coast of the Liaodong Bay, which could be called the eastern Bohai fault (Figs. 3 and 4).

3.3 Southeast coast of the Liaodong Peninsula

A Neogene red layer, with nearly horizontal bedding, outcrops in the Dajiao area in the city of Dalian on the southeast coast of the Liaodong Peninsula. It is a kind of residual deposit of weathered paleo-crust, mainly composed of a ca. 1 m thick magenta clay layer. It is covered by Quaternary clastic deposits in parallel unconformity and underlain by folded dark gray shales of the Early–Middle Jurassic Wafangdian Formation (Fig. 6d). The Wafangdian Formation is a set of fluvial to lacustrine facies with coal-bearing strata, mainly composed of sandstones, mudstones, and dark gray shales, interbedded with mudstones. Significant tectonic relief between the coastal zone and the Cenozoic sediments in the Yellow Sea implies the existence of an active normal fault at the coastal cliff. It may be a branch of the North Yellow Sea Fault (NYSF in Figs. 3 and 4). As a reasonable inference, the southwestward extending of the North Yellow Sea Fault should compose the Jiao–Liao fault that separates the Jiaodong Block from the Liaodong Block (Figs. 3 and 4).

Active normal faulting also appears in the Laotieshan area in the southwest corner of the Liaodong Peninsula. In this area, the significant tectonic relief occurs between the Neoproterozoic Nanhua System and offshore deposits in the northern Yellow Sea, expressed by coastal landforms such as the Elephant Trunk Hill. The Nanhua System here is composed of pure white medium- to coarse-grained quartz sandstone with thin layers of meta-argillaceous siltstones.

3.4 Aeromagnetic anomaly and fault system

An aeromagnetic anomaly map may reflect the distribution of an aged basement controlled by the fault system. The polarized aeromagnetic anomaly map shows that there is a NE-extending high-aeromagnetic-anomaly belt in the Liaodong Bay area (Fig. 7; Xiong et al., 2015). This can be explained as a result of uplifted Archean basement, which is similar to those in the Liaodong and Jiaodong peninsulas. The uplifting of the Archean basement corresponds to the NW to NNW extension in the late Mesozoic and early Cenozoic. Perpendicular to the abovementioned NE-extending anomaly belts, there are also some NW-striking anomaly belts in the Bohai Sea and northern Yellow Sea Basin, which represent NE extension in the Cenozoic (Fig. 7). In the Bohai Bay area, a circular aeromagnetic anomaly indicates a possible small mantle plume since the late Mesozoic.

In Fig. 7, the most eastern fault of the Yi–Shu fault zone, part of the Tan–Lu fault, can be tracked along the Jiao–Liao fault (JLF) to the North Yellow Sea Fault (NYSF, as the northern branch of the Jiao–Liao fault) and Yalvjiang fault (YF) in the north. It separates the Liaodong Peninsula from the Jiaodong Peninsula. However, it is hard to track the most western boundary fault of the Yi–Shu fault zone to the north in order to find a connection with the eastern Bohai fault (EBF) or Yilan–Yitong fault (YYF). Between the Yi–Shu fault zone and eastern Bohai fault, NW-striking aeromagnetic anomaly belts indicate apparently NE extension in the Cenozoic, which implies expanding displacement between the Liaodong Peninsula and Laizhou Bay area.

4 Geological comparison and proposal of tectonic model

4.1 Tectonic relationship among the Jiaodong, Liaodong, and Jidong Blocks

The Liaodong Block and Jiaobei Terrane are both parts of the NCC. They are commonly referred to as the Jiao–Liao Block or a part of the Jiao–Liao–Ji tectonic belt (Zhu et al., 2020). However, there is still some controversy over the way in which the two peninsulas are connected. Most researchers believe that both the Jiaodong and Liaodong Blocks are located on the eastern side of the Tan–Lu fault zone (Figs. 2 and 9a; Xu et al., 1987; Allen et al., 1997; Wang et al., 2000; Zhu et al., 2004; Li et al., 2012; Clinkscales and Kapp, 2019; Zhu et al., 2020, 2024; Yan et al., 2021; X. P. Chen et al., 2022; X. H. Chen et al., 2022; Hu et al., 2022; Zhou et al., 2022; Qiu et al., 2023; Ren et al., 2023). Additionally, such a configuration does not really resolve the problem of how they are interconnected. Nevertheless, if we take the early Cretaceous granitoids and extensional structures into consideration, the situation will be greatly improved.

