Origin of the Bohai Sea Basin, North China Craton and implication for bi-directional back-arc extension in East Asia 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 to: Xuanhua Chen (xhchen@cags.ac.cn)

Abstract. The Bohai Sea Basin in eastern China is located at the 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 is one of the regions with frequent earthquakes. Previous recognition of the origin of the Bohai Sea Basin was limited by the understanding of back-arc extensional mode perpendicular to the subduction zone in 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 major fault system and investigation of several main boundaries enclosing the Bohai Sea ~~region~~Basin. We have made field investigation 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, and revealed left-lateral strike-slip faults along the northwest coast of the Liaodong Bay and western margin of the Liaodong Peninsula. Then, we conducted geological comparison of the Liaodong and Jiaodong Blocks and surrounding areas, and a structural interpretation of aeromagnetic anomaly map of this region. We proposed 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 been resulted from the NE stretching which is parallel to the subduction zone in northwestern Pacific margin. Therefore, we suggest that the formation of the Bohai Sea Basin is 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 spherical-geometric effect.

1 Introduction

The Bohai Sea is located at eastern part of the North China Craton (NCC; Fig. 1; Chen et al., 2022a). Traditionally, the Bohai Sea Basin is 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 as an intracontinental extensional rift basin in back-arc setting, resulted from the westward subduction of the Pacific Plate underneath the Eurasian Plate in late Mesozoic and Cenozoic (Allen et al., 1997; Liang et al., 2016). The BBB and surrounding region is also 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 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 meters, however, the Cenozoic sediments are widely distributed in the BBB and Bohai Sea Basin, with total thicknesses of over 8000 and 11000 meters, respectively, making them as an important source rock series of oil and gas (Xiao et al., 2004; Wang et al., 2016).

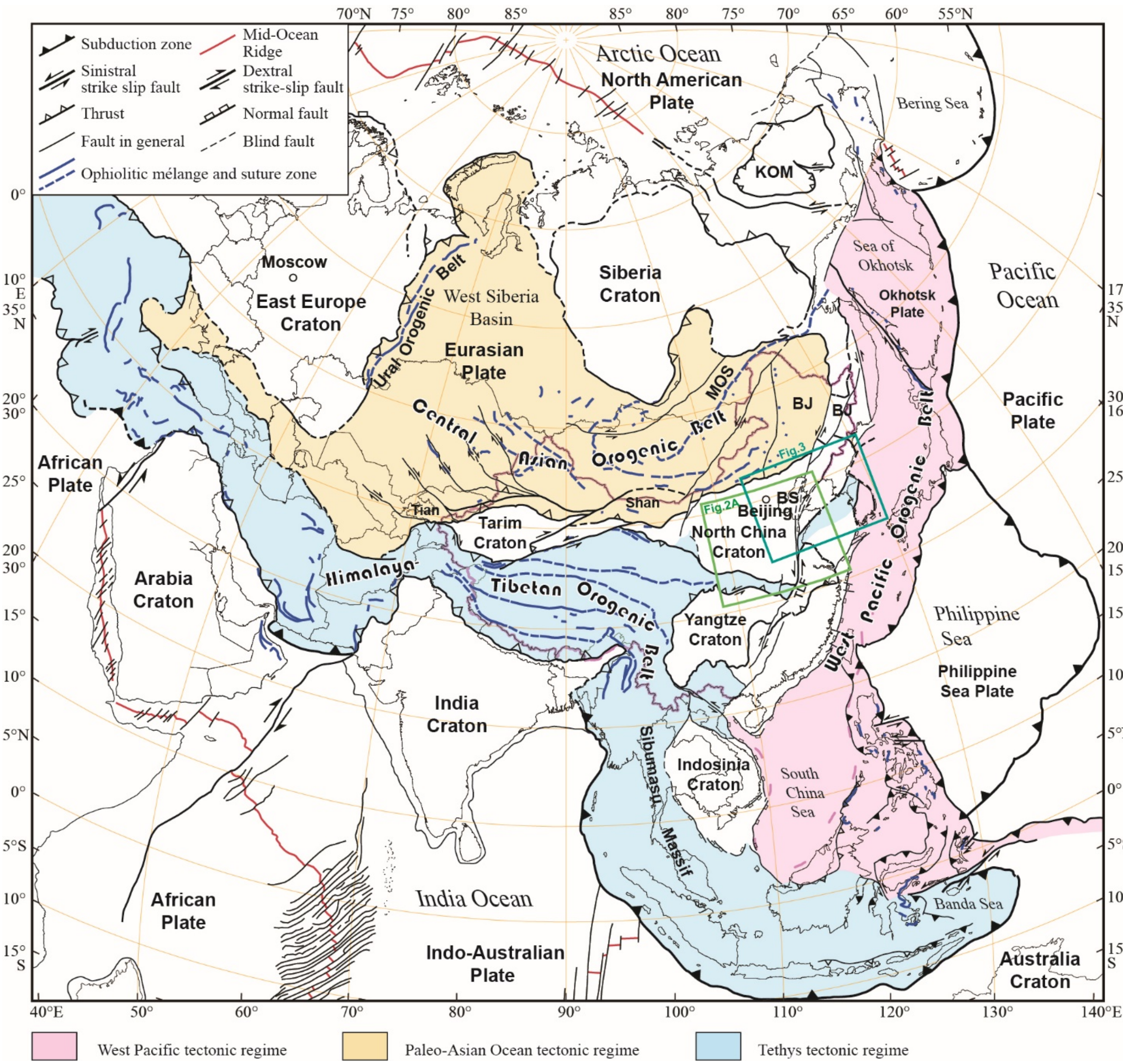


Figure 1: Simplified tectonic map of Asia, showing the location of the Bohai Sea in eastern China. Modified from Chen et al. (2022a). BS, Bohai Sea. KOM, Kolyma-Omolon superterrane (Ar-P). BJ, Bureya-Jiamusi superterrane (Ar-J). TLF, the Tan-Lu fault. Locations of Figs. 2A and 3 are also shown.

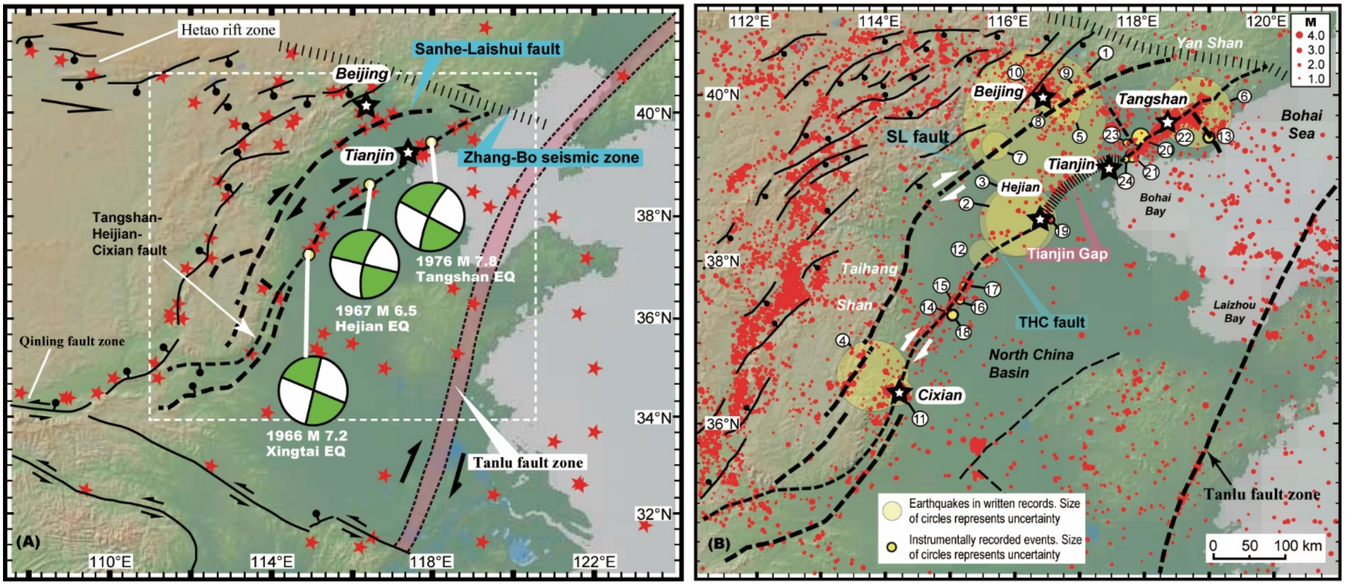


Figure 2: (A) Pre-instrumentation historical earthquakes (EQ) with M ≥ 6 across north China and focal mechanisms of the A.D. 1966 Xingtai, 1967 Hejian, and 1976 Tangshan earthquakes (mainly right-lateral strike-slipping along the THC; after Yin et al., 2015). (B) M≥6 earthquakes from A.D. 1000 to the 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 labelled sequentially, such as 1966-1, 1966-2, 1976-1, and 1976-2. Earthquakes: (1) A.D. 1057 S. Beijing Earthquake (M 6.8); (2) A.D. 1068 Hejian Earthquake I (M 6.5); (3) A.D. 1144 Hejian Earthquake II (M 6.0); (4) A.D. 1314 Shexian Earthquake (M 6.0); (5) A.D. 1536 Tongxian Earthquake (M 6.0); (6) A.D. 1624 Luanxian Earthquake (M 7.0); (7) A.D. 1658 Laishui Earthquake (M 6.0); (8) A.D. 1665 W.Tongxian Earthquake (M 6.5); (9) A.D. 1679 Sanhe Earthquake (M 8.0); (10) A.D. 1730 W. Beijing Earthquake (M 6.5); (11) A.D. 1830 Cixian Earthquake (M 7.5); (12) A.D. 1882 Shenxian Earthquake (M 6.0); (13) A.D. 1945 Luanhe Earthquake (M 6.3); (14) A.D. 1966-1 Xingtai Earthquake (M 6.8); (15) A.D. 1966-2 Xingtai Earthquake (M 6.7); (16) A.D. 1966-3 Xingtai Earthquake (M 7.2); (17) A.D. 1966-4 Xingtai Earthquake (M 6.2); (18) A.D. 1966-5 Xingtai Earthquake (M 6.0); (19) A.D. 1967 Hejian Earthquake (M 6.5); (20) A.D. 1976-1 Tangshan Earthquake (M 7.8); (21) A.D. 1976-2 Changli Earthquake (M 6.2); (22) A.D. 1976-3 Luanxian Earthquake (M 7.4); (23) A.D. 1976-4 Ninghe Earthquake (M 6.9); (24) A.D. 1977 Tanggu Earthquake (M 6.2) (from Yin et al., 2015).

Regarding to the origin of the Bohai Sea Basin and BBB, there is still significant controversy. The main viewpoints proposed by previous studies are: 1) The BBB is 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 resulted from right-lateral strike slipping along the Tan-Lu and Taihang Shan faults due to subduction of the Pacific Plate in Cenozoic (Hou et al., 1998; Xu et al., 2014; Hu et al., 2022; Liu and Wu, 2022)~~, as a part of the right-lateral pull-apart basin system in NW Pacific region (Xu et al., 2014)~~; 3) a result of active mantle plume with a diameter of ca. 600-800 km (Xiao et al., 2004); 4) 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 reflects 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 M8.0 Sanhe, 1830 M7.5 Cixian, 1888 M7.5, 1966 M7.2 Xingtai, 1969 M7.4 Bohai Bay, 1975 M7.3 Haicheng, 1976 M7.8 Tangshan, and 1976 M7.4 Luanxian earthquakes (Fig. 2; Deng et al., 1976; Yin et al., 2015; Chen et al., 2020). Present GPS velocity field and focal mechanism solution of the 1975 M7.3 Haicheng earthquake showed NNW-SSE stretching stress in the Liaodong Bay and surrounding area (Deng et al., 1976; Wang et al., 2014; Zhao et al., 2015).

