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New Insights into the Distribution and Evolution of WNW-Directed Faults in the Liaodong Bay Subbasin of the Bohai Bay Basin, Eastern China

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WNW-directed faults are widespread in eastern China, but debates regarding their distributions and evolutionary processes remain unsettled. Based on the latest 3-D seismic data, a series of WNW-directed faults south of the Liaodong Bay subbasin was identified, for which the evolution and formation mechanisms were discussed. The results show that four WNW-directed faults are characterized by poor continuity and nearly parallel orientations. Vertically, they exhibit listric geometries and cut through Paleozoic and Mesozoic formations. Since the late Triassic, these faults began as reverse faults under nearly S-N horizontal compression. In the Jurassic, those faults maintained their reverse-faulting activities with dramatically decreased intensities. In the Early Cretaceous, the WNW-directed faults were changed into normal faults under regional extension and were influenced by the sinistral strike-slip movement along the Tan-Lu fault zone. In the Late Cretaceous, the WNW-directed normal faults probably stopped moving due to a regional compressional event. During the Paleogene, the WNW-directed faults were reactivated with decreased intensities and were cut by NNE-directed faults. Here, we emphasize that the evolution of the WNW-directed faults could shed light on the regional tectonics. The WNW-trending faults that developed in the Liaodong Bay subbasin are closely related to the faults in the Yanshan orogenic belt. Therefore, investigating the characteristics and origin of WNW-induced faults will provide evidence for the tectonic evolution of the North China Block. In addition, the development of WNW-directed faults in the southern Liaodong Bay subbasin was conducive to the formation of buried Mesozoic and Paleozoic hills and hydrocarbon accumulations. In addition, we suggest that the compressional segment of the conjugated strike-slip transition zone that was formed by the interaction of the WNW- and NNE-directed strike-slip faults was conducive to hydrocarbon accumulations.

Keywords: WNW-directed faults, development characteristics, evolution process, formation mechanism, Liaodong Bay subbasin

INTRODUCTION

The North China block (NCB) is bounded by the Qinling-Dabie orogenic belt (QDOB) to the south and Yinshan–Yanshan orogenic belt to the north (Menzies and Xu, 1998; Zhao, 2001; Ren et al., 2002; Hu et al., 2006; Yang et al., 2008; Zhu et al., 2011; Wang et al., 2018b) (**Figure 1A**). Numerous faults with various orientations have developed since the Mesozoic in this area due to plate subduction, mantle upwelling, and lithospheric thinning. Previous studies have focused mainly on the NE-, NNE-, and nearly E-W-directed faults (Jia et al., 2021), while the WNW-directed faults have not been deeply studied. In particular, the distribution ranges and the formation mechanisms of the WNW-directed faults are still frequently debated (Li, et al., 2009; Suo, et al., 2013; Guo et al., 2015; Zhang, et al., 2017).

The Liaodong Bay subbasin is located in the northeastern Bohai Bay Basin (BBB), offshore China (**Figure 1B**) (Qi et al., 2008; Li L et al., 2012) and covers an area of more than 20,000 km^2. The Liaodong Bay subbasin includes six ENE-oriented subunits and from west to east are the Liaoxinan uplift, Liaoxi sag, Liaoxi uplift, Liaozhong sag, and Liaodong uplift (**Figure 1B**) (Hsiao et al., 2004; Xu et al., 2015; Hu et al., 2018; Li et al., 2018; Liu L et al., 2019). The formation and evolution of this subbasin is mainly controlled by diverse faults, which have caused the most important tectonic deformations in this subbasin. Various fault types have developed in the LDB, which include extensional, strike-slip, and transtensional faults (Hu et al., 2018; Hu P et al., 2019; Hu Z W et al., 2019; Liu Y M et al., 2019). According to their orientations, the faults in the Liaodong Bay subbasin can be divided into three groups: NNE-directed, NE-directed, and NEE- or nearly E-W-directed, among