Early Cretaceous granitic plutons and extensional structures such as MCCs or extensional domes occur in both the Liaodong and Jiaodong Blocks (Lin et al., 2007, 2008; Charles et al., 2013; Lin and Wei, 2020; Zhu et al., 2020, 2024; Wu et al., 2021; Yan et al., 2021; Qiu et al., 2023; Ren et al., 2023). The plutons and MCCs are coeval, like the case in North America (Zuza et al., 2022). They are the two critical control factors related to the Jiaodong- or decratonization-type gold mineralization in the late Early Cretaceous (125–115 Ma; Yang et al., 2021). Therefore, we can take the Early Cretaceous granitoids, extensional structures, and gold deposits as piercing points to reconstruct the spatial relationship between the two peninsulas in the Early Cretaceous. Our reconstruction is shown in Fig. 8b, which predicts the existence of a right-lateral strike-slip fault, referred to as the Jiao–Liao fault, between the Jiaodong and Liaodong Blocks (Figs. 3, 4, and 9b). Through the recovery of strike slipping along the Jiao–Liao fault, the Liaonan MCC in the Liaodong Block can be joined with the Linglong dome in the Jiaodong Block (Fig. 8b). Meanwhile, gold deposits clustering in the Wulong–Sidaogou area of the Liaodong Block can also be buckled up on the Linglong–Jiaojia area of the Jiaodong Block. The northeastward extending of the Jiao–Liao fault may be connected to the Yalvjiang fault (Figs. 3 and 4).

The Jidong and Liaodong Blocks have similar geological compositions and tectonic evolution histories. They share a common tectonic history in the Mesozoic, with typical intracontinental Yanshanian compression in the Late Jurassic to early Early Cretaceous and significant craton destruction and extensional faulting in the late Early Cretaceous (Dong et al., 2015; Yang et al., 2020; Qiu et al., 2023). They have approximately simultaneous granitic intrusion events in the Early Cretaceous. With a nearly east–west zonal distribution of the Early Cretaceous plutons, our restoration shows that the Liaodong Bay Basin opened through the NW–SE extension in the late Mesozoic and early Cenozoic, modified by the left-lateral strike slipping along the Honglazi and/or eastern Bohai faults (Fig. 8b). Before the opening of the Liaodong Bay Basin, these two faults may have been branches of the same major fault, which could be inferred to be the Honglazi fault zone.

4.2 Tectonic relationship between the Jiaodong and Korean peninsulas

The Jiaobei Terrane and northern Korean Peninsula are both components of the NCC, with the outcrop of Archean TTG metamorphic rocks (Zhai et al., 2019). They are characterized by Early Cretaceous NW–SE extension (Dong et al., 2015) and Cenozoic WNW-striking normal faults. They both suffered from basalt eruption in the Quaternary (Fig. 3). They have a similar pre-Cenozoic history in geological evolution and the same tectonic setting in the Cenozoic. Previous correlation between the Sulu Orogen in the south of the Wulian–Qingdao–Yantai fault and Gyeonggi Massif in Korea indicates that they both belong to the high- and ultrahigh-pressure metamorphic belt formed during the North and South China collision in the Triassic (Fig. 3; Li et al., 2012; Kim et al., 2018). Therefore, the Jiaodong Block is not simply connected to the Liaodong Block in the NNE direction but is a wedge-like connection with both the Liaodong and Korean peninsulas (Figs. 3, 9, and 10). Restoration of tectonic processes, such as strike-slip and normal faulting in an extensional setting, is necessary.

4.3 A genetic model of the Bohai Sea Basin based on tectonic comparison

According to the comparison of the Jiaodong, Liaodong, and Jidong Blocks, combined with field observations and structural analyses, we propose a three-stage kinematic model for the formation and evolution of the Bohai Sea Basin (Fig. 9). In stage 1, in the late period of the Early Cretaceous to early period of the Late Cretaceous (ca. 135–90 Ma), regional extension and normal faulting occurred in the Jidong, Liaodong, Jiaodong, and Luxi Blocks. In the late phase of stage 1, strike-slip faulting initiated among the Jidong, Liaodong, and Jiaodong Blocks, parallel to the paleo-subduction zone, forming the strike-slipping Jiao–Liao, eastern Bohai, and Honglazi faults (Fig. 9a). In this time, the left-lateral slip faults such as the eastern Bohai and Honglazi faults (Figs. 5 and 6) belonged to the same fault zone, which is closely related to the Tan–Lu fault (i.e., the Yi–Shu fault zone). Along with the left-lateral strike-slip faults, there are some imbricate thrusts and flower structures (Fig. 5). In stage 2, in the late period of the Late Cretaceous to Early Cenozoic (ca. 90–34 Ma), as a result of the roll-back of the