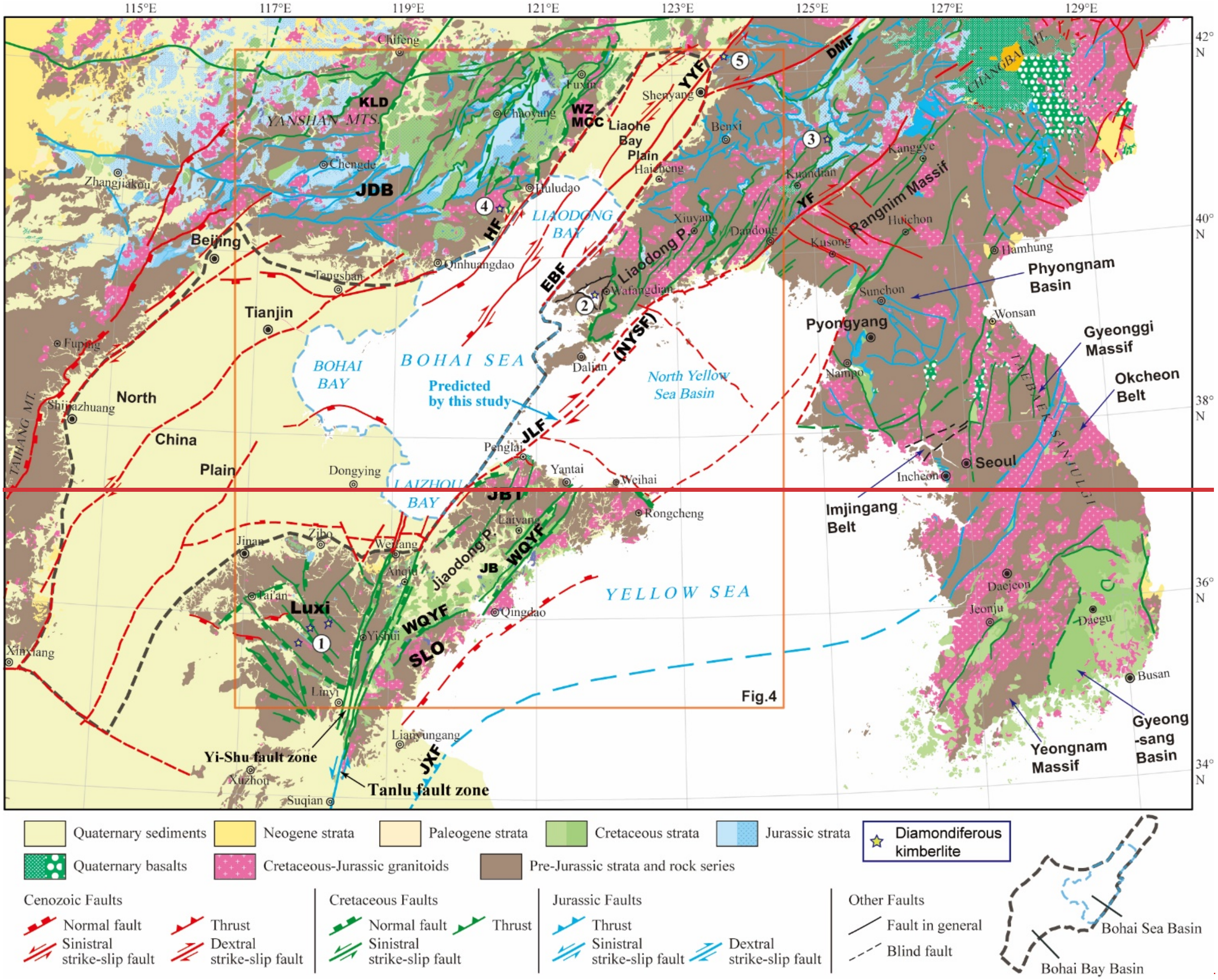
Some unresolved key scientific issues on the genesis of Bohai Sea Basin and BBB are listed as follows: 1) Did the activity of the Tan-Lu fault or other tectonic factors control the formation of the Bohai Sea Basin? 2) Has the Tan-Lu fault extended northward through the Bohai Sea region, or has the formation 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 Bohai Sea Basin, based on detailed analyses on boundary geometry and fault system 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 southeast, the Liaodong Peninsula in northeast, the Jidong Block and Yanshan fold-thrust ~~orogenic~~ belt in northwest, the North China Plain in south, and the Liaohe Bay Plain in north (Figs. 3 and 4). 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 at the central part of eastern coast of China. It is mainly composed of three major tectonic units: the Jiaobei Terrane in the north, Jiaolai Basin in the central, 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 Ma and 121-116 Ma; Koua et al., 2022; Dong et al., 2023). The Jiaobei Terrane experienced rapid exhumation in 120-95 Ma (Zhang et al., 2022a), with development of extensional structures, such as the Linglong extensional dome (Figs. 3 and 4; Zhu et al., 2020; Yan et al., 2021) or metamorphic core complex (MCC; Charles et al., 2013), as well as supersized Jiaodong-type or decratonization-type gold deposits in late Early Cretaceous (Deng et al., 2020; Zhu et al., 2020, 2024; Yang et al., 2021; Zhang et al., 2022a). The Sulu Orogen is located on the southeast side of the Wulian-Qingdao-Yantai fault zone (WQYF), characterized by the occurrence of high to ultra-high pressure metamorphic rocks. It is considered as the eastern segment of 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; Li et al., 2023a; Qiu et al., 2023), coeval with the South China-Indochina collision (Faure et al., 2014).


115°E
117°E
119°E
121°E
123°E
125°E
127°E
129°E
42° N
40° N
38° N
36° N
34° N
YANSHAN MTS.
KLD
JDB
WZ MCC
Liaohe Bay Plain
YYF
DMF
CHANGBAI MT.
Rangnim Massif
YF
HF
LIAODONG BAY
EBF
Liaodong P.
(NYSF)
Beijing
Tianjin
North China Plain
TAIHANG MT.
BOHAI BAY
BOHAI SEA
Predicted by this study
North Yellow Sea Basin
JLF
LAIZHOU BAY
JBT
Jiaodong P.
JB
WQYF
Luxi
SLO
YELLOW SEA
Yi-Shu fault zone
Tanlu fault zone
JXF
Fig.4
Phyongnam Basin
Pyongyang
Gyeonggi Massif
Okcheon Belt
TAEBAEK SANJULGI
Seoul
Imjingang Belt
Yeongnam Massif
Gyeong -sang Basin
Chifeng
Fuxin
Chaoyang
Shenyang
Benxi
Chengde
Zhangjiakou
Huludao
Haicheng
Kuandian
Kanggye
Xiuyan
Dandong
Huichon
Kusong
Hamhung
Qinhuangdao
Tangshan
Wafangdian
Sunchon
Wonsan
Fuping
Dalian
Nampo
Shijiazhuang
Penglai
Yantai
Weihai
Dongying
Rongcheng
Incheon
Zibo
Jinan
Weifang
Laiyang
Anqiu
Tai'an
Qingdao
Daejeon
Jeonju
Daegu
Yishui
Xinxiang
Busan
Linyi
Lianyungang
Xuzhou
Suqian
Quaternary sediments
Neogene strata
Paleogene strata
Cretaceous strata
Jurassic strata
Diamondiferous kimberlite
Quaternary basalts
Cretaceous-Jurassic granitoids
Pre-Jurassic strata and rock series
Cenozoic Faults
Normal fault
Thrust
Sinistral strike-slip fault
Dextral strike-slip fault
Cretaceous Faults
Normal fault
Thrust
Sinistral strike-slip fault
Jurassic Faults
Thrust
Sinistral strike-slip fault
Dextral strike-slip fault
Other Faults
Fault in general
Blind fault
Bohai Sea Basin
Bohai Bay Basin

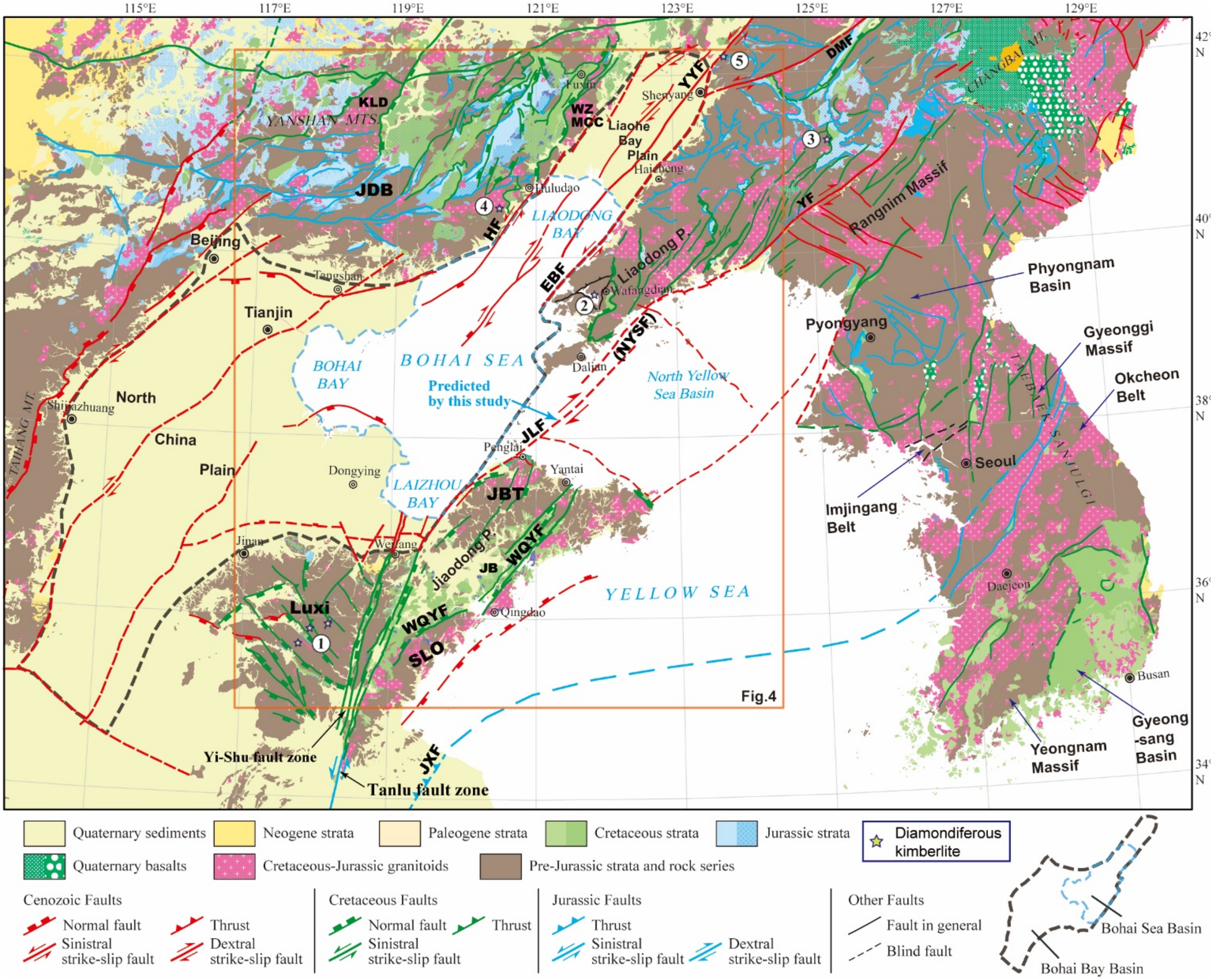


Figure 3: Sketched structural geological map of the Bohai Bay Basin and surrounding region (modified from Allen et al., 1997, China Geological Survey, 2004, Ren et al., 2013, Yin et al., 2015, Kim et al., 2018, Zhai et al., 2019, Yang et al., 2020, Lin et al., 2021, Ren et al., 2023, and Zhu et al., 2024). The Tan-Lu and Yi-Shu fault zones share a common segment of 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, East 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.

The Jiaolai Basin is located between the Jiaobei Terrane and Sulu Orogen, as a graben basin formed in late Early Cretaceous. It has a high elevation ⩾2.0 km in 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).

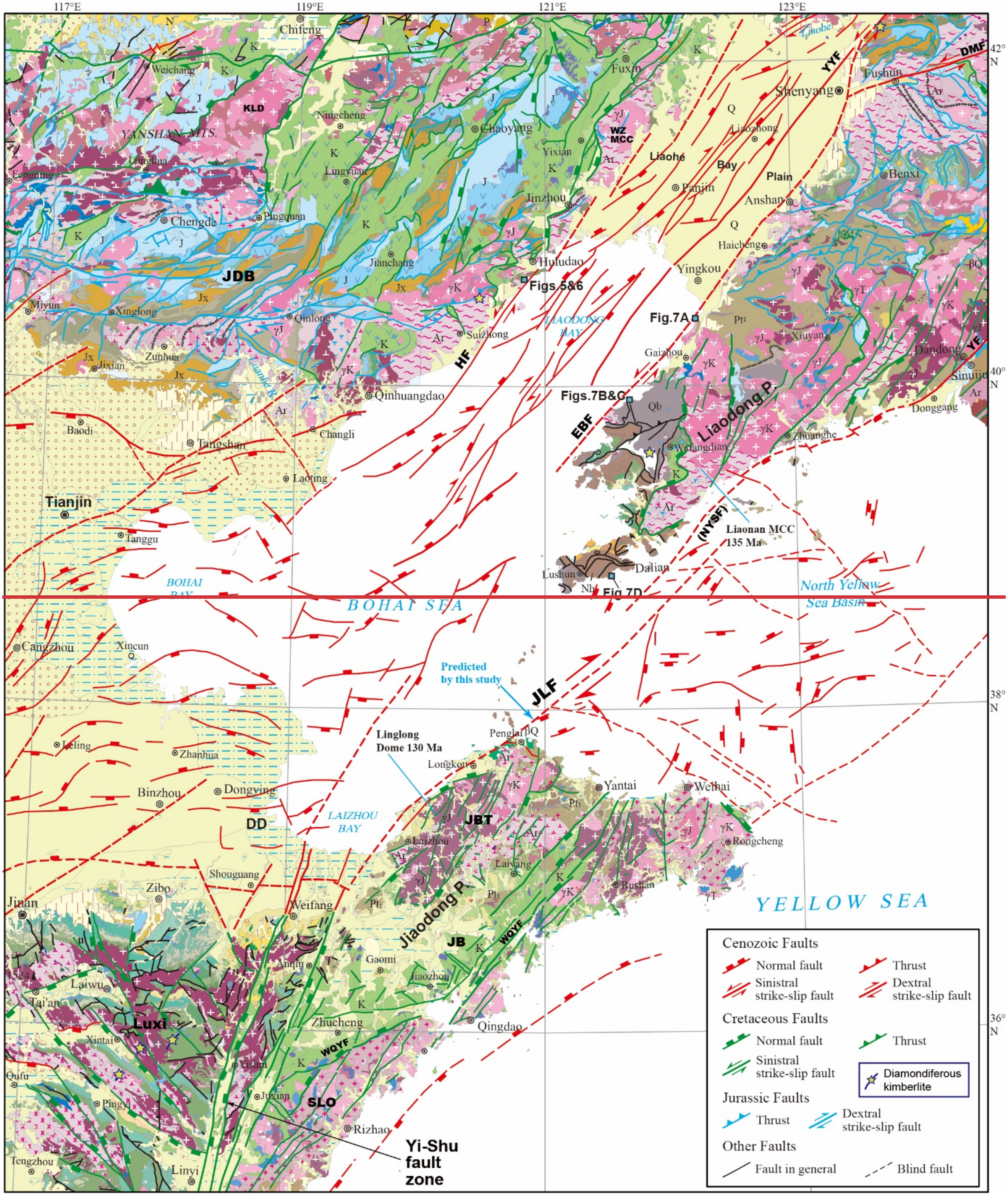
The Liaodong Block is located at the northeast of the NCC. It is bordered by the North Yellow Sea fault (NYSF) with the North Yellow Sea Basin (Tian et al., 2007). It is mainly composed of Archean TTG rocks, Paleoproterozoic Liaohe Group metamorphic rocks, Mesoproterozoic to Paleozoic metamorphic sedimentary 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 has experienced Yanshanian intracontinental compressional deformation initiated at ca. 171 Ma in 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). Granitoids plutons intruded with ages ranging from 130 to 126 Ma, indicating asthenosphere upwelling-related craton destruction in Early Cretaceous (Wu et al., 2021; Yang et al., 2021; Wang et al., 2022). Simultaneously, extensional structures, such as the Liaonan MCC, developed in 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 (Zhang et al., 2022b).