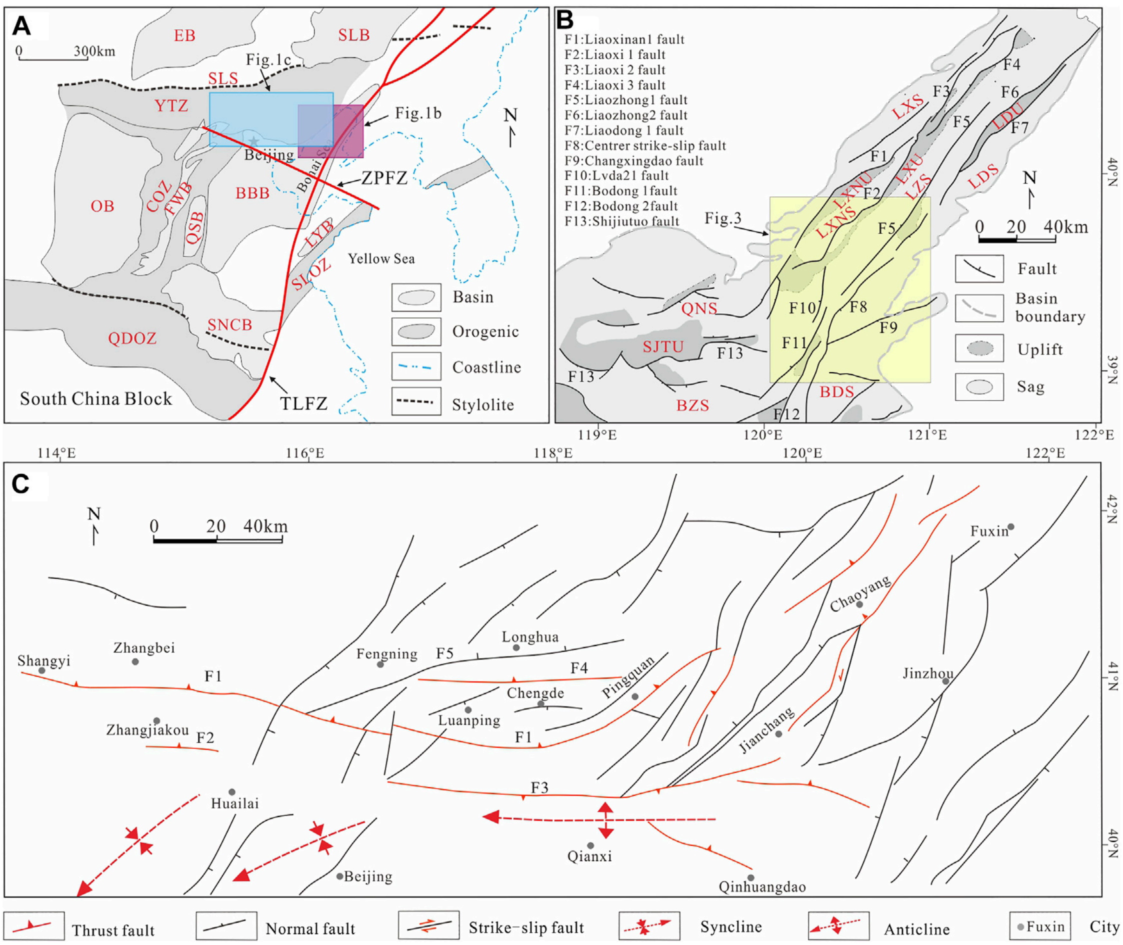

FIGURE 1 | (A) Simplified tectonic map showing the North China block (NCB) and adjacent geologic elements. (Modified from Zheng Yadong et al., 2000 and Zheng Jianping et al., 2018). The purple box is the location of **(B)**. The blue box is the location of **(C)**. Abbreviations are as follows: EB, Erlian Basin; SLB; Songliao Basin; OB, Ordos Basin: LYB, Laiyang Basin; QSB, Qinshui Basin; BBB, Bohai Bay Basin; FWB, Fenwei Basin; SNCB, southern North China Basin. YOB, Yanshan Orogenic Belt; COZ, Central Orogenic Zone; QDOZ, Qinling, Dabie Orogenic Zone; SLOZ, Sulu Orogenic Zone; SLS, Suolun Stylolite; TLFZ, Tanlu Fault Zone; ZPFZ, Zhangjiakou, Penglai Fault Zone. (b) Map of the tectonic framework of Liaodong Bay Depression. The yellow box is the location of **Figure 3**. Abbreviations are as follows: LXS, Liaoxi Sag; LXNS, Liaoxinan Sag; LZS, Liaozhong Sag; LDS, Liaodong Sag; QNS, Qinnan Sag; BZS, Bozhong Sag; BDS, Bodong Sag; LXNU, Liaoxinan Uplift; LXU, Liaoxi Uplift; LDU, Liaodong Uplift; SJTU, Shijiutuo Uplift. **(C)** Map of the tectonic framework of the northern margin of the North China Craton Modified from (Deng et al., 2007; Liu et al., 2015) Abbreviations are as follows: F1, Shangyi; Pingquan fault; F2, Zhangjiakou fault; F3, Qianxi fault; F4, Chengde fault.

which there are seven main NNE-directed faults, and the secondary fault directions are diverse (Cheng et al., 2015; Nan et al., 2015; Xu et al., 2015; Wu et al., 2016; Li et al., 2018).

The Yanshan orogenic belt (YOB) is located west of the Liaodong Bay subbasin. The western and central parts are characterized by nearly E-W- and WNW-directed compressional structures (Davis et al., 1998; Davis et al., 2001; Zhang et al., 2001; Ge et al., 2014; Wang et al., 2018a; Wang et al., 2018b), e.g., the Fengning-Longhua fault and Shangyi-Pingquan fault (Liu et al., 2004; Liu et al., 2018), and the Shangyi-Chongli-Chicheng fault (Zhang et al., 2006), which developed across Chengde, Luanping and Zhangjiakou Cities, Hebei Province, and Northern China.

In summary, although the research on the YOB (Davis et al., 2001; Zhang et al., 2001; Zhang et al., 2006; Cope et al., 2007; Zhang et al., 2011; Li et al., 2019; Li et al., 2021a) and Liaodong Bay subbasin (Cheng et al., 2015; Xu et al., 2015; Liu et al., 2016; Hu et al., 2018; Li et al., 2018; Li et al., 2021b) has achieved much progress and scientific understanding in previous studies, there are few results that are related to the origin of the WNW-directed faults. Regionally, the Liaodong Bay subbasin is located east of the YOB and is related to the E-W-directed tectonic system of the YOB in the extensional direction; thus, there may be an evolutionary and genetic relationship between them. It is suggested that the large-scale WNW-directed Zhangjiakou-Penglai Fault Zone (ZPFZ) developed north of the NCB and passes through the YOB, BBB, and Tan-Lu Fault Zone (TLFZ) (Wang et al., 2005; Suo et al., 2013; Guo et al., 2015; Peng et al., 2018). However, the ZPFZ traverses the middle of the BBB (Fu et al., 2004; Suo et al., 2013; Guo et al., 2015; Peng et al., 2018), and there have been no previous, relevant discussions regarding the WNW-directed fault system in the Liaodong Bay subbasin.

In this study, the fault system and stratigraphic features were explained in detail based on the latest 3-D seismic data. More importantly, WNW-directed fault systems were first recognized in the southern Liaodong Bay subbasin. The spatial geometries and temporal evolution processes were systematically investigated, and the genetic mechanisms were discussed. This study provides new evidence for the existence of the WNW-directed fault in the northern NCB and is conducive to clarifying the tectonic evolution and transition mechanism of the Liaodong Bay subbasin and even the entire eastern part of the NCB and will provide a reference for hydrocarbon exploration in the Liaodong Bay subbasin.

GEOLOGICAL SETTING

The Liaodong Bay subbasin is located in the northeastern Bohai Sea, which is a part of the BBB, and is situated in eastern offshore China (**Figure 1A**) and consists of a Mesozoic-Cenozoic superimposed basin that developed on a Paleozoic platform (Chang, 1991; He and Wang, 2003; Qi, 2004; Qi and Yang, 2010; Zuo et al., 2011). The numerous faults in different regions of the Bohai Sea differ greatly in their orientations: (1) in the Bozhong subbasin, the faults mainly strike NE, NEE, and WNW (Sun et al., 2008); (2) in the Bodong subbasin, the faults mainly strike NNE, NE, and NEE (Wu et al., 2013); (3) in the Bonan subbasin, the faults mainly strike WNW, EW, and NNE (Zhang et al., 2017; Liu et al., 2020); and (4) in the Liaodong Bay subbasin, the faults mainly strike NNE and NE (Cheng et al., 2015; Li et al., 2015; Nan et al., 2015; Xu et al., 2015; Li et al., 2018; Hu et al., 2018) (**Figure 1B**). These faults with different directions controlled the formation and evolution of the Bohai Sea in the Mesozoic and Cenozoic and caused differences in basin architectures, hydrocarbon migration, and accumulation in different regions (Qi, 2004; Qi and Yang, 2010; Zuo et al., 2011; Li S et al., 2012).