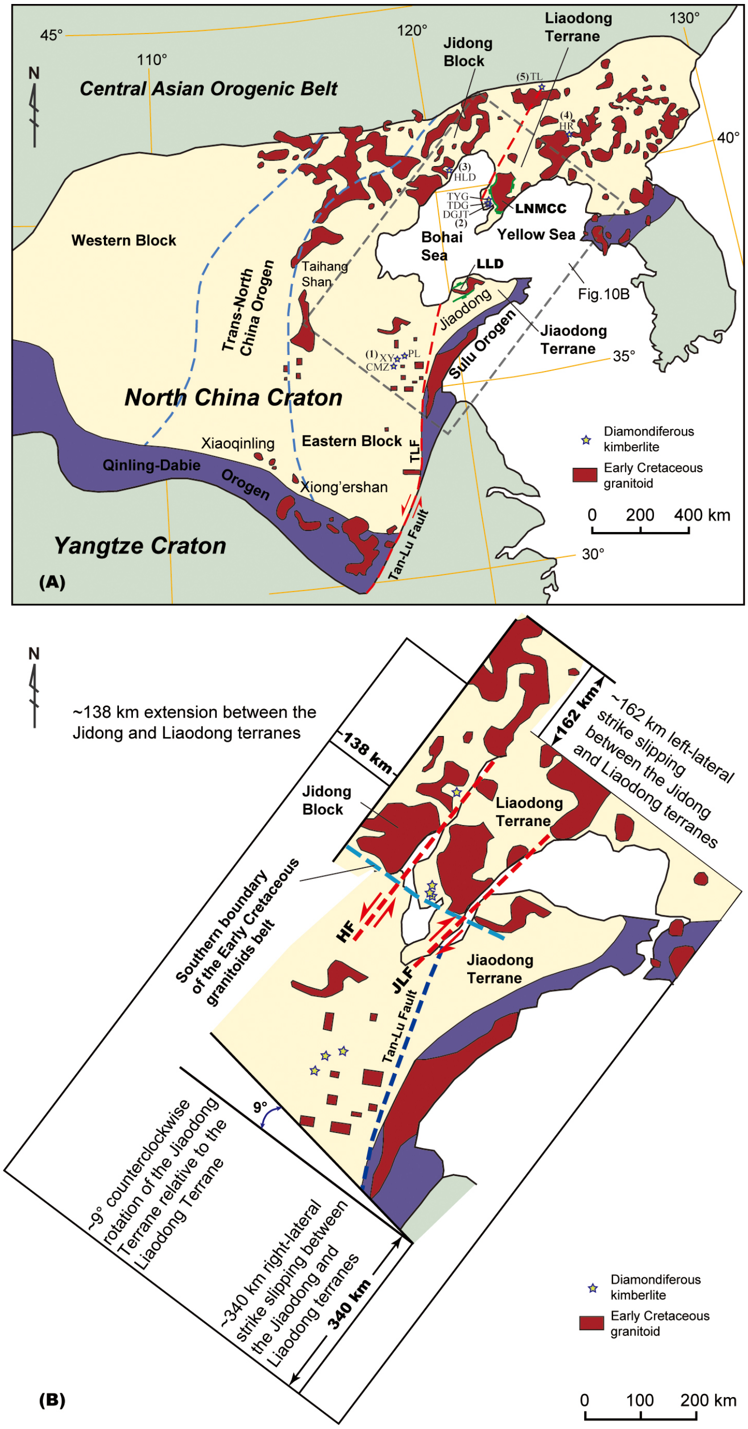

Figure 8. Correlation of the Jidong (Yanshan), Jiaodong, and Liaodong terranes, according to the distribution of Early Cretaceous magmatic intrusions and diamondiferous kimberlites. **(a)** Distribution of Early Cretaceous granitoids and diamondiferous kimberlites in the Jiaodong and Liaodong peninsulas (modified from Liu et al., 2019, and Wu et al., 2021). HF, the Honglazi fault. JLF, the Jiao–Liao fault. TLF, the Tan–Lu fault predicted by previous research. LLD, the Linglong dome. LNMCC, the Liaonan MCC. Diamondiferous kimberlites – (1) Mengyin area: PL, Poli; XY, Xiyu; CMZ, Changma Zhuang. (2) Wafangdian area: TYG, Taiyang Gou; TDG, Toudao Gou; DGJT, Dagaojia Tun. (3) HLD, Huludao. (4) HR, Huanren. (5) TL, Tieling. **(b)** Reconstruction of the Ji–Lu–Jiao–Liao Terrane, regarding the restoration of the Early Cretaceous magmatic complex.