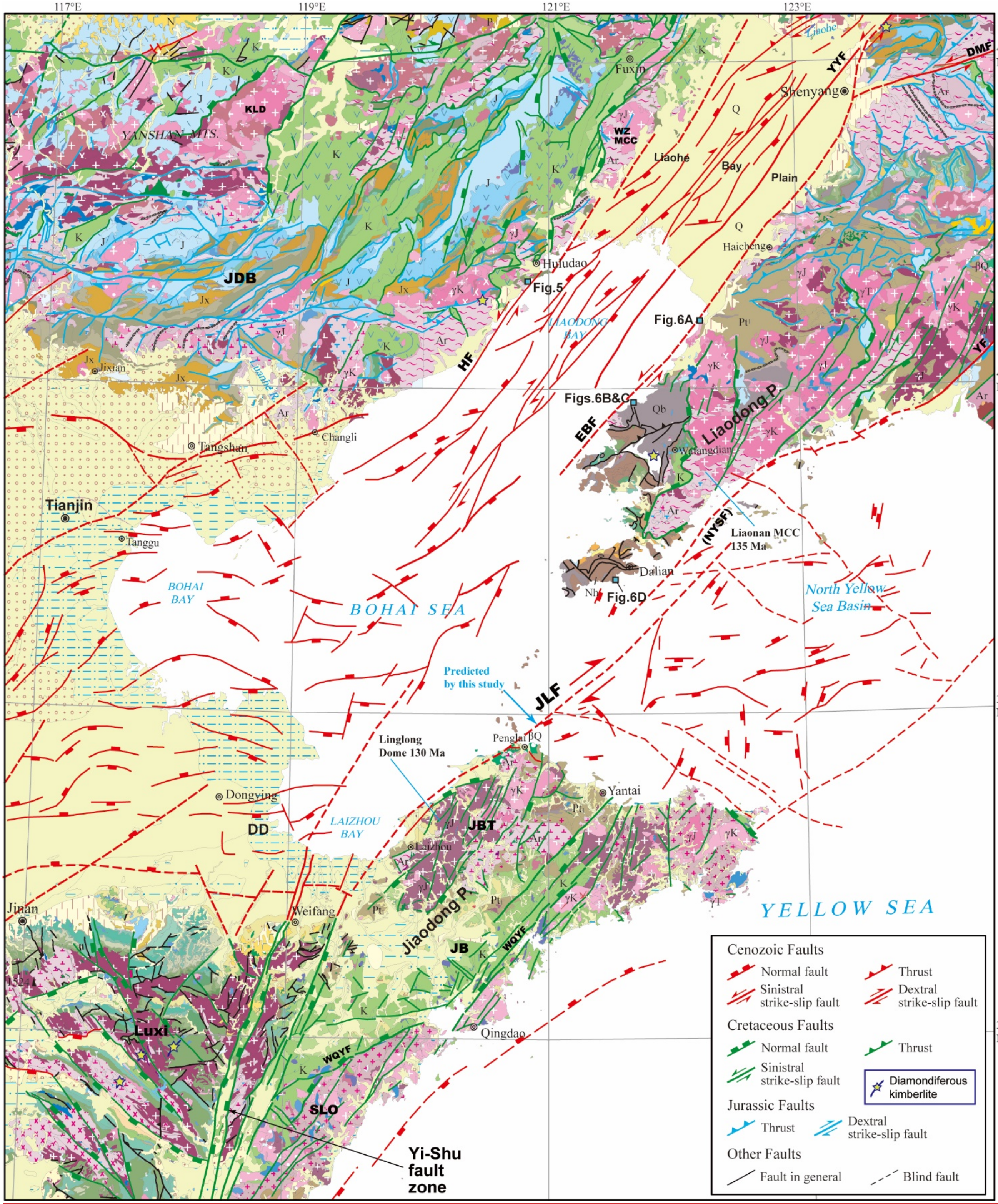
The Jidong Block and Yanshan ~~orogenic~~ fold-thrust belt is located at northern NCC and northwest coast of the Bohai Sea (Figs. 3 and 4). The Archean basement rocks outcrop here are mainly gray gneisses and TTG rocks, as well as supracrustal rock series in granulite facies metamorphism (Zhu et al., 2020). The Jidong Block has experienced the development of Late Paleoproterozoic to Mesoproterozoic Yanliao Rift System (Zhu et al., 2020), and intracontinental Yanshanian compression~~orogeny~~ in late Middle Jurassic to early Early Cretaceous (Dong et al., 2015; Yang et al., 2020; Qiu et al., 2023). Post orogenic extension occurred in 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, composing of Archean metamorphic rocks and Proterozoic greenstone belts. They have suffered similar geological evolution processes in Phanerozoic. They are all located in the back-arc setting of the subducted west Paleo-Pacific Plate, i.e., the Izanagi Plate. They have undergone intracontinental Yanshanian compression~~orogeny~~ in late Middle Jurassic to early Early Cretaceous, and extensional faulting in the late Early Cretaceous, with extensive crustal melting in Mesozoic (Dong et al., 2015; Yang et al., 2017; Clinkscales and Kapp, 2019; Zhu et al., 2020; Yan et al., 2021; Chen et al., 2022a; Sun et al., 2022; Dong et al., 2023; Qiu et al., 2023).

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

The Bohai Sea is divided into the main sea and three bays, such as the Bohai Bay in the west, Laizhou


117°E
119°E
121°E
123°E
42° N
40° N
38° N
36° N
Chifeng
Weichang
KLD
YANSHAN MTS.
Ningcheng
Chaoyang
WZ MCC
Fuxin
Shenyang
Fushun
YYF
DMF
Liaohe
Liaozhong
Liaohe
Bay
Plain
Panjin
Anshan
Benxi
Yixian
Jinzhou
Lingyuan
Longhua
Chengde
Pingquan
Jianchang
Huludao
Haicheng
Yingkou
JDB
Figs.5&6
Fig.7A
Miyun
Xinglong
Qinlong
Suizhong
LIAODONG BAY
Xiuyan
Dandong
YF
Sinuiju
Donggang
Jixian
Zunhua
HF
Gaizhou
Qinhuangdao
Figs.7B&C
Liaodong P.
EBF
Wafangdian
Zhuanghe
Baodi
Tangshan
Changli
Laoting
Tianjin
Tanggu
(NYSF)
Liaonan MCC 135 Ma
Lushun
Dalian
Fig.7D
BOHAI BAY
BOHAI SEA
North Yellow Sea Basin
Cangzhou
Xincun
Predicted by this study
JLF
Linglong Dome 130 Ma
Penglai
Longkou
Yantai
Weihai
Leling
Zhanhua
Binzhou
Dongying
DD
LAIZHOU BAY
JBT
Laizhou
Rongcheng
Laiyang
Rushan
Shouguang
Zibo
Jinan
Weifang
Jiaodong P.
JB
WQYF
YELLOW SEA
Anqiu
Gaomi
Jiaozhou
Laiwu
Tai'an
Luxi
Zhucheng
Qingdao
Xintai
WQYF
Yishui
Qufu
Juxian
SLO
Pingyi
Rizhao
Yi-Shu fault zone
Tengzhou
Linyi
Cenozoic Faults
Normal fault
Thrust
Sinistral strike-slip fault
Dextral strike-slip fault
Cretaceous Faults
Normal fault
Thrust
Sinistral strike-slip fault
Diamondiferous kimberlite
Jurassic Faults
Thrust
Dextral strike-slip fault
Other Faults
Fault in general
Blind fault



117°E
119°E
121°E
123°E
42° N
40° N
38° N
36° N
YANSHAN MTS.
KLD
JDB
Fuxin
Shenyang
WZ MCC
Liaohe
Bay
Plain
YYF
DMF
Huludao
Fig.5
Fig.6A
LIAODONG BAY
Haicheng
Jixian
HF
Figs.6B&C
EBF
Liaodong P.
Wafangdian
Changli
Tangshan
Tianjin
Tanggu
BOHAI BAY
BOHAI SEA
Liaonan MCC 135 Ma
(NYSF)
Dalian
Fig.6D
North Yellow Sea Basin
Predicted by this study
JLF
Linglong Dome 130 Ma
Penglai
Yantai
Dongying
DD
LAIZHOU BAY
JBT
Laizhou
Jinan
Weifang
Jiaodong P.
JB
WQYF
YELLOW SEA
Luxi
Qingdao
SLO
Yi-Shu fault zone
Cenozoic Faults
Normal fault
Thrust
Sinistral strike-slip fault
Dextral strike-slip fault
Cretaceous Faults
Normal fault
Thrust
Sinistral strike-slip fault
Diamondiferous kimberlite
Jurassic Faults
Thrust
Dextral strike-slip fault
Other Faults
Fault in general
Blind fault

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 distribution of fault system and location of field observation sits (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, East 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.

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

The North 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 NE to NNE, ENE to EW, and NW to NNW directions in Neogene and Quaternary (Shen et al., 2013).

3 Field observation and structural analyses

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

Near the Honglazi Bay, Huludao City, 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 relieves of tens to one hundred meters. 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).

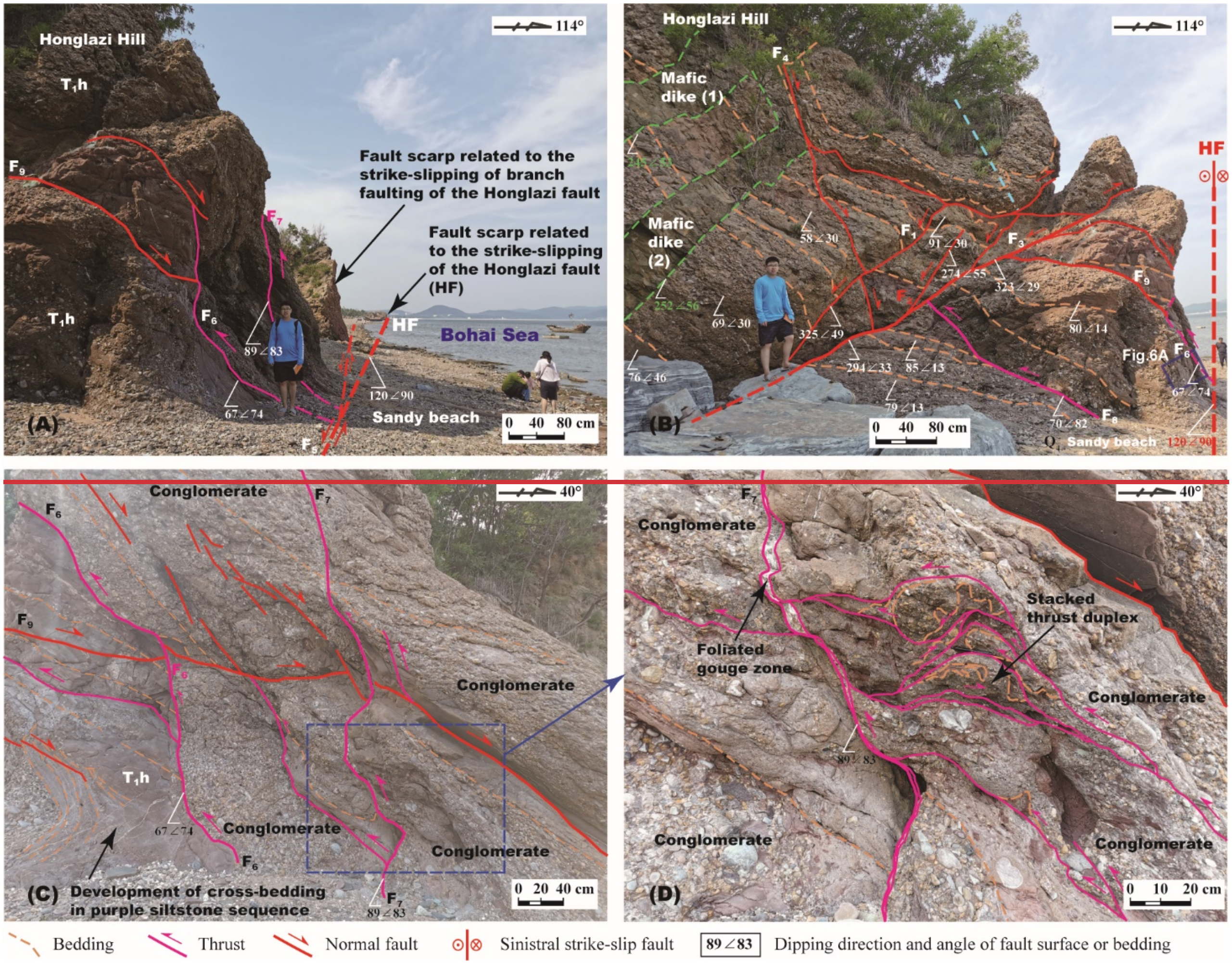
Field observations show several greyish-green mafic dikes intruded in clastic rock series of the Hongla Formation, and a series of thrusts, extensional normal faults, and strike-slip faults developed on the outcrop (Figs. 5A and 5B). The dikes are nearly parallel to the normal faults with en echelon arrangement (such as the F_1 and F_2 in Fig. 5B). These normal faults and dikes are truncated by the normal faults formed in later stage (such as the F_3), and then cut by a detachment fault (the 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) inversed (Fig. 5B). A thin layer of fault gouge is also observed on the detachment plane. We interpret the mafic dikes as formed during the lithosphere extension in late Early Cretaceous, which is almost coeval with the detachment fault (the F_4). This is similar to the gravitational collapse in post-orogenic stage, with local thrusting developed in detachment front.