The TLFZ traverses the eastern part of the Bohai Sea (**Figure 1A**) and now acts as a right-lateral strike-slip zone. It consists of several NNE-directed, steeper erect basement faults. The TLFZ controls the structural deformation and basin evolution of its interior and nearby areas and causes obvious transformations in these areas. The TLFZ exhibits obvious segmentation along the distribution direction in the Bohai Sea and can be divided into the Liaodong Bay segment, Bodong segment, and Bonan segment. From north to south, the TLFZ gradually widens, and the number of faults gradually increases (Deng, 2001; Hu et al., 2003; Wang et al., 2006; Gong et al., 2007; Wan et al., 2009).

The YOB is located north of the NCB and to the northwest of the Bohai Sea. It can extend westward to Baotou, Inner Mongolia, with a total length of over 1100 km (Xu and Liu, 2017). The YOB is characterized by folds and reverse faults, and the distribution directions of the structures are mainly E-W (in the west) and NE-NNE (in the east), with a gradual transition between them (**Figure 1C**) (Davis et al., 2001; Liu et al., 2004; Yang et al., 2006; Cope and Graham, 2007; Hu et al., 2010; Liu et al., 2015; Liu et al., 2018).

Since the Late Paleozoic, the NCB, where the Bohai Sea and YOB are located, has experienced plate subduction and continental collision in different directions (Menzies and Xu, 1998; Zhai and Liu, 2003; Zhu et al., 2011; Liu et al., 2013; Liu J et al., 2017; Liu et al., 2018). At the same time, it has been under the joint control of the Tethys tectonic domain, Paleo-Asian tectonic domain, and Paleo-Pacific tectonic domain (Chen, 1998; Dong et al., 2015; Wang et al., 2018a; Liu et al., 2021). The transformations and interactions of the three tectonic domains led to spatial and temporal differences at different stages between the regional dynamic background and local tectonic stress fields. In turn, these factors caused complex structural characteristics, evolution (Meng, 2003; Lin S Z et al., 2013; Meng et al., 2014; Dong et al., 2015; Liu S et al., 2017; Liu et al., 2018), and metamorphic core complexes (Liu et al., 2005; Lin et al., 2008; Davis and Darby, 2010; Wang et al., 2011; Ji et al., 2015; Zhu et al., 2015; Liu J et al., 2017).

Regarding the stratigraphic units, the LDB developed on the Archean and Paleoproterozoic metamorphic crystalline basement, which is consistent with the NCB. The overlying strata consist of Meso- to Neo-Proterozoic shallow sea carbonate and clastic sediments, Cambrian and Ordovician (Ꞓ + O) shallow sea carbonate and clastic sediments, Carboniferous and Permian (C + P) marine to continental transitional sediments, and Mesozoic and Cenozoic continental clastic

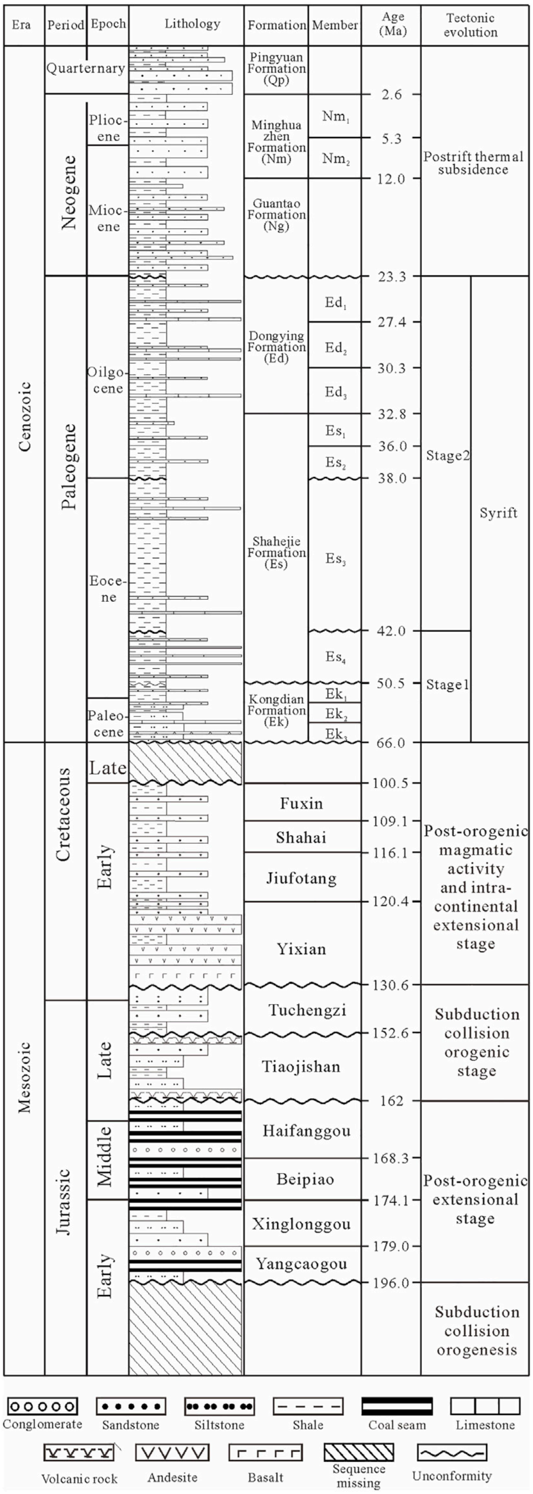

FIGURE. 2 | The Mesozoic and Cenozoic stratigraphic column of the Bohai Sea area (modified from Hsiao et al., 2004; Hu et al., 2018; Huang, 2019; Xi et al., 2019).