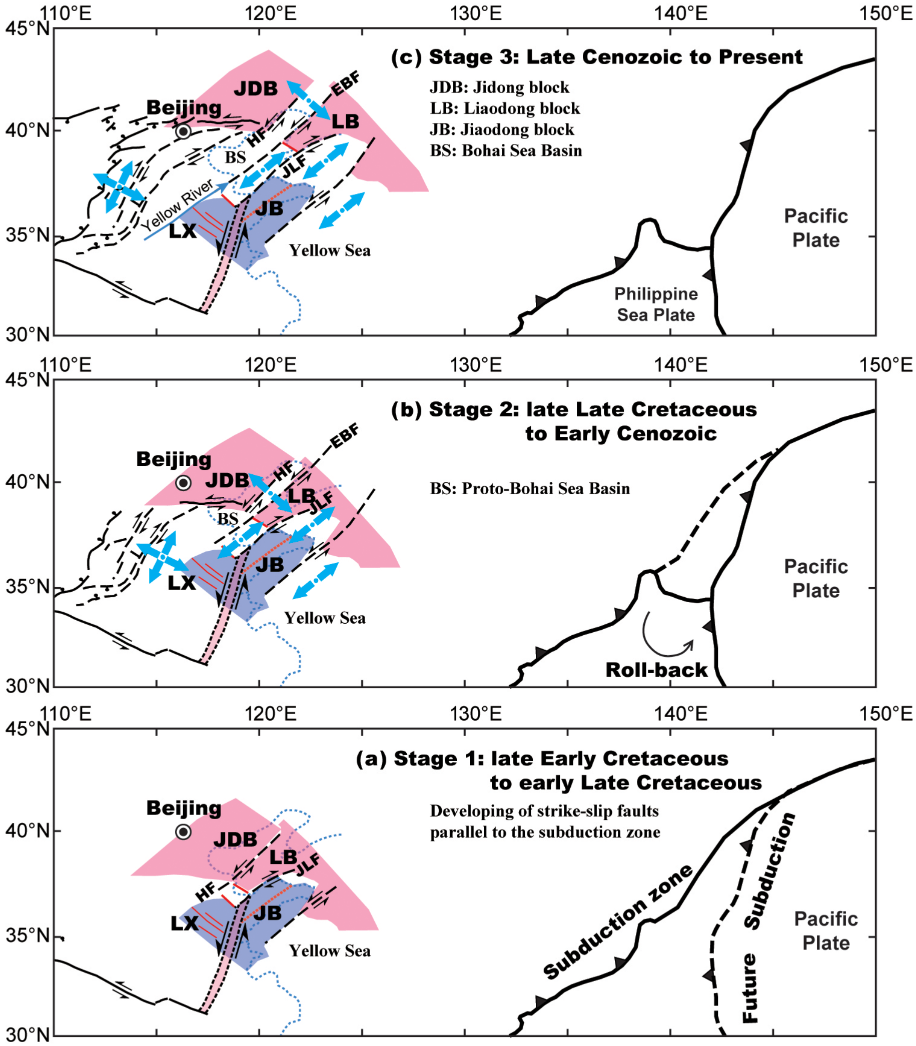

Figure 9. Proposed three-stage model for the formation of the Bohai Sea Basin as a result of complex faulting in the Bohai Sea area and roll-back of the western Pacific and Philippine Sea plate subduction. JDB, the Jidong Block. LB, the Liaodong Block. JB, the Jiaodong Block. LX, the Luxi Block. BS, the Bohai Sea Basin.

subducting Pacific Plate, extensive back-arc extension occurred at the continental margin of East Asia. The extension deformation is expressed in two directions, i.e., parallel and perpendicular to the subduction zone. The proto-Bohai Sea Basin formed in this stage, as the combined result of the extension and accompanying strike-slip faulting (Fig. 9b). In this stage, the eastern Bohai and Honglazi faults were split into two faults, located at the northwest and southeast coasts of the Liaodong Bay, respectively. In stage 3 (< 34 Ma), the present-day Bohai Sea Basin formed as a result of the continuous bidirectional back-arc extension and strike slipping along the Jiao–Liao, eastern Bohai, and Honglazi faults in the late Cenozoic (Fig. 9c). The continuous strike slipping along the Jiao–Liao fault merged into the North Yellow Sea Fault and Yalvjiang fault.