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

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 time of Early Cretaceous; 2) Left-lateral strike slipping along the Honglazi fault, accompanied by imbricate thrusts, flower structure, and stacked anticline, in early time of Late Cretaceous; 3) Normal faulting along the Honglazi fault in early Cenozoic. Resulting from the continuous extensional faulting and strike slipping in 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 abundance of wetlands.

3.2 Northwest coast of the Liaodong Peninsula

In the Beizuizi area, 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 as the Beizuizi fault, which could be a branch of the East Bohai fault (EBF in Figs. 3 and 4). Early-stage extensional fractures indicate the left-lateral strike slipping along the Beizuizi fault (Fig. 6A), which is consistent with the movement direction of the Honglazi fault in northwest coast of the Liaodong Bay. The fault truncated the two-stage extensional fractures in the granitoids (Fig. 6A), implying the faulting later than ca. 120 Ma. Orientated arrangement of potassium feldspars in the granitoids forms ~~general~~ sub-horizontal stretching lineation with an



Honglazi Hill
T1h
F9
F7
F6
F5
114°
Fault scarp related to the strike-slipping of branch faulting of the Honglazi fault
Fault scarp related to the strike-slipping of the Honglazi fault (HF)
HF
Bohai Sea
89∠83
120∠90
67∠74
Sandy beach
(A)
0 40 80 cm
Mafic dike (1)
Mafic dike (2)
F4
F1
F3
58∠30
91∠30
274∠55
323∠29
325∠49
69∠30
252∠56
76∠46
294∠33
85∠13
79∠13
80∠14
70∠82
Fig.6A
F8
Q4
(B)
Conglomerate
40°
T1h
Development of cross-bedding in purple siltstone sequence
(C)
0 20 40 cm
Foliated gouge zone
Stacked thrust duplex
(D)
0 10 20 cm
Bedding
Thrust
Normal fault
Sinistral strike-slip fault
Dipping direction and angle of fault surface or bedding

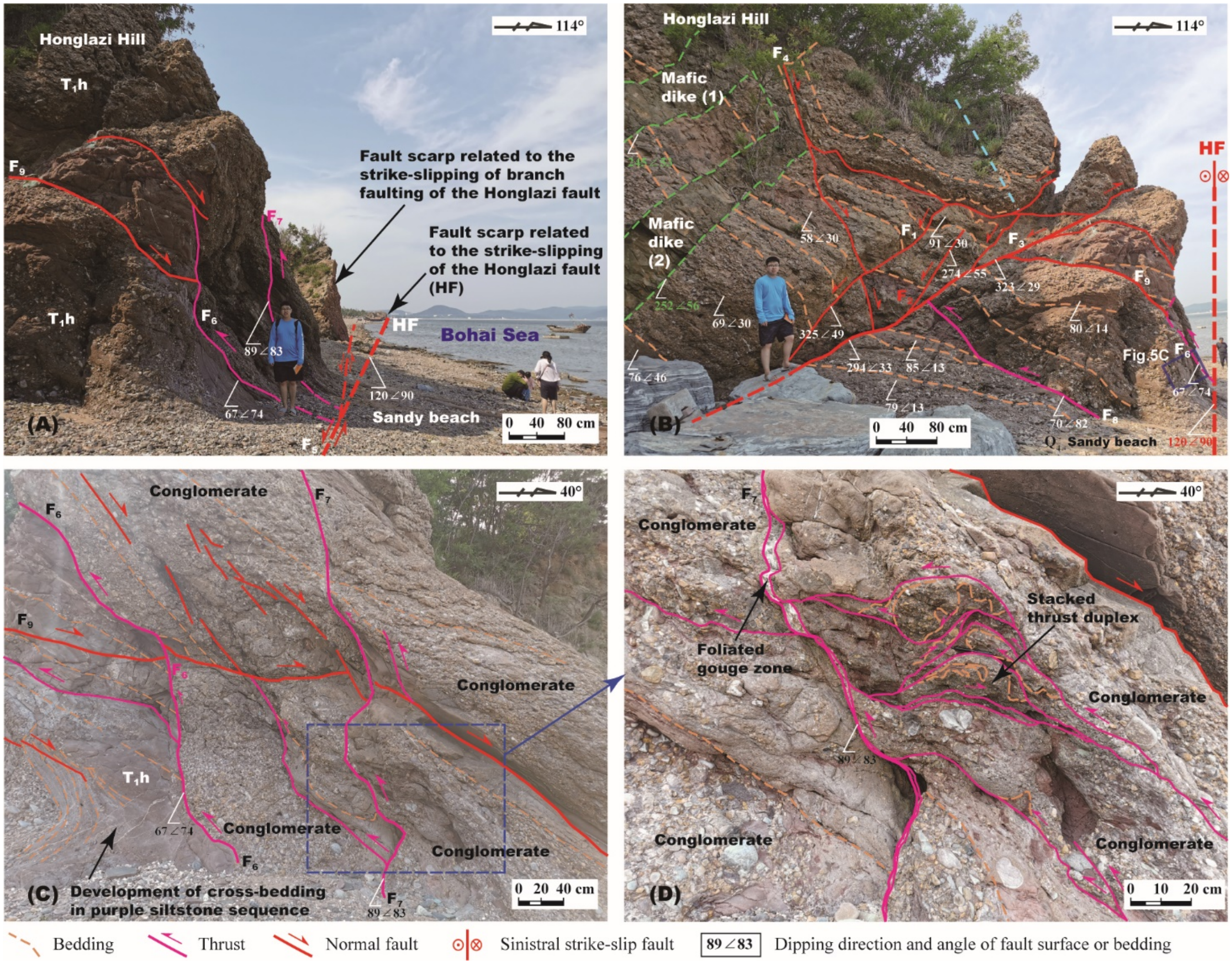


Figure 5: Structural analyses in northwestern coast of the Bohai Sea. (A) The Honglazi fault (HF) with flower structure in western coast of the Bohai Sea, formed in the Early Cretaceous. The flower structure is truncated by normal fault system. (B) Development of the extensional normal fault system with 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 Fig. 5B for location. T_1h, Hongla Formation of the Lower Triassic. Section view.

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 occurrence of bookshelf structures obliquely to the fault, implying transtensional dextral movement along the fault in 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 develop in the early Cenozoic, which is consistent with the widespread right-lateral strike-slip faulting in the Liaodong Bay and surrounding area in early Cenozoic (Figs. 3 and 4; Allen et al., 1997; Hu et al., 2022).

~~Horizontal l~~Left-lateral strike-slip faulting is also found in the Jiangjunshi area, central of northwest coast of the Liaodong Peninsula. The Qingbaikou System (Qb) of the Neoproterozoic in this area is mainly composed of pure white quartz sandstones in medium to coarse grained, with nearly horizontal bedding (Fig. 6B). Multiple sets of joints are developed perpendicular to the bedding of the Qingbaikou System. Striations on joint surface indicate left-lateral movement striking in direction of 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 in southeast coast of the Liaodong Bay, which could be named as the East Bohai fault (Figs. 3 and 4).

3.3. Southeast coast of the Liaodong Peninsula

Neogene red layer, with nearly horizontal bedding, outcrops in the Dajiao area, Dalian City on southeast coast of the Liaodong Peninsula. It is a kind of residual deposits of weathered paleo-crust, mainly composed of ca. one-meter-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 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 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, southwest corner of the Liaodong Peninsula. In this area, the significant tectonic relief occurs between the Neoproterozoic Nanhua System and offshore deposits in the North Yellow Sea, expressed by the coastal landform such as the Elephant Trunk Hill. The Nanhua System here is composed of pure white medium coarse grained quartz sandstone with thin layers of meta-argillaceous siltstones.

3.4. Aeromagnetic anomaly and fault system

Aeromagnetic anomaly map may reflect the distribution of aged basement controlled by 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 is corresponding to the NW to NNW extension in late Mesozoic and early Cenozoic. Perpendicular to the above-mentioned NE extending anomaly belts, there are also some NW striking anomaly belts in the Bohai Sea and North 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 late Mesozoic.