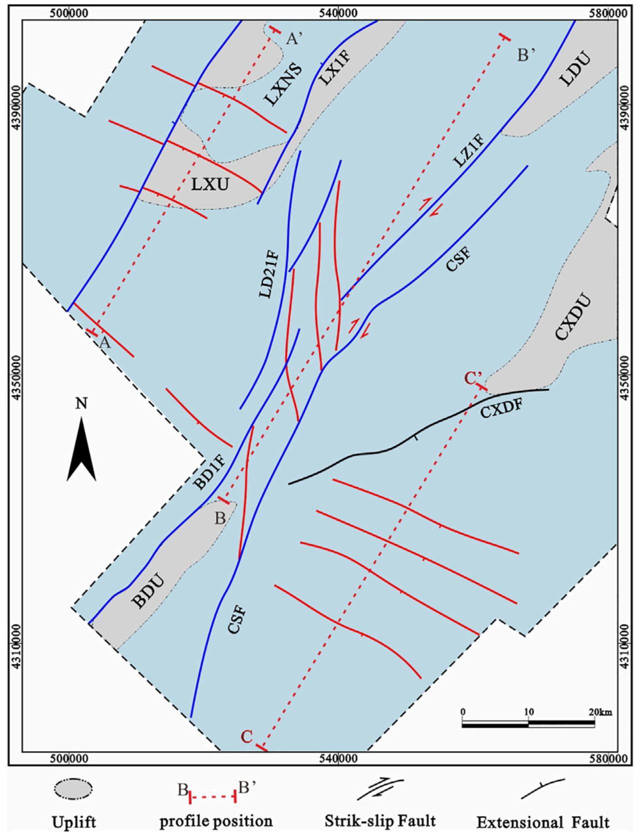

FIGURE 3 | Map of the tectonic framework of the south of Liaodong Bay sub-basin. The position is shown in the yellow box in **Figure 1B**, the dotted line is the section position in **Figure 4**. The NE-directed faults are indicated by blue lines. The WNW-directed faults are indicated by red lines. The NEE-directed fault is indicated by black lines. Abbreviations are as follows: LXNS, Liaoxinan Sag; LZS, Liaozhong Sag; LDS, Liaodong Sag; LXNU, Liaoxinan Uplift; LXU, Liaoxi Uplift; LDU, Liaodong Uplift; BDU, Bodong Uplift; LX1F, Liaoxi 1 Fault; LD21F, Lvda 21 Fault; LZ1F, Liaozhong 1 Fault; CSF, Central Strike, slip Fault; CXDF, Changxingdao Fault; BD1F, Bodong 1 Fault.

sequences. Among these, the Mesozoic and Cenozoic deposits are mainly controlled by fault activity and can be subdivided into two mega-sequences. The Mesozoic mega-sequence can be divided into two sequences: the Jurassic (J) and Lower Cretaceous (K1) (Huang, 2019; Tong et al., 2019; Xi et al., 2019). The Triassic and Upper Cretaceous sequences are missing (Tong et al., 2019; Xi et al., 2019) (**Figure 2**). The Cenozoic is relatively complete in the Bohai Sea and includes Paleogene synrift and Neogene-Quaternary postrift mega-sequences (Hsiao et al., 2004; Cheng et al., 2015; Nan et al., 2015; Hu et al., 2018). The sediments that were deposited during the syn-rift stage are primary lacustrine formations, which include the Kongdian (Ek), Shahejie (Es), and Dongying (Ed) Formations, and the postrift stage is characterized by the deposition of the Guantao (Ng), Minghuazhen (Nm), and Pingyuan (Qp) Formations (**Figure 2**) (Hsiao et al., 2004; Hu et al., 2018).

DATA AND METHODS

This study is based on 3-D seismic reflection data that were provided by the Tianjin Oil Company Ltd., CNOOC (China