5 Tectonic significance of the genetic model

5.1 Reconstruction of the fault system and re-recognition of the Tan–Lu fault

Some researchers believe that the formation of the Bohai Sea Basin is mainly controlled by the northeast-striking left-lateral strike-slipping Tan–Lu fault zone (Zhu et al., 2004; Min et al., 2013; Zhang et al., 2015). The Tan–Lu fault zone is considered to be a major long-term active fault zone in eastern China, starting from the city of Lujiang in the Anhui Province, with a total length of ca. 2400 km (Xu et al., 1987; Wang et al., 2000; Zhu et al., 2004; Min et al., 2013; Zhang et al., 2015; Zhu et al., 2020). It is divided into several segments, such as the south segment in Anhui and Jiangsu provinces, the Shandong segment (i.e., the Yi–

Shu fault zone; Figs. 3 and 4), the Bohai Sea segment from the city of Weifang in the Shandong Province to the city of Shenyang in the Liaoning Province (Zhang et al., 2015), and the northeast segment in northeast China, with a total left-lateral displacement of 1000–1500 km (Xu et al., 1987). It is considered to be the eastern boundary of the BBB (Hou et al., 1998; Zhou et al., 2022). The main extensional structures in the Bohai Sea region are considered to be derivatives of the Tan–Lu fault (Hou et al., 1998) or result from the dextral transpression of the pre-existing large-scale NNE strike-slipping fault (i.e., the Tan–Lu fault) in the basement (Xiao et al., 2004). Some researchers believe that the Tan–Lu fault can be divided into two segments, the south and the north, with the Bohai Sea region in the middle. These two segments have different faulting histories and formed the single Tan–Lu fault in the Late Jurassic due to opposite growth of the faults (C. M. Li et al., 2023).

The Tan–Lu fault zone is characterized by large-scale sinistral strike-slip faulting (Xu et al., 1987), especially in its southern segment (Liu et al., 2017). It truncated the Hong'an–Dabie and Sulu high- and ultrahigh-pressure metamorphic belts, with a sinistral displacement of ca. 540 km (Leech and Webb, 2013). It possibly initiated during the collision between the North China and Yangtze blocks in the Triassic (244–209 Ma; Yin and Nie, 1993; Chen et al., 2000) and suffered from counterclockwise rotation of the lower Yangtze Block on the eastern side of the Tan–Lu fault in the Jurassic (189–164 Ma; Chen et al., 2000; Wang et al., 2000). In the late Early and early Late Cretaceous (130–94 Ma), the Tan–Lu fault zone extended northwards into the Yi–Shu fault zone, a rift zone between the Luxi and Jiaodong Blocks (Figs. 3 and 4; Chen et al., 2000). In this time, both the Luxi and Jiaodong regions were characterized by normal faulting, implying a close connection of the extension with the NCC destruction (Li et al., 2018; Zhu and Xu, 2019; Zhu et al., 2020, 2024). A new paleomagnetic study yields sinistral slip of ca. 100 km along the southern segment of the Tan–Lu fault during the early Late Cretaceous (100–80 Ma; Qin et al., 2022).

However, there are still some controversies over whether the Bohai Sea segment is a part of the Tan–Lu fault zone (Zhang et al., 2015) and whether the Tan–Lu fault is connected with the Yilan–Yitong fault and/or Dunmi fault to the north (Min et al., 2013). For example, a large number of nearly east–west-trending normal faults, as well as some NE-trending normal faults and right-lateral strike-slip faults, formed in the Dongying Depression (DD in Fig. 4), southwestern Laizhou Bay, in the Cenozoic (Yuan et al., 2022). This indicates that there is no continuous northeastwards extending of the Tan–Lu and/or Yi–Shu fault zone in the Cenozoic. If the Tan–Lu fault zone is designated as a large-scale left-lateral strike-slip fault in East Asia (Chen et al., 2000), the Cenozoic normal faulting and right-lateral strike-slipping activities in the Bohai Sea Basin and surrounding area (Allen et al., 1997; X. P. Chen et al., 2022; Hu et al., 2022; Yuan et al., 2022) should be excluded as a part of the Tan–Lu and/or Yi–Shu fault zone.