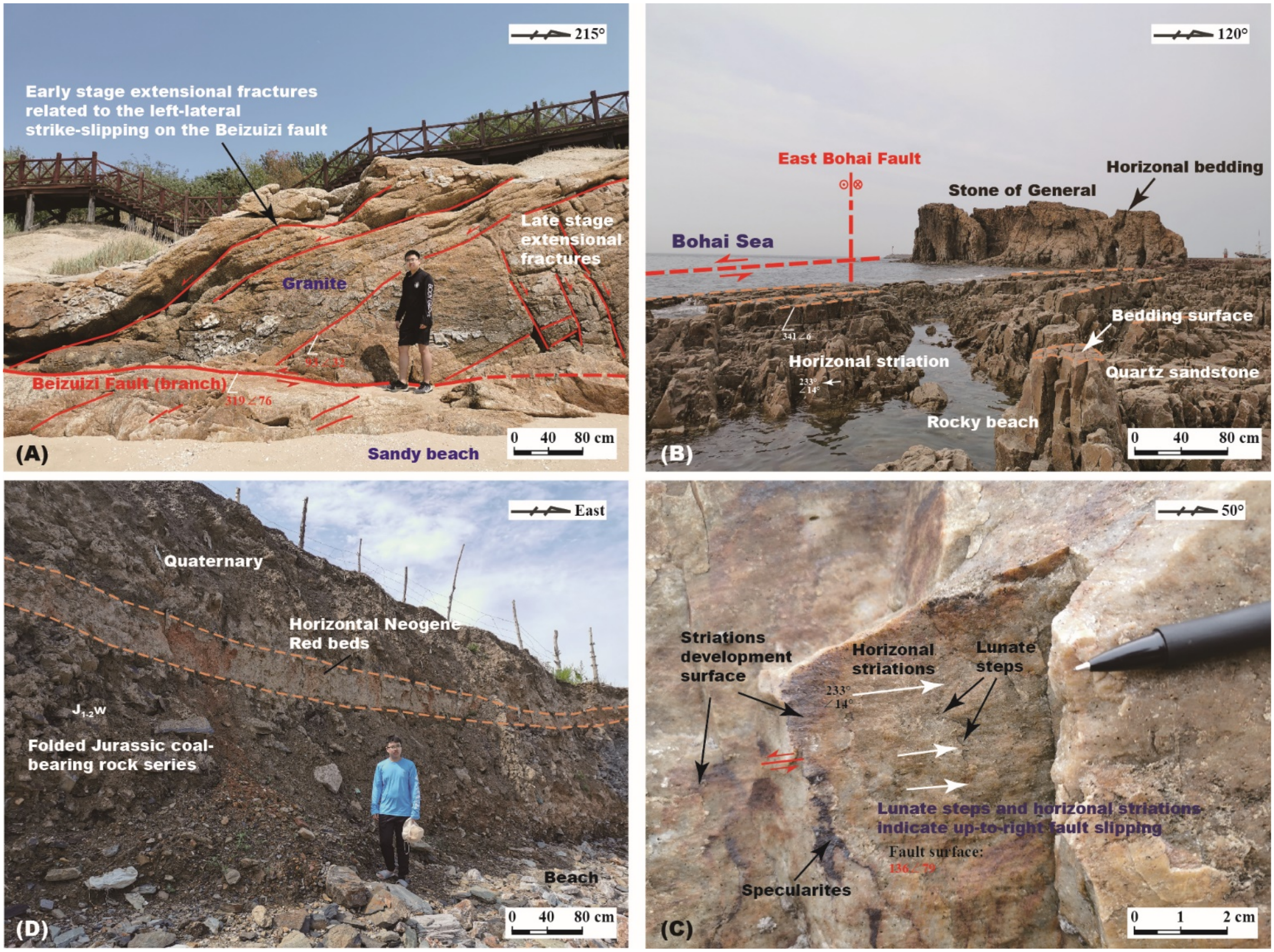
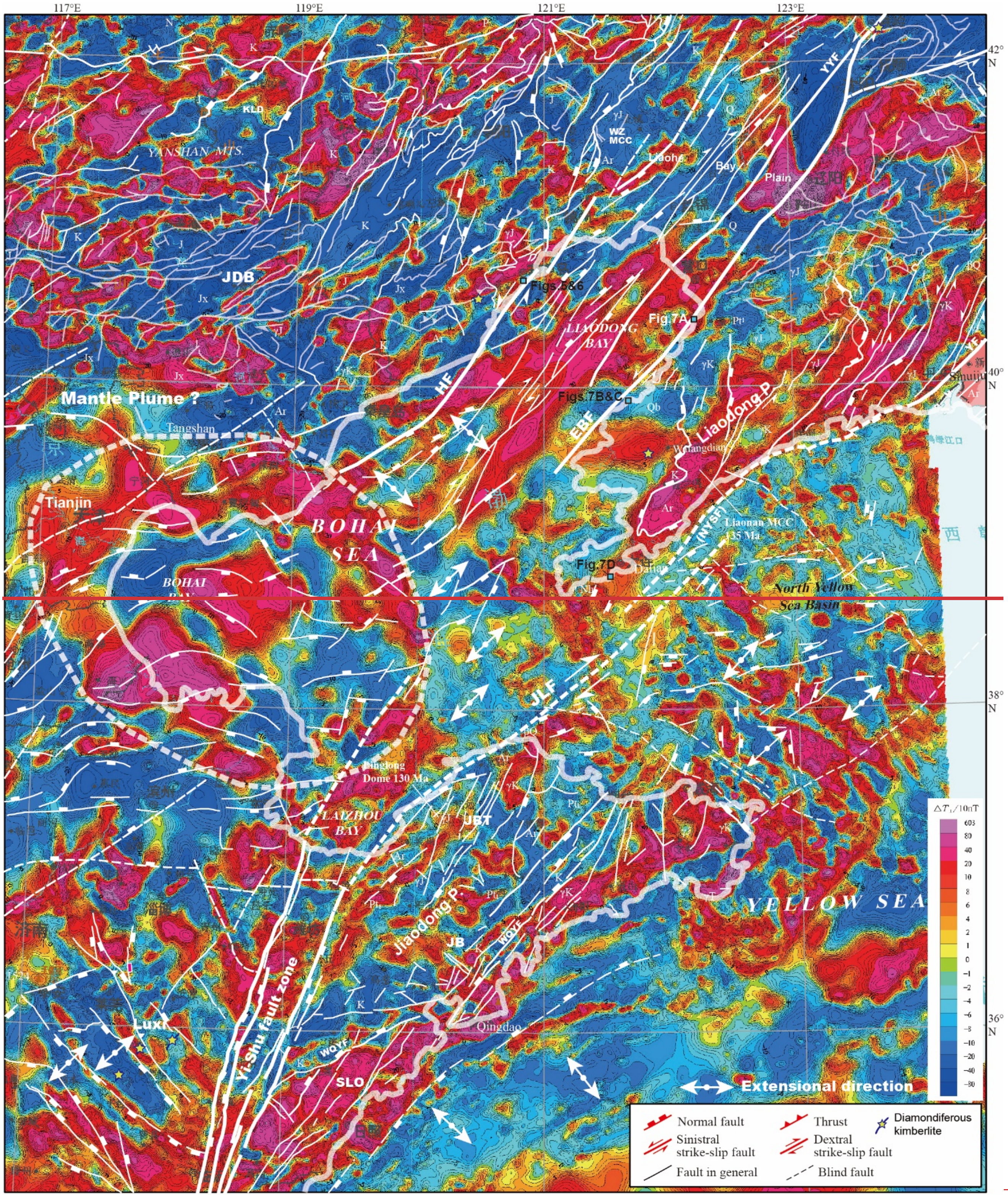
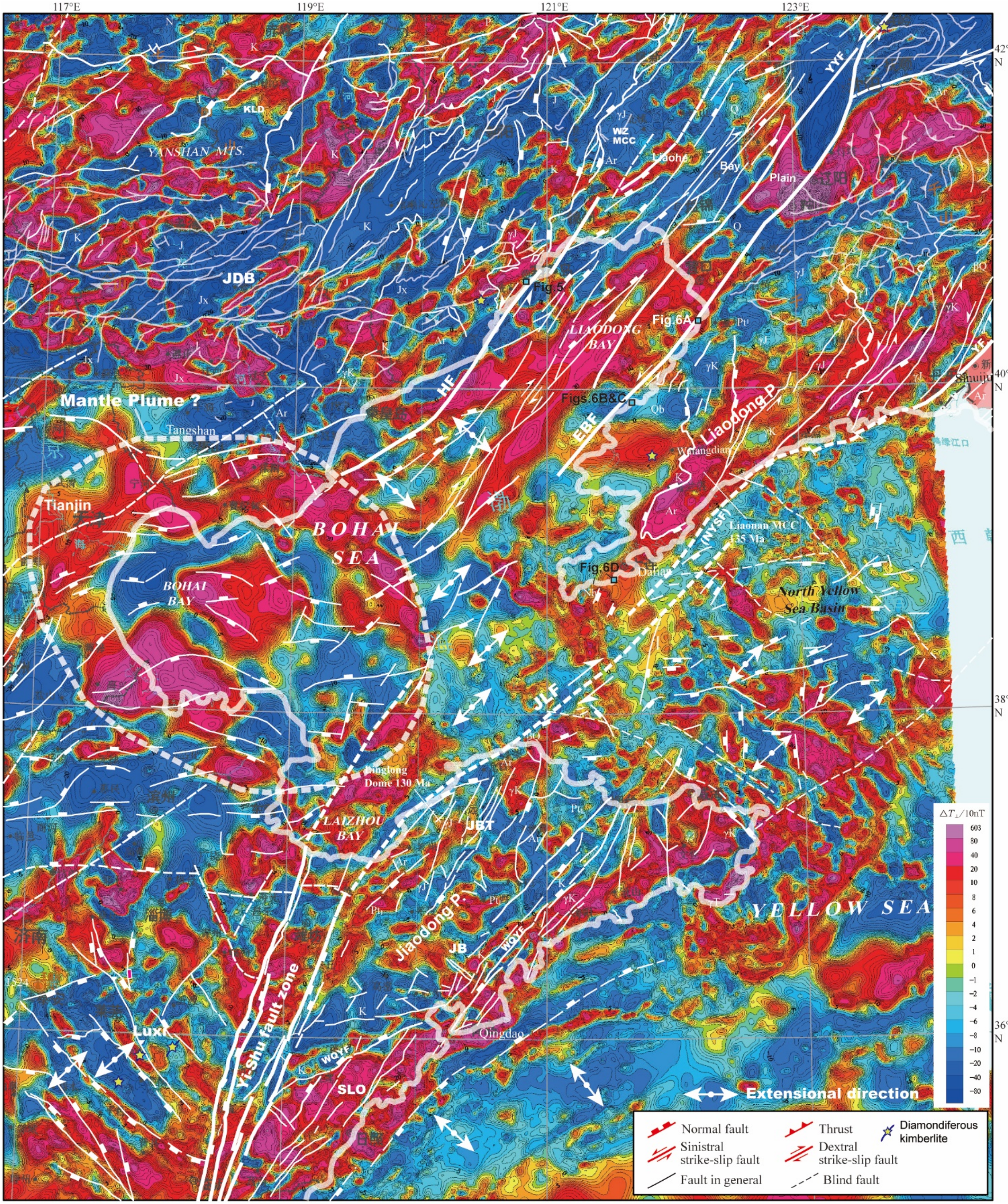


Figure 6: (A) The Beizuizi fault, a branch of the East Bohai fault, occurs in northwestern coast of the Liaodong Peninsula, showing a left-lateral strike-slip movement similar to that on the Honglazi fault in Fig. 5. Section view. Both the Beizuizi and Honglazi faults are considered as relic faults formed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

In Fig. 7, the most eastern fault of the Yi-Shu fault zone, part of the Tan-Lu fault, could be tracked along the Jiao-Liao fault (JLF) to the North Yellow Sea fault (NYSF, as 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 hardly to track the most western boundary fault of the Yi-Shu fault zone to the north, to get connection with the East Bohai fault (EBF) or Yilan-Yitong fault (YYF). Between the Yi-Shu fault zone and East Bohai fault, NW striking aeromagnetic anomaly belts indicate apparently NE extension in Cenozoic, which implies expanding displacement between the Liaodong Peninsula and Laizhou Bay area.


117°E
119°E
121°E
123°E
42° N
40° N
38° N
36° N
KLD
YANSHAN MTS.
JDB
WZ MCC
Liaohe
Bay
Plain
YYF
Figs.5&6
LIAODONG BAY
Fig.7A
Figs.7B&C
HF
EBF
Liaodong P.
Wafangdian
Mantle Plume ?
Tangshan
Tianjin
BOHAI SEA
BOHAI BAY
Liaonan MCC 135 Ma
NYSF
Fig.7D
Dalian
North Yellow Sea Basin
Sinuiju
JLF
Linglong Dome 130 Ma
LAIZHOU BAY
JBT
YELLOW SEA
Jiaodong P.
JB
WQYF
Yi-Shu fault zone
Luxi
WQYF
SLO
Qingdao
Extensional direction
△T⊥/10nT
Normal fault
Thrust
Diamondiferous kimberlite
Sinistral strike-slip fault
Dextral strike-slip fault
Fault in general
Blind fault



117°E
119°E
121°E
123°E
42° N
40° N
38° N
36° N
YANSHAN MTS.
KLD
JDB
WZ MCC
Liaohe
Bay
Plain
YYF
Fig.5
Fig.6A
Figs.6B&C
Fig.6D
LIAODONG BAY
HF
EBF
Liaodong P.
Mantle Plume ?
Tangshan
Tianjin
BOHAI SEA
BOHAI BAY
Wafangdian
Dalian
Liaonan MCC 135 Ma
NYSF
North Yellow Sea Basin
Shuiju
JLF
Linglong Dome 130 Ma
LAIZHOU BAY
JBT
Jiaodong P.
JB
WQYF
YELLOW SEA
Yi-Shu fault zone
Luxi
Qingdao
WQYF
SLO
Extensional direction
△T⊥/10nT
603
80
40
20
10
8
6
4
2
1
0
−1
−2
−4
−6
−8
−10
−20
−40
−80
Normal fault
Thrust
Diamondiferous kimberlite
Sinistral strike-slip fault
Dextral strike-slip fault
Fault in general
Blind fault

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 grey ellipse delineates the possible range of a mantle plume. See Fig. 4 for other explanations.

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~~lin~~ 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; Chen et al., 2022a; Chen et al., 2022b; 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 that 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 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 Early Cretaceous. Our reconstruction is shown in Fig. 8B, which predicts the existence of a right-lateral strike-slip fault, referred 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 jointed with the Linglong dome in the Jiaodong Block (Fig. 8B). Meanwhile, gold deposits cluster in the Wulong-Sidaogou area of the Liaodong Block can also be buckled up on that in 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 Mesozoic, with the typical intracontinental Yanshanian compression~~orogeny~~ in Late Jurassic to early Early Cretaceous, and significant craton destruction and extensional faulting in late Early Cretaceous (Dong et al., 2015; Yang et al., 2020; Qiu et al., 2023). They have approximately simultaneously granitic intrusion events in Early Cretaceous. With nearly east-west zonal distribution of the Early Cretaceous plutons, our restoration shows that the Liaodong Bay Basin has opened through the NW-SE extension in late Mesozoic and early Cenozoic, and modified by the left-lateral strike-slipping along the Honglazi and/or East Bohai faults (Fig. 8B). Before the opening of the Liaodong Bay Basin, these two faults should be branches of the same major fault, which could be inferred as 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 the Early Cretaceous NW-SE extension (Dong et al., 2015), and Cenozoic WNW-striking normal faults. They are both suffered from basalt eruption in Quaternary (Fig. 3). They have a similar pre-Cenozoic history in geological evolution, and the same tectonic setting in Cenozoic. Previous correlation between the Sulu orogen in the south of the Wulian-Qingdao-Yantai fault and Gyeonggi Massif in ~~northern~~ Korea, indicates they are both belong to the high- and ultra-high pressure metamorphic belt formed during the North and South China collision in Triassic (Fig. 3; Li et al., 2012; Kim et al., 2018). Therefore, the Jiaodong Block is not simply connected to the Liaodong Block in NNE direction, but 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 proposed a three-stage kinematic model for the formation and evolution of the Bohai Sea Basin (Fig. 9). Stage 1, in ~~early~~ late period of Early Cretaceous to early period of Late Cretaceous (ca. 135-90 Ma), regional extension and normal faulting occurred in the Jidong, Liaodong, Jiaodong, and Luxi Blocks . In 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, East Bohai, and Honglazi faults (Fig. 9A). In this time, the left lateral slip faults such as the East Bohai and Honglazi faults (Figs. 5 and 6) belonged to the same fault zone which 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). Stage 2, in late period of Late~~Early~~ Cretaceous to Early Cenozoic (ca. 90-34 Ma), as a result of the roll-back of 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-~~strike-slip faulting (Fig. 9B). In this stage, the East Bohai and Honglazi faults were splitted into two faults, located at the northwest and southeast coasts of the Liaodong Bay, respectively. Stage 3 (<34 Ma), the present-day Bohai Sea Basin formed as a result of the continuous bi-directional back-arc extension and strike-slipping along the Jiao-Liao, East Bohai, and Honglazi faults in Late Cenozoic (Fig. 9C). The continuous strike slipping along the Jiao-Liao fault will be merged into the North Yellow Sea and Yalvjiang faults.