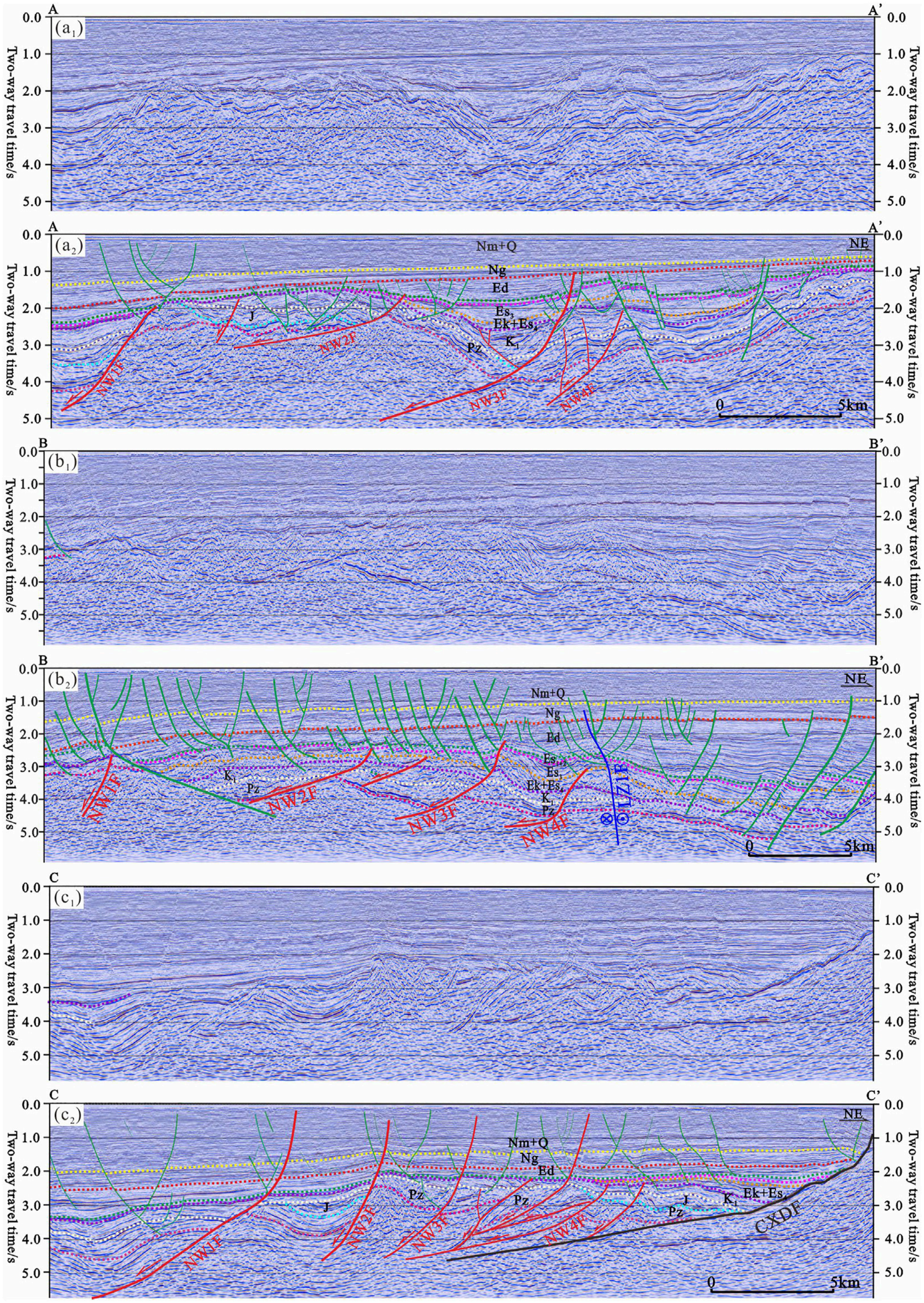

FIGURE 4 | (a1) Uninterpreted and **(a2)** interpreted versions of SW-NE-direction seismic profile of A-A'. **(b1)** Uninterpreted and **(b2)** interpreted versions of the SW-NE-direction seismic profile of B-B'. **(c1)** Uninterpreted and **(c2)** interpreted versions of the SW-NE-direction seismic profile of C-C'. See Panel 4 for its location of the faults and profile. The section position was shown by a dotted line in **Figure 3**.

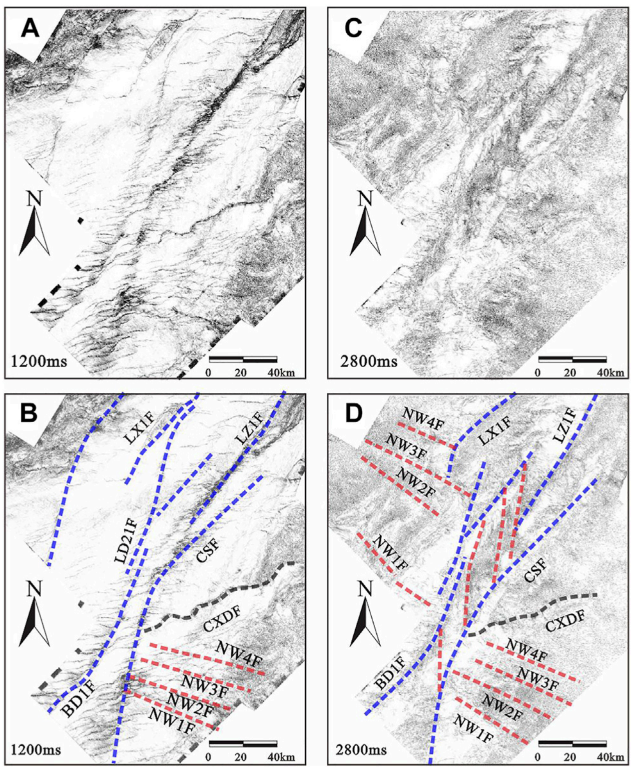

FIGURE 5 | **(A)** Uninterpreted **(A, C)** and interpreted **(B, D)** coherent slices of the southern part of Liaodong Bay Depression, with their locations given in **Figure 3**. Major faults are the same as those in **Figure 3**.

National Offshore Oil Corporation). The 3-D seismic data include an intact seismic cube that was merged by the Tianjin Oil Company Ltd., CNOOC from several seismic cubes. The seismic cube covers an area of approximately 18,000 km^2 with a line spacing of 12.5 m, and it images down to 6.0 s TWT. The 3-D seismic data were also processed by the companies introduced above by using calibrations with several deep wells.

A three-dimensional seismic interpretation was employed to identify and describe the geometry of the WNW-directed faults, and well logging and lithological data were also used to improve the correlations among the seismic reflectors and well data. This was followed by an interpretation of the main, regionally continuous seismic reflections and reflection terminations. The fault activity rate parameters and balanced cross-sections were used to determine the evolution of the WNW-directed faults.

RESULTS

Geometric Characteristics of the WNW-Directed Faults in the Southern Liaodong Bay Subbasin

Detailed seismic data interpretations provide the basis for fault identification in petroliferous basins. Based on the detailed interpretation of the latest seismic data mentioned above, four WNW-directed faults were identified south of the LBD (**Figure 3**).

In this section, these WNW-directed faults mainly developed in the pre-Paleogene and deep Paleogene, with some extending to the Neogene. These WNW-directed faults are mostly characterized by low-angle listric normal faults, with great cutting depths and multiple cutting layers. In some segments, the WNW-directed faults and other secondary faults comprise multiple Y-shaped or negative flower-shaped structures (**Figure 4**), so we infer that these WNW-directed faults are probably transtensional faults. In addition, some of the WNW-directed faults are terminated by NE- or ENE-directed faults, which indicates that the WNW-directed faults formed earlier than the NE- or NEE-directed faults.

In the plane view, the seismic coherency time slices reveal that (1) the WNW-directed faults are discontinuous and are cut by the NNE-directed Lvda-21 Fault (LD21F) and Central Strike-slip Fault (CSF). (2) The WNW-directed faults are mainly distributed on both sides of the NNE-directed strike-slip faults. However, between the LD21F and CSF, those faults become N-S-directed. (3) The WNW-directed faults are relatively apparent at depth, with a parallel orientation. In the shallow layers, the WNW-directed faults were barely detected on both sides of the CSF and LD21F (**Figure 5**).