The Luxi Block experienced multi-stage extensional faulting that is NE-striking at ca. 61, 49–42, and 36–32 Ma (Li et al., 2018). The extensional direction is parallel to the strike of the Honglazi, eastern Bohai, and Jiao–Liao faults, implying close connection between the normal faulting and strike-slip movement in the Cenozoic. Widespread right-lateral strike-slip faulting in the Bohai Sea Basin since the middle Eocene should be tightly connected with the right-lateral slipping along the Jiao–Liao fault and its northern branch, the North Yellow Sea Fault (NYSF in Figs. 3 and 4). It deeply cuts through the lower crust and extends northeastward to connect with the Yalvjiang fault (Tian et al., 2007).

5.2 Tectonic reconstruction of the Bohai Sea Basin and general pattern of back-arc extension

Based on our reconstruction of the fault system and genetic model of the Bohai Sea and surrounding area (Fig. 9), as well as the distribution of Early Cretaceous granites, we got some estimations of the displacements among several blocks around the Bohai Sea region (Fig. 8b). Among them, the Jiaodong and Liaodong Blocks are connected through the Jiao–Liao fault, with a right-lateral displacement of ca. 340 km. Meanwhile, the Jiaodong Block may have undergone a counterclockwise rotation of ca. 9° relative to the Liaodong Block. The displacement between the Jidong Block (or Yanshan fold–thrust belt) and Liaodong Block can be partitioned into left-lateral displacement of ca. 162 km along the Honglazi fault zone and stretching displacement of ca. 138 km perpendicular to the strike-slip fault (Fig. 8b). Our model does not need to consider the influence of the Tan–Lu fault in the Cenozoic.

Our model has also considered the constraints from the distribution of kimberlites, which were emplaced during the middle Ordovician (470–456 Ma) in the Mengyin (Shandong) and Wafangdian (Liaoning) areas (Fig. 3; Liu et al., 2019). Most previous studies allocated the diamond-bearing kimberlites to both sides of the Tan–Lu fault, with a north–south distance of ca. 550 km between them. If we take these two kimberlites as piercing points, they have a left-lateral displacement of ca. 550 km for the Tan–Lu fault. This magnitude is roughly equivalent to the left-lateral displacement of ca. 540 km estimated by Leech and Webb (2013), with the correlation constraint of the Dabie and Sulu orogens. However, there are also some diamond-bearing kimberlites in other areas, such as the Huanren, Huludao, and Tieling in Liaoning, as well as the Ji'an in Jilin, in eastern China (Fig. 3; Liu et al., 2019). In fact, the distribution of kimberlites in eastern China is oriented in a nearly northeast direction, not as an east–west trend (Figs. 3 and 9). In this model, the bidirectional extensions perpendicular and parallel to the subduction zone have the same importance.

6 Conclusions

Based on field investigation, structural analyses, and geological comparison, we constructed a new framework of the fault system of the Bohai Sea Basin and surrounding area and reached the following conclusions.

1. The fault system of the Bohai Sea Basin and surrounding area is mainly composed of normal faults and strike-slip faults. Superimposed on the rift system of the Bohai Sea Basin, a left-lateral strike-slip fault formed in the Liaodong Bay Basin in the Late Cretaceous and early Paleogene, while a right-lateral strike-slip fault between the eastern margin of Liaodong Peninsula and the northwestern margin of Jiaodong Peninsula formed at the same time. This new mode of movement may have resulted from the NE stretching, which is parallel to the subduction zone in the eastern margin of the Asian continent.

2. We propose that the formation and evolution of the Bohai Sea Basin fault system are a result of the superimposition of NE extension parallel to the western Pacific and Philippine Sea subduction zone on the NW extension perpendicular to the subduction zone. The two-direction extension perpendicular and parallel to the subduction zone should be the basic pattern of back-arc extension with a spherical geometric effect, especially in the Bohai Sea Basin.

3. The Tan–Lu fault has at least a two-stage evolution: left-lateral strike-slipping in the Middle–Late Triassic and Jurassic and rifting plus left-lateral strike-slipping in the Early Cretaceous, respectively. The opening of the Bohai Sea Basin in the early Cenozoic destroyed the previously existing Tan–Lu fault system, resulting in the break-up of the Tan–Lu fault into two segments: the south and north segments. Both the Honglazi and eastern Bohai faults belong to the north segment of the Tan–Lu fault, while only a few remnants of the Tan–Lu fault remain in the Bohai Sea Basin.

Data availability. No data sets were used in this article.

Author contributions. XC and ALC conceptualized the study, conducted the fieldwork and structural analyses, and prepared and revised the paper and figures.

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