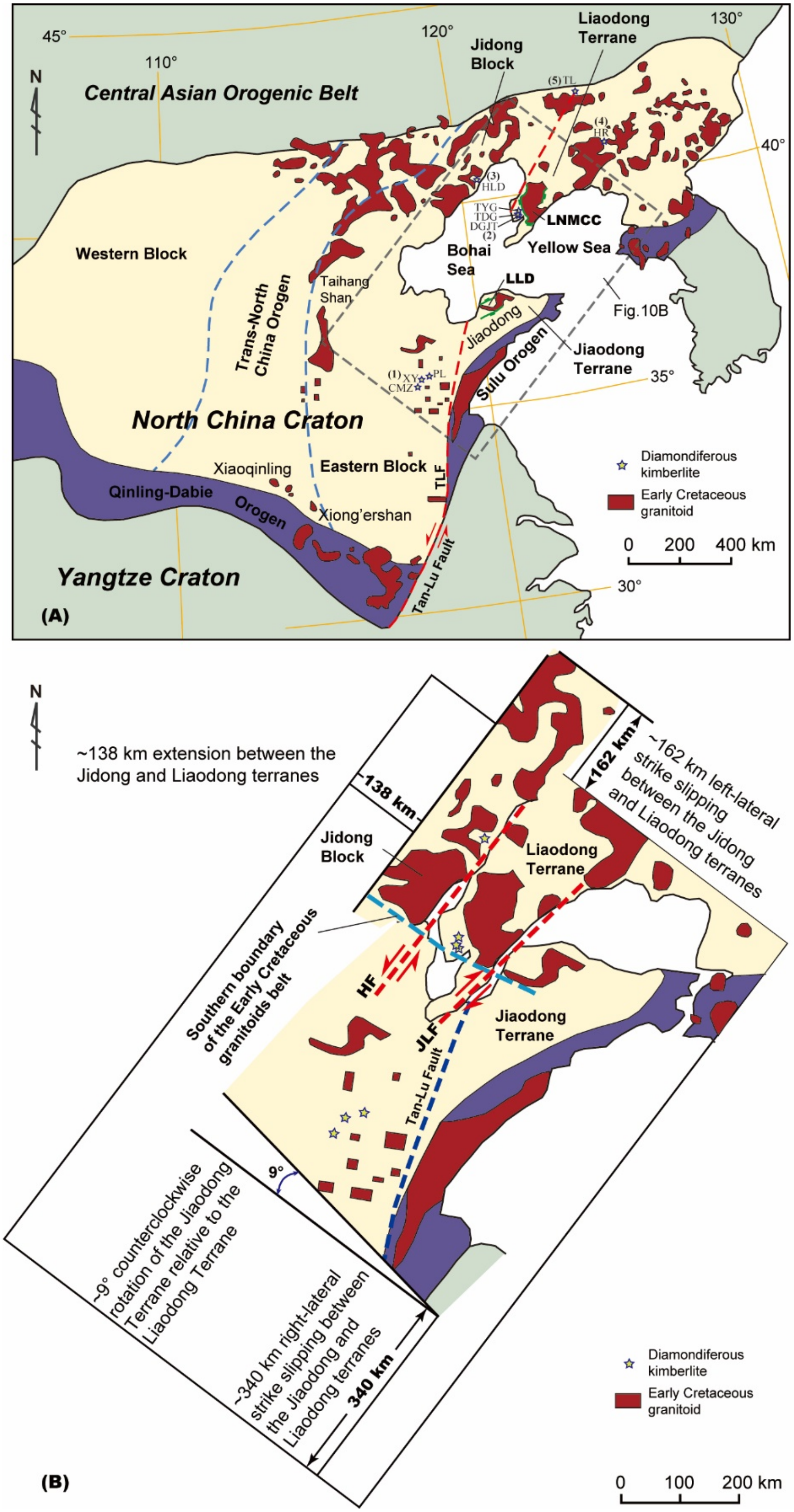

45°
120°
130°
110°
40°
35°
30°
N
Central Asian Orogenic Belt
Jidong Block
Liaodong Terrane
(5) TL
(4) HR
(3) HLD
TYG
TDG
DGJT
(2)
LNMCC
Western Block
Trans-North China Orogen
Taihang Shan
Bohai Sea
Yellow Sea
LLD
Fig.10B
Jiaodong
Jiaodong Terrane
Sulu Orogen
(1) XY PL
CMZ
North China Craton
Xiaoqinling
Eastern Block
TLF
Qinling-Dabie Orogen
Xiong'ershan
Tan-Lu Fault
Yangtze Craton
Diamondiferous kimberlite
Early Cretaceous granitoid
0 200 400 km
(A)
N
~138 km extension between the Jidong and Liaodong terranes
138 km
162 km
~162 km left-lateral strike slipping between the Jidong and Liaodong terranes
Jidong Block
Liaodong Terrane
Southern boundary of the Early Cretaceous granitoids belt
HF
JLF
Jiaodong Terrane
Tan-Lu Fault
9°
~9° counterclockwise rotation of the Jiaodong Terrane relative to the Liaodong Terrane
~340 km right-lateral strike slipping between the Jiaodong and Liaodong terranes
340 km
Diamondiferous kimberlite
Early Cretaceous granitoid
(B)
0 100 200 km

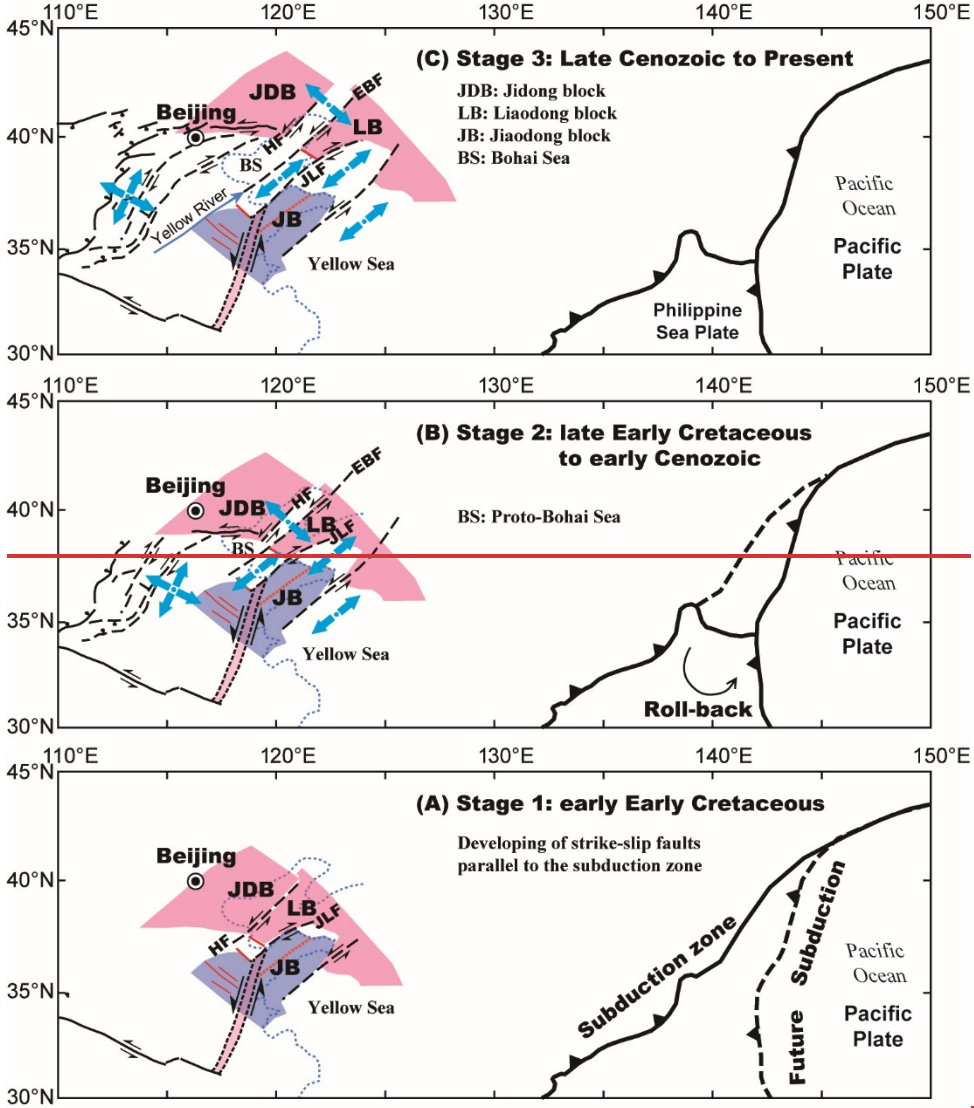
Figure 8: Correlation of the Jidong (Yanshan), Jiaodong and Liaodong terranes, according to the distribution of Early Cretaceous magmatic intrusions and diamondiferous kimberlites. (A) Distribution of Early Cretaceous granitoids and diamondiferous kimberlites in the Jiaodong and Liaodong peninsulas (modified 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 researches. 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 to the restoration of Early Cretaceous magmatic complex.

5 Tectonic significances 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 as a major long term active fault zones in eastern China, starting from the Lujiang City in 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-S~~s~~hu Fault Zone; Figs. 3 and 4), the Bohai Sea segment from the Weifang City in Shandong Province to the Shenyang City in 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 as 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~~as derivatives of the Tan-Lu fault (Hou et al., 1998), or resulted 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 Late Jurassic due to opposite growth of the faults (Li et al., 2023b).

The Tan-Lu fault zone is characterized by a 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 ultra-high 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 Triassic (244-209 Ma; Yin and Nie, 1993; Chen et al., 2000), and suffered from counterclockwise rotation of the Lower Yangtze Block, east side of the Tan-Lu fault, in Jurassic (189-164 Ma; Chen et al., 2000; Wang et al., 2000). In late Early and early Late Cretaceous (130-94 Ma), the Tan-Lu fault zone extended northwards into the Yi-S~~s~~hu 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 are 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). Newly achieved paleomagnetic study yields sinistral slip of ca. 100 km, along the southern segment of the Tan-Lu fault during early Late Cretaceous (100-80 Ma; Qin et al., 2022).


(C) Stage 3: Late Cenozoic to Present
JDB: Jidong block
LB: Liaodong block
JB: Jiaodong block
BS: Bohai Sea
Beijing
JDB
LB
JB
BS
EBF
HF
JLF
Yellow River
Yellow Sea
Pacific Ocean
Pacific Plate
Philippine Sea Plate
(B) Stage 2: late Early Cretaceous to early Cenozoic
BS: Proto-Bohai Sea
Roll-back
(A) Stage 1: early Early Cretaceous
Developing of strike-slip faults parallel to the subduction zone
Subduction zone
Future Subduction
110°E
120°E
130°E
140°E
150°E
45°N
40°N
35°N
30°N

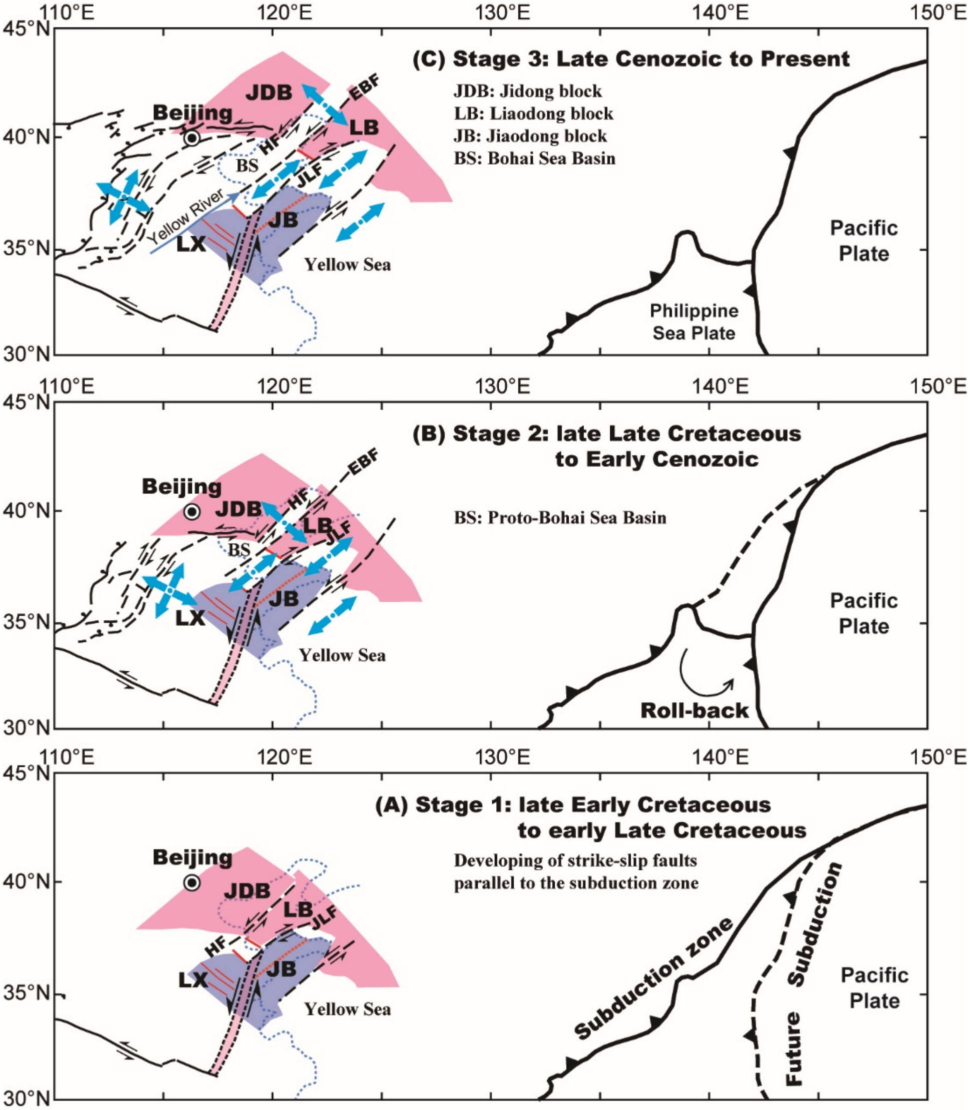


Figure 9: Proposed three-stage model for the formation of the Bohai Sea Basin as a result of complex faulting in Bohai Sea area and roll-back of the West Pacific and Philippine Sea plate subduction. JDB, the Jidong Block. LB, the Liaodong Block. JB, the Jiaodong Block. LX, the Luxi Block. BS, the Bohai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