Stratigraphic Units Controlled by WNW-Directed Faults

The seismic reflection analysis shows that the strata controlled by the WNW-directed faults in the local area mainly include the Є + O, C + P, J, K1, and Ek to the fourth member of Es (Ek-Es4) and the third member of Es to Ed (Es3-Ed). The Є + O and C + P are characterized by continuous parallel high-amplitude seismic reflections, which gradually thin toward the WNW-directed faults (**Figure 4**). The Jurassic is characterized by mid-continuous high-amplitude seismic reflections, which gradually overlap and thin toward the WNW-striking faults (**Figure 4**). The Lower Cretaceous is characterized by basinward prograding discontinuous, low-amplitude chaotic seismic reflections that are thick and generally wedge-like, which gradually overlap and thin toward the WNW-striking faults (**Figure 4**). The Ek-Es4 sequence consists of chaotic, low-amplitude, discontinuous seismic reflections that are locally developed in the deep depression areas (**Figures 4A,B**). Es3-Ed is widely deposited in the LDB but in local areas, it is controlled by WNW-directed faults (**Figure 4A**).

In addition, the Jurassic-Paleozoic and Lower Cretaceous units exhibit two opposite wedges and when combined with the characteristics of the seismic reflections, suggest that WNW-directed faults may have undergone structural inversion.

Regional Geophysical Evidence for the Existence of WNW-Directed Faults in the Southern Liaodong Bay Subbasin

Apart from the properties indicated by the 3-D seismic reflection data, the Bouguer gravity anomalies, aeromagnetic anomalies,

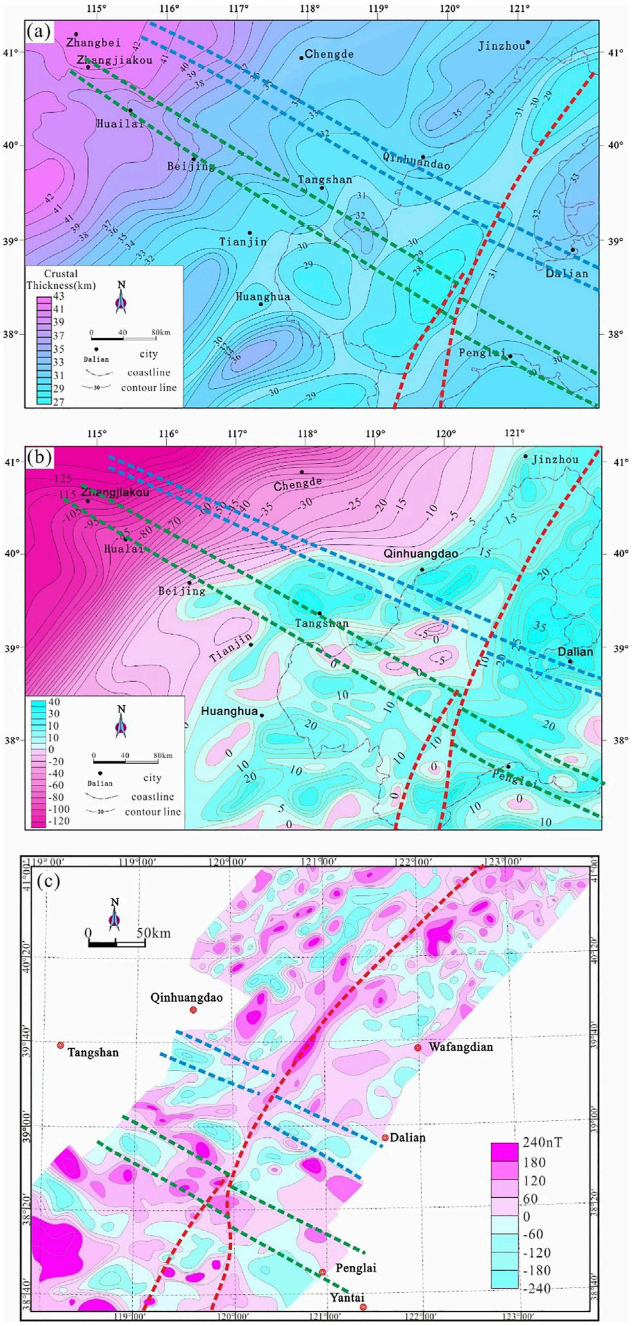

FIGURE 6 | Crustal thickness isopach map **(A)**, Bouguer gravity anomaly isopach map **(B),** and aeromagnetic anomaly isopach map **(C)** in the Bohai area and adjacent area. The red, green, and blue dotted lines, respectively, represent the TLFZ, the ZPFZ, and the QLFZ (Qi et al., 2010).

and crustal thicknesses also effectively reveal the existence of WNW-directed faults. (1) On the crustal thickness isopach map, along Chengde to Qinhuangdao, the contour trend changes from NE to NW. To the east of Qinhuangdao, two NE-trending Moho high values are separated (**Figure 6A**), and the separation belt extends southeast to Dalian. (2) On the Bouguer gravity anomaly map, the contour trend changes from NE to NW near Qinhuangdao. To the south of Qinhuangdao and Dalian, although the anomaly contours are complex, a NW-trending separation belt still exists (**Figure 6B**). (3) On the aeromagnetic anomaly map, NNE-NE-trending beading, such as positive anomaly zones, indicates the existence of the TLFZ (**Figure 6C**). On both sides of the NNE-NE-directed positive anomaly zone and south of Qinhuangdao and Dalian, the anomaly contours are clearly WNW-NW oriented.

Based on the above analysis, the presence of WNW-directed faults in the southern Liaodong Bay subbasin can be inferred. In previous studies, the Liaodong Bay subbasin and Bodong-Bozhong subbasin were thought to be separated by the WNW-directed Dalian-Qinhuangdao (Gong et al., 2007) or Qinhuangdao-Lvshun fault zone (Zhan et al., 2013), which contributed to confirming the existence of the WNW-directed faults in the southern Liadong Bay subbasin.