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 Cenozoic (Yuan et al., 2022). This indicates that there is no continuous NE-wards extending of the Tan-Lu and/or Yi-S~~s~~hu fault zone in Cenozoic. If the Tan-Lu fault zone be 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; Chen et al., 2022b; Hu et al., 2022; Yuan et al., 2022), should be excluded as a part of the Tan-Lu and/or Yi-S~~s~~hu fault zone.

The Luxi block has experienced multi-stage extensional faulting in NE striking, at ca. 61 Ma, 49-42 Ma, and 36-32 Ma, respectively (Li et al., 2018). The extensional direction is parallel to the strike of the Honglazi, East Bohai, and Jiao-Liao faults, implying close connection between the normal faulting and strike-slip movement in Cenozoic. Widespread right-lateral strike slip faulting in the Bohai Sea ~~area~~ Basin since 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 be connected with the Yalvjiang fault (Tian et al., 2007).

5.2 Tectonic reconstruction of the Bohai Sea ~~area~~ 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 ~~Orogenic~~ fold-thrust ~~Belt~~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 Cenozoic.

Our model has also considered the constraints from distribution of kimberlites which emplaced during Middle Ordovician (470-456 Ma) in the Mengyin (Shandong) and Wafangdian (Liaoning) areas (Fig. 3; Liu et al., 2019). Most of previous studies allocated the diamond-bearing kimberlites on both sides of the Tan-Lu fault, with a north-south distance of ca. 550 km between them. Take these two kimberlites as piercing points, they got 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 constrain 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, and 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 nearly northeast direction, not in the 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 Bohai Sea Basin and surrounding area, and reach the following conclusions.

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

2. We propose that the formation and evolution of Bohai Sea Basin fault system is a result from the superimposition of NE extension parallel to the West 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 spherical-geometric effect, especially in the Bohai Sea ~~area~~Basin.

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

Acknowledgements

We appreciate critical reviews and constructive suggestions from referees and editors that made significant improvements of the manuscript.

Author contributions

XC and AC conceptualized the study, conducted the fieldwork and structural analyses, and prepared and revised the paper and figures.

Competing interests

The contact author has declared that none of the authors has any competing interests.

References

Allen, M.B., Macdonald, D.I.M., Zhao, X., Vincent, S.J., and Brouet-Menzies, C.: Early Cenozoic two-phase extension and late Cenozoic thermal subsidence and inversion of the Bohai Basin, northern China, Mar. Petrol. Geol., 14, 95l–972, 1997.

Charles, N., Augier, R., Gumiaux, C., Monié, P., Chen, Y., Faure, M., and Zhu, R.X.: Timing, duration and role of magmatism in wide rift systems: Insights from the Jiaodong Peninsula (China, East Asia), Gondwana Res., 24, 412–428, 2013.

Chen, X.H., Wang, X.F., Zhang, Q., Chen, B.L., Chen, Z.L., Harrison, T.M., and Yin, A.: Geochronologic study on the formation and evolution of Tan-Lu fault [in Chinese with English abstract], J. Changchun Univ. Sci. Tech., 30 (3), 215–220, 2000.

Chen, X.H., Dong, S.W., Shi, W., Ding, W.C., Zhang, Y.P., Li, B., Shao, Z.G., and Wang, Y.: Construction of the continental Asia in Phanerozoic: A review, Acta Geol. Sin.-Engl., 96, 26–51, doi: 10.1111/1755-6724.14867, 2022.

Chen, X.P., Li, W., Wu, Z.P., Yang, H.F., Zhang, Q., Meng, M.F., Wang, G.Z., and Jia H.B.: The tectonic transition from rifting to strike-slip in the Liaodong Bay Depression, offshore China, Mar. Petrol. Geol., 139, 105598, doi: 10.1016/j.marpetgeo.2022.105598, 2022.

Chen, Y., Liang, X.F., Yan, H.F., Jiang, M.M., and Ai, Y.S.: Seismicity of the northern section of the Tanlu fault zone in the Bohai Bay and its implications [in Chinese with English abstract], Chinese J. Geophys., 63, 2566–2578, doi: 10.6038/cjg2020N0159, 2020.

China Geological Survey: Geological Map of the People's Republic of China (1:2500000), with explanation [in Chinese], Beijing, China, SinoMaps Press, 1–246, 2004.

Clinkscales, C. and Kapp, P.: Structural style and kinematics of the Taihang-Luliangshan fold belt, North China: Implications for the Yanshanian orogeny, Lithosphere, 11, 767–783, doi: 10.1130/L1096.1, 2019.

Deng, J., Yang, L.Q., Groves, D.I., Zhang, L., Qiu, K.F., and Wang, Q.F.: An integrated mineral system model for the gold deposits of the giant Jiaodong province, eastern China, Earth-Sci. Rev., 208, 103274, doi: 10.1016/j.earscirev.2020.103274, 2020.

Deng, Q.D., Wang, T.M., Li, J.G., Xiang, H.F., and Cheng, S.P.: A discussion on source model of Haicheng earthquake [in Chinese with English abstract], Scientia Geol. Sin., 11 (3), 3-12, 1976.

Dong, S.W., Zhang, Y.Q., Zhang, F.Q., Cui, J.J., Chen, X.H., Zhang, S.H., Miao, L.C., Li, J.H., Shi, W., Li, Z.H., Huang, S.Q., and Li, H.L.: Late Jurassic-Early Cretaceous continental convergence and intracontinental orogenesis in East Asia: A synthesis of the Yanshan Revolution, J. Asian Earth Sci., 114, 750–770, doi: 10.1016/j.jseaes.2015.08.011, 2015.

Dong, L.L., Yang, Z.M., Bai, X., and Deng, C.: Generation of the Early Cretaceous granitoid in the Dazeshan region, Jiaodong Peninsula: Implications for the crustal reworking in the North China Craton, Front. Earth Sci., 10, 1083608, doi: 10.3389/feart.2022.1083608, 2023.

Faure, M., Lepvrier, C., Nguyen, V.V., Vu, V.T., Lin, W., and Chen, Z.C.: The South China block-Indochina collision: Where, when, and how? J. Asian Earth Sci., 79, 260–274, doi: 10.1016/j.jseaes.2013.09.022, 2014.

Guo, H., Xia, B., Chen, G.W., Wang, R.H., Ding, J.H., Wang, J.J., and Huang, T.: Geochemistry of basalts during Oligocene in Huimin depression and its geotectonic significance [in Chinese with English abstract], Geotectonica et Metallogenia, 29, 303–315, 2005.

Hou, G.T., Qian, X.L., and Song, X.M.: The origin of the Bohai Bay Basin [in Chinese with English abstract], Acta Scientiarum Naturalium Universitatis Pekinensis, 34, 503–509, 1998.

Hu, P.P., Yang, F.L., Zhang, R.C., Wang, W., and Dong, R.W.: Cenozoic extension to strike-slip transition in the Liaodong Bay Subbasin along the Tan-Lu Fault Zone, Bohai Bay Basin: New insights from stress field modelling, Tectonophysics, 822, 229163, doi: 10.1016/j.tecto.2021.229163, 2022.

Kim, H.S., Kwon, S., Kim, S.W., and Santosh, M.: Permo-Triassic high-pressure metamorphism in the central western Korean Peninsula, and its link to Paleo-Tethyan Ocean closure: Key issues revisited, Geosci. Front., 9, 1325–1335, doi: 10.1016/j.gsf.2018.01.007, 2018.

Koua, K.A.D., Sun, H.S., Li, J.W., Li, H., Xie, J.L., Sun, Q.M., Li, Z.K., Yang, H., Zhang, L.G., and Mondah, O.R.: Petrogenesis of Early Cretaceous granitoids and mafic enclaves from the Jiaodong Peninsula, eastern China: Implications for crust-mantle interaction, tectonic evolution and gold mineralization, J. Asian Earth Sci., 228, 105096, doi: 10.1016/j.jseaes.2022.105096, 2022.

Leech, M.L. and Webb, L.E.: Is the HP–UHP Hong'an–Dabie–Sulu orogen a piercing point for offset on the Tan–Lu fault? J. Asian Earth Sci., 63, 112–129, doi: 10.1016/j.jseaes.2012.08.005, 2013.

Li, S.Z., Zhao, G.C., Dai, L.M., Zhou, L.H., Liu, X., Suo, Y.H., and Santosh, M.: Cenozoic faulting of the Bohai Bay Basin and its bearing on the destruction of the eastern North China Craton, J. Asian Earth Sci., 47, 80–93, doi: 10.1016/j.jseaes.2011.06.011, 2012.

Li, L., Zhong, D.L., Chen, X.F., and Chen, Y.: Characteristics of NW-trending faults and evidence of fission track in the Luxi Block [in Chinese with English abstract], Acta Geol. Sin., 92 (3), 413–436, 2018.

Li, X., Wang, Y., Liang, C., Li, B., Zheng, C., and Zhang, M.: Mesozoic stratigraphic sequence and its characteristics in southern Western Liaoning Province, Northeast China [in Chinese with English abstract], J. Stratigraphy, 44 (3), 299–309, doi: 10.19839/j.cnki.dcxzz.2020.0027, 2020.

Li, H.P., Li, J.L., Luo, S., Bem, T.S., Yao, H.J., Huang, X.L.: Continent-continent collision between the South and North China plates revealed by seismic refraction and reflection at the southern segment of the Tanlu Fault Zone, JGR Solid Earth, 128, e2022JB025748, doi: 10.1029/2022JB025748, 2023a.

Li, C.M., Zhang, C.H., and Cope, T.D.: A new model for the segmentation, propagation and linkage of the Tan-Lu fault zone, East Asia, J. Asian Earth Sci., 241, 105466, doi: 10.1016/j.jseaes.2022.105466, 2023b.

Liang, J.T., Wang, H.L., Bai, Y., Ji, X.Y., and Duo, X.M.: Cenozoic tectonic evolution of the Bohai Bay Basin and its coupling relationship with Pacific Plate subduction, J. Asian Earth Sci., 127, 257–266, doi:

10.1016/j.jseaes.2016.06.012, 2016.

Lin, W., Faure, M., Monié, P., and Wang, Q.C.: Polyphase Mesozoic tectonics in the eastern part of the North China Block: Insights from the Eastern Liaoning Peninsula massif (NE China), Geol. Soc. Lond. Spec. Publ., 280, 153–169, 2007.

Lin, W., Faure, M., Monié, P., Schärer, U., and Panis, D.: Mesozoic extensional tectonics in Eastern Asia: The south Liaodong Peninsula metamorphic core complex (NE China), J. Geol., 116, 134–154, 2008.

Lin, W., and Wei, W.: Late Mesozoic extensional tectonics in the North China Craton and its adjacent regions: A review and synthesis, Int. Geol. Rev., 62, 811–839, doi: 10.1080/00206814.2018.1477073, 2020.

Lin, W., Zeng, J.P., Meng, L.T., Qiu, H.B., Wei, W., Ren, Z.H., Chu, Y., Li, S.J., Song, C., and Wang, Q.C.: Extensional tectonics and North China Craton destruction: Insights from the magnetic susceptibility anisotropy (AMS) of granite and metamorphic core complex, Science China Earth Sciences, 64 (9), 1557–1589, doi: 10.1007/s11430-020-9754-1, 2021.

Liu, S.F., Gurnis, M., Ma, P.F., and Zhang, B.: Reconstruction of northeast Asian deformation integrated with western Pacific plate subduction since 200 Ma, Earth-Sci. Rev., 175, 114–142. doi: 10.1016/j.earscirev.2017.10.012, 2017.

Liu, F., Yang, J.S., Lian, D.Y., Yu, X.Y., and Gwandu, K.R.: Metallogenic features of diamondiferous kimberlites in Botswana and China: Enlightenment for exploration of the same type deposits [in Chinese with English abstract], Geol. Chin., 46, 43–76, 2019.

Liu, Q.Y., He, L.J., and Chen, L.C.: Tectono-thermal modeling of Cenozoic multiple rift episodes in the Bohai Bay Basin, eastern China and its geodynamic implications, Int. J. Earth Sci., 107, 53–69, doi: 10.1007/s00531-017-1550-1, 2018.

Liu, Y.M., and Wu, Z.P.: Diachronous characteristics and genetic mechanism of the Paleogene tectonic transition in Bohai Bay basin: a case study of the southwest Bohai Sea and Jiyang Depression [in Chinese with English abstract], J. Central South University (Science and Technology), 53, 1095–1110, 2022.

Ma, Q.L., Yang, J.H., Du, Y.S., Dai, X.D., Chai, R., Guo, H., and Xu, Y.J.: Early Triassic initial collision between the North China and South China blocks in the eastern Qinling Orogenic Belt, Tectonophysics, 814, 228965, doi: 10.1016/j.tecto.2021.228965, 2021.

Min, W., Liu, Y.G., Jiao, D.C., Shen, J., and Pan, X.L.: Evidence for Holocene activity of the Yilan-Yitong fault, northern section of the Tan-Lu fault zone in Northeast China, J. Asian Earth Sci., 67-68, 207–216, doi: 10.1016/j.jseaes.2013.02.031, 2013.

Qin, H.F., Hao, W.X., Deng, C.L., Zhao, P., Shen, Z.S., Han, F., He, H.Y., Pan, Y.X., and Zhu, R.X.: Sinistral displacement along the Tan–Lu Fault during the Cretaceous induced by Paleo-Pacific subduction: Constraints from new paleomagnetic and U–Pb geochronological data, J. Asian Earth Sci., 237, 105362, doi: 10.1016/j.jseaes.2022.105362, 2022.

Qiu, H.B., Lin, W., Chen, Y., and Faure, M.: Jurassic-Early Cretaceous tectonic evolution of the North China Craton and Yanshanian intracontinental orogeny in East Asia: New insights from a general review of stratigraphy, structures, and magmatism, Earth-Science Reviews, 237, 104320, 2023.

Ren, J.S., Niu, B.G., Wang, J., Jin, X.C., and Xie, L.Z.: International Geological Map of Asia (1:5000000), Beijing, China, Geological Publishing House, 2013.

Ren, J.Y., Tamaki, K., Li, S.T., and Zhang, J.X.: Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas, Tectonophysics, 344, 175–205, 2002.

Ren, Z.H., Dong, S.W., Zhang, Y.Q., Chen, X.H., Shi, W., and Zhang, Y.: Middle Jurassic intracontinental evolution of East Asia: Insights from the Tianshifu-Dongyingfang basin of the Liaodong Peninsula, NE China, Geol. Soc. Am. Bull., 135, 915–936, doi: 10.1130/B36373.1, 2023.

Shen, Z.Y., Gao, J.Y., Yang, C.G., Yang, Y., Zhang, T., and Wu, Z.C.: Characteristics of the Neogene-Quaternary faults in the North Yellow Sea Basin and the inheritance to the Paleogene faults [in Chinese with English abstract], Earth Sci., 38 (Suppl.1), 53–60, 2013.

Sun, S., Qiu, L., Yan, D.P., Zhou, Z., Zhang, J., Wang, X., Wu, B., Shi, H., Ariser, S., Chu, R., Fu, Y., and Wang, Y.: Formation and evolution of supradetachment basins during continental extension: Insights from the Fuxin Basin in NE China, Front. Earth Sci., 10, 845812, doi: 10.3389/feart.2022.845812, 2022.

Tian, Z.X., Zhang, X.H., Xiao, G.L., and Meng, X.J.: The north edge fracture of the north Yellow Sea basin and its characters [in Chinese with English abstract], Mar. Geol. Quat. Geol., 27 (2), 59–63, 2007.

Wang, C., Sun, J., Shen, Y., Tian, T., Li, J., Qian, Y., and Sun, F.: Petrogenesis of Early Cretaceous adakites from the Liaodong Peninsula: insight into the lithospheric thinning of the North China Craton, Geol. Mag., 160, 60–74, doi: 10.1017/S0016756822000644, 2023.

Wang, K., Wei, B., and Zhao, Z.S.: Magma assembly and evolution of the Early Cretaceous Sanguliu pluton in the Liaodong Peninsula, NE China, J. Asian Earth Sci., 226, 105077, doi: 10.1016/j.jseaes.2021.105077, 2022.

Wang, T., Pan, X., and Hao, F.: Hydrocarbon accumulation and distribution prediction in Bohai Basin [in Chinese], Beijing, China, Geological Publishing House, 1–492, 2016.

Wang, W., Wang, D.J., Zhao, B., Huang, Y., Zhang, C.H., Tan, K., and Yang, S.M.: Horizonal crustal deformation in Chinese Mainland analyzed by CMONOC GPS data from 2009-2013, Geodesy and Geodynamics, 5 (3), 41–45, doi: 10.3724/sp.j.1246.2014.03041, 2014.

Wang, X.F., Li, Z.J., Chen, B.L., Chen, X.H., Dong, S.W., and Zhang, Q.: On Tan-Lu Fault Zone [in Chinese with English abstract], Beijing, China, Geological Publishing House, 1–374, 2000.

Wu, J.J., Zeng, Q.D., Yang, J.H., Li, R., Yu, B., Wang, R.L., Chen, P.W., Zhang, Z.M., and Xie, W.: Petrogenesis and magmatic evolution of the intermediate–felsic Early Cretaceous Shizhuzi magmatic complex on Liaodong Peninsula, NE China, Lithos, 398–399, 106338, doi: 10.1016/j.lithos.2021.106338, 2021.

Xiao, L., Wang, F.Z., Wang, H., and Pirajno, F.: Mantle plume tectonics constraints on the formation of Songliao and Bohaiwan basins [in Chinese with English abstract], Earth Sci., 29 (3), 283–292, 2004.

Xiong, S.Q., Fan, Z.G., Zhang, H.R., Ding, Y.Y., Huang, X.Z., Li, Z.K., Guo, Z.H., Yang, X., Tong, J., Liu, Q.K., Zhou, D.Q., Tan, L., and Zhang, J.W.: Aeromagnetic Series Maps of Mailand China (1:2500000), with explanation [in

Chinese], Beijing, China, Geological Publishing House, 1–19, 2015.

Xu, J.W., Zhu, G., Tong, W.X., Cui, K.R., and Liu, Q.: Formation and evolution of the Tancheng-Lujiang wrench fault system: a major shear system to the northwest of the Pacific Ocean, Tectonophysics, 134, 273–310, 1987.

Xu, J.Y., Ben-Avraham, Z., Kelty, T., and Yu, H.S.: Origin of marginal basins of the NW Pacific and their plate tectonic reconstructions, Earth-Sci. Rev., 130, 154–196, doi: 10.1016/j.lithos.2021.106338, 2014.

Yan, D.P., Kong, R.Y., Dong, X.Y., Qiu, L., Liu, and H.L.: Late Jurassic-Early Cretaceous tectonic switching in Liaodong Peninsula of the North China Craton and the implications for gold mineralization, Sci. China Earth Sci., 64, 1537–1556, doi: 10.1007/s11430-020-9770-6, 2021.

Yang, J.H., Xu, L., Sun, J.F., Zeng, Q., Zhao, Y.N., Wang, H., and Zhu, Y.S.: Geodynamics of decratonization and related magmatism and mineralization in the North China Craton, Sci. China Earth Sci., 64, 1409–1427, doi: 10.1007/s11430-020-9732-6, 2021.

Yang, L. Q., Dilek, Y., Wang, Z. L., Weinberg, R. F., and Liu, Y.: Late Jurassic, high Ba–Sr Linglong granites in the Jiaodong Peninsula, east China: Lower crustal melting products in the eastern north China craton, Geol. Mag., 155, 1040–1062, doi:10.1017/ s0016756816001230, 2017.

Yang, Q., Shi, W., Hou, G.T., Zhang, Y., Wang, T.Y., and Zhao, Z.X.: Late Mesozoic intracontinental deformation at the northern margin of the North China Craton: A case study from the Kalaqin massif, southeastern Inner Mongolia, China, Tectonophysics, 793, 228591, doi: 10.1016/j.tecto.2020.228591, 2020.

Yin, A., and Nie, S.Y.: An indentation model for the North and South China collision and the development of the Tan-Lu and Honam fault systems, eastern Asia, Tectonics, 12 (4), 801–813, 1993.

Yin, A., Yu, X.J., Shen, Z.K., and Liu-Zeng, J.: A possible seismic gap and high earthquake hazard in the North China Basin, Geology, 43, 19–22, doi: 10.1130/G35986.1, 2015.

Yuan, H.W., Chen, S.P., Dai, K., Jia, G.H., Wang, P.F., Li, J.Y., and Gou, Q.W.: Cenozoic tectonic evolution of the Bohai Bay Basin: Constraints from strike-slip activities of the Wangjiagang fault zone, NE China, J. Asian Earth Sci., 233, 105262, doi: 10.1016/j.jseaes.2016.06.012, 2022.

Zeng, R.Y., Allen, M.B., Mao, X.C., Lai, J.Q., Yan, J., and Wan J.J.: Whole-rock and zircon evidence for evolution of the Late Jurassic high-Sr /Y Zhoujiapuzi granite, Liaodong Peninsula, North China Craton, Solid Earth, 13, 1259–1280, doi: 10.5194/se-13-1259-2022, 2022.

Zhai, M.G., Zhang, X.H., Zhang, Y.B., Wu, F.Y., Peng, P., Li, Q.L., Li, Z., Guo, J.H., Li, T.S., Zhao, L., Zhou, L.G., and Zhu, X.Y.: The geology of North Korea: an overview, Earth-Sci. Rev., 194, 57–96, doi: 10.1016/j.earscirev.2019.04.025, 2019.

Zhang, J.D., Hao, T.Y., Dong, S.W., Chen, X.H., Cui, J.J., Yang, X.Y., Liu, C.Z., Li, T.J., Xu, Y., Huang, S., and Re, F.L.: The structural and tectonic relationships of the major fault systems of the Tan-Lu fault zone, with a focus on the segments within the North China region, J. Asian Earth Sci., 110, 85–100, doi: 10.1016/j.jseaes.2014.11.011, 2015.

Zhang, L.M., Wang, C.S., Cao, K., Wang, Q., Tan, J., and Gao, Y.: High elevation of Jiaolai Basin during the Late

Cretaceous: Implication for the coastal mountains along the East Asian margin, Earth Planet. Sc. Lett., 456, 112–123, doi: 10.1016/j.epsl.2016.09.034, 2016.

Zhang, Q.B., Song, M.C., Ding, Z.J., Guo, M.L., Zhou, M.L., Dai, C.G., Huo, G., and Zhang, P.: Exhumation history and preservation of the Jiaojia giant gold deposit, Jiaodong Peninsula, Sci. China Earth Sci., 65, 1161–1177, doi: 10.1007/s11430-021-9887-1, 2022a.

Zhang, P., Kou, L.L., and Zhao, Y.: Three periods of gold mineralization in the Liaodong Peninsula, North China Craton, Int. Geol. Rev., 64, 2922–2940, doi: 10.1080/00206814.2021.2009046, 2022b.

Zhao, B., Huang, Y., Zhang, C.H., Wang, W., Tan, K., and Du, R.L.: Crustal deformation on the Chinese mainland during 1998-2014 based on GPS data, Geodesy and Geodynamics, 6 (1), 7–15, doi: 10.1016/j.geog.2014.12.006. 2015.

Zhou, Q.J., Liu, Y.J., Wang, D.Y., Guan, Q.B., Wang, G.Z., Wang, Y., Li, Z.T., and Li, S.Z.: Mesozoic- Cenozoic tectonic evolution and buried hill formation in central Bohai Bay [in Chinese with English abstract], Earth Sci. Front., 29 (5), 147–160, 2022.

Zhu, G., Wang, D.X., Liu, G.S., Niu, M.L., and Song C.Z.: Evolution of the Tanlu fault zone and its responses to plate movements in west Pacific basin [in Chinese with English abstract], Scientia Geologica Sinica, 39 (1), 36–49, 2004.

Zhu, R.X. and Xu, Y.G., The subduction of the west Pacific plate and the destruction of the North China Craton, Sci. China Earth Sci., 62, 1340–1350, doi: 10.1007/s11430-018-9356-y, 2019.

Zhu, R.X., Zhu, G., and Li, J.W.: The North China Craton Destruction [in Chinese], Beijing, China, Science Press, 1–417, 2020.

Zhu, R.X., Yang, J.H., Wang, G.W., Zeng, Q.D., Xue, G.Q., Xu, T., Li, X.H., Zhang, P., Lei, D., and Zhu, G.: The genesis and resource potential of gold deposits in the Liaodong Peninsula, Sci. China Earth Sci., doi: 10.1007/s11430-023-1258-4, 2024.

Zuza, A.V., Levy, D.A., Dee S., DesOrmeau, J.W., Cheng, F., and Li, X.Z.: Structural architecture and attenuation of the ductile lower plate of the Ruby Mountain-East Humboldt Range metamorphic core complex, Northeast Nevada, Tectonics, 41, e2021TC007162, 2022.