DISCUSSION

Kinematics of the WNW-Directed Faults in the South Part of the Liaodong Bay Subbasin

Previous studies have suggested that the NNE- and NE-directed faults were the main basin-controlling faults in the Liaodong Bay subbasin, and their formation mechanism has been discussed in detail (Hsiao et al., 2004; Xu et al., 2015; Hu et al., 2018; Li et al., 2018). In contrast, the WNW-directed faults in the Liaodong Bay subbasin are rarely mentioned, which contain significant information regarding the regional tectonics. Therefore, an integrated investigation of the kinematics of the WNW-directed faults is overdue. By combining the dip-slip faulting rates, balanced cross-sections, and newly published geological evidence, the evolution of these faults and their coupling relationships to the surrounding plates were discussed.

Thrusting Stage During the Late Triassic and Jurassic

The WNW-directed faults were initiated during the Late Triassic of the Mesozoic era, and the negative fault activity rate suggests that these faults are reverse faults (**Figures 7**, **8H**). Since the Middle Triassic, the Yangtze Plate has experienced the subduction of the southern Tethys Plate, which gradually strengthened in the Late Triassic (Lv et al., 2003; Hacker et al., 2009). This subduction event led to northward drifting of the Yangtze Plate, which ended up colliding with the NCB (Li et al., 2007; Li et al., 2013). After this collision, the Yangtze Plate continued to move northward with the NCB. Previously, the NCB collided and was spliced with the Siberian Plate during the Late Paleozoic, and the Mongolia-Okhotsk Ocean closed (Kravchinsky et al., 2002), so the northern margin of the NCB became a fixed boundary in the Late Triassic. From that time, the NCB experienced SSW- or SN-directed horizontal extrusion (Davis et al., 2001; Liu et al., 2012; Kim and Ree, 2013), which caused an overall uplift of the NCB that was accompanied by erosion of the Lower-Middle Triassic strata. Apatite fission track

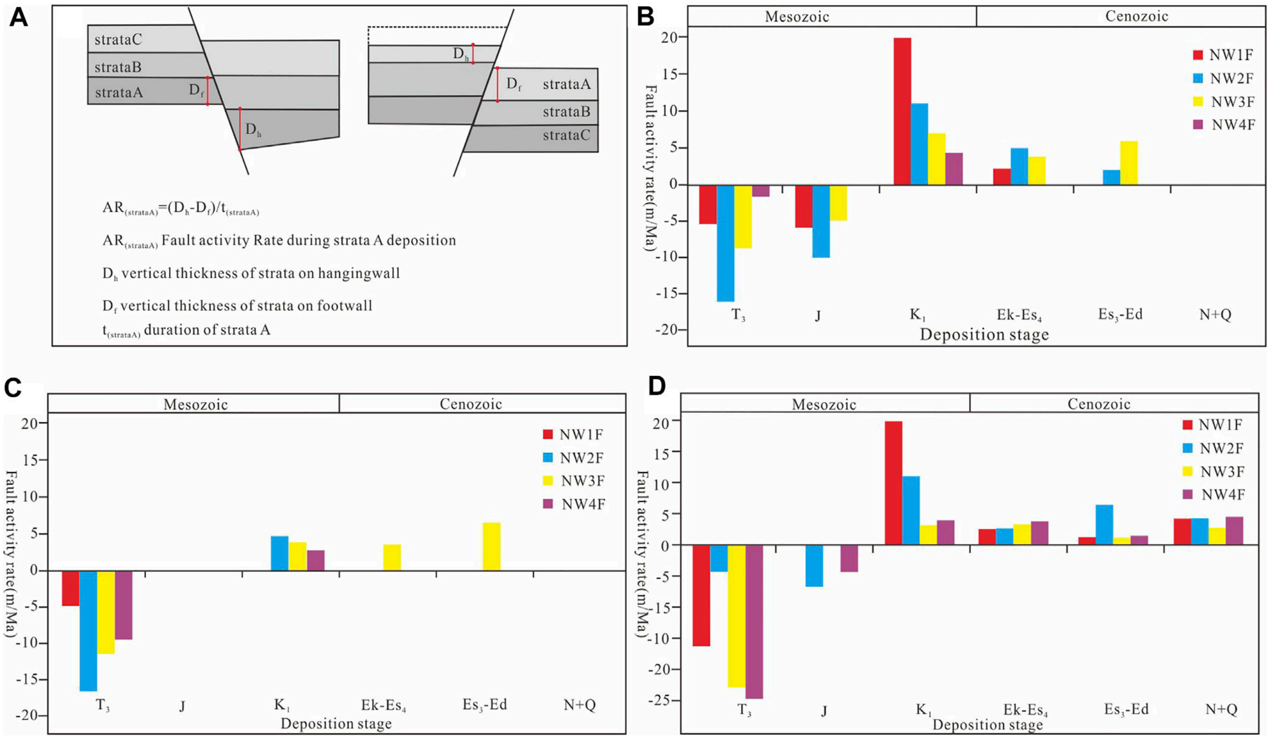

FIGURE 7 | (A) Map showing how the faulting activity rate is measured. Fault activity rates of the WNW-striking faults in different areas (the western **(B)**, central **(C),** and eastern **(D)** part of Liaodong Bay subbasin) during different periods are shown **(B–D)**.

analysis of the samples from the Huanghua depression reveals uplift and cooling in the Late Triassic (239–200 Ma) and Jurassic (160–140 Ma) (Wu et al., 2020). The zircon shrimp dating of the inner-basin debris also shows 2 orogenic events in that period (Zhu et al., 2020). All the above results indicate a compressional stress field. Meanwhile, a series of compressional structures developed in the NCB, which included the embryonic form of WNW-directed faults that exhibited thrust faulting signatures.

During the Jurassic (196–136 Ma), the tectonic setting of eastern China transformed from the Tethys domain to the marginal Pacific domain; subsequently, Paleo-Pacific tectonics dominated the evolution of eastern China (Zhao et al., 2004; Zhang et al., 2007; Wang et al., 2018a). At that time, North China experienced a complicated convergent process between the Eurasian and Paleo-Pacific Plates, along with variations in the convergence directions, rates, and subduction angles of the slab. This dynamic background caused a weakened SSW or N-S horizontal contraction. New geochronological data reveal that the strata that were previously considered to be Late Jurassic should belong to the Early Cretaceous, which indicates that the Jurassic strata in the study area were deposited earlier than ~136 Ma (Zhang et al., 2019). As a result, the NCB experienced intracontinental deformation, and the WNW-directed faults in the Liaodong Bay subbasin retained their reverse faulting characteristics (**Figures 7, 8G, 9B**). Consequently, the region evolved into a fold-thrust belt-induced flexural basin system and a high-standing block (horst)-rift-basin system (Liu S et al., 2017), which is consistent with the contemporaneous development of thrust nappe structures and molasse formation (Dong et al., 2013).

Extension Stage During the Early Cretaceous

The tectonic contraction in the Jurassic extended into the earliest Early Cretaceous (Meng, 2003; Liu J et al., 2017) and from approximately 136 Ma, the regime changed to extension (Cheng et al., 2018). Lithospheric thinning occurred underneath the NCB (Yang, 2003; Zhai et al., 2007; Zhu et al., 2011; Wu et al., 2014) and led to the formation of widespread and intensive extensional structures (**Figure 9C**). Meanwhile, some metamorphic core complexes and extensional domes developed in Yanshan and southern Liaoning Provinces, such as the Fangshan magma dome (Shan et al., 2006; Yan et al., 2006), Yunmengshan core complex (Zhu et al., 2015), Kalaqin extensional dome (Lin et al., 2014), Waziyu core complex (Zhang et al., 2012), and Linglong extensional dome (Lin W et al., 2013). The isotopic ages of these structures are constrained to between 135 and 129 Ma. Analysis of volcanic rocks and debris in the BBB also shows that there were 2 ages of volcanic rocks (e.g., 125–120 Ma and 110–100 Ma)., which indicated that regional extension occurred in the Early Cretaceous. In addition, the NNE-directed TLFZ experienced large-scale sinistral shear at the beginning of the Early Cretaceous (Zhu et al., 2005), which could have been derived from NNE- or SN-directed extension. Under the joint control of the deep dynamic

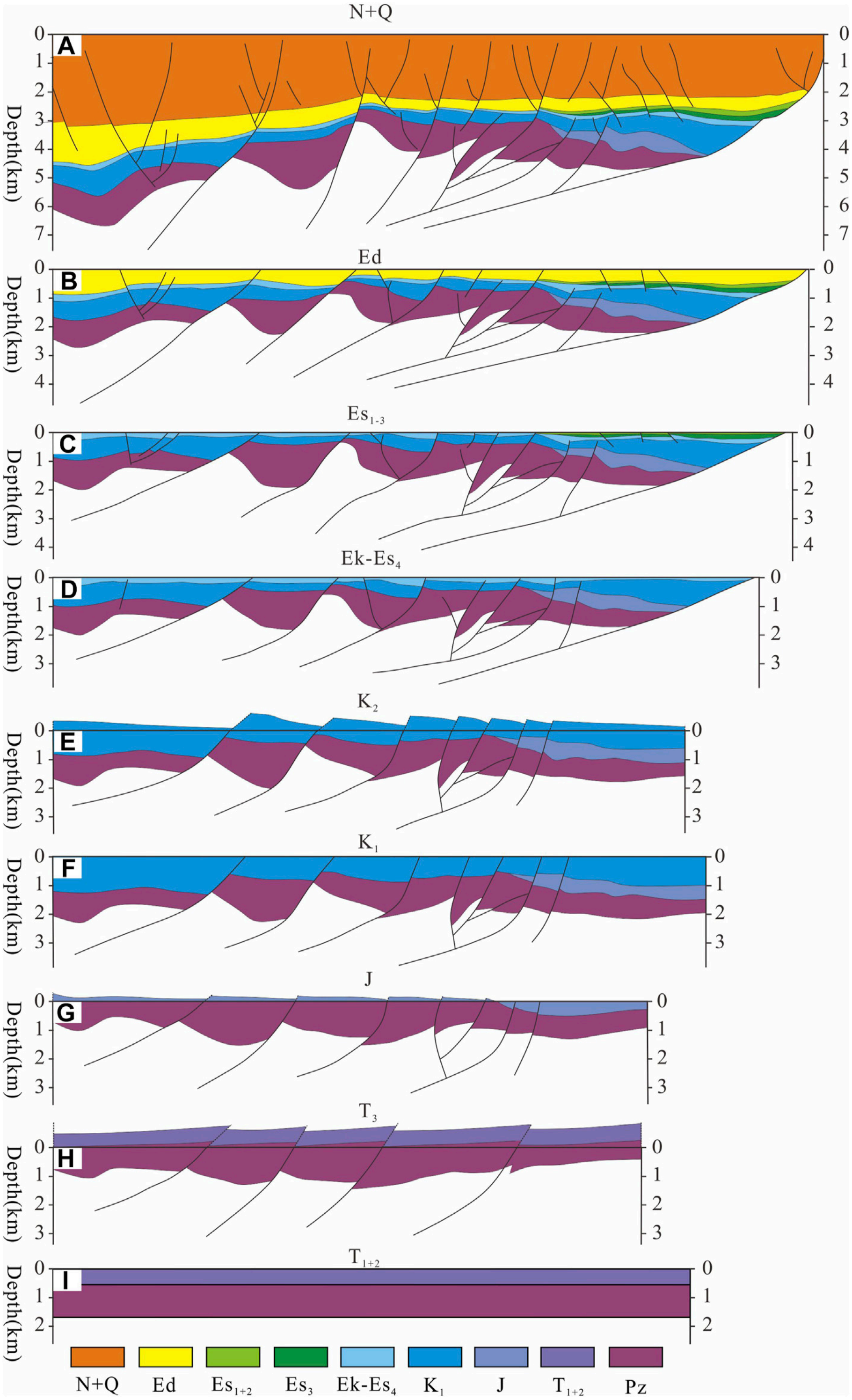

FIGURE 8 | The balanced cross-section restoration of line C-C'. **(A)** Seismic line C-C′ converted to depth. **(B)** Entire converted section restored to the Ed sequence. **(C)** Entire converted section restored to the $Es_{1\text{-}3}$ sequence. **(D)** Entire converted section restored to the Ek-Es_4 sequence. **(E)** Entire converted section restored to the erosion of the K_2 sequence. **(F)** Entire converted section restored to the K_1 sequence. **(G)** Entire converted section restored to the J sequence. **(H)** Entire converted section restored to T_3 compression. **(I)** Entire converted section restored to T_{1+2}. See **Figure 3** for its location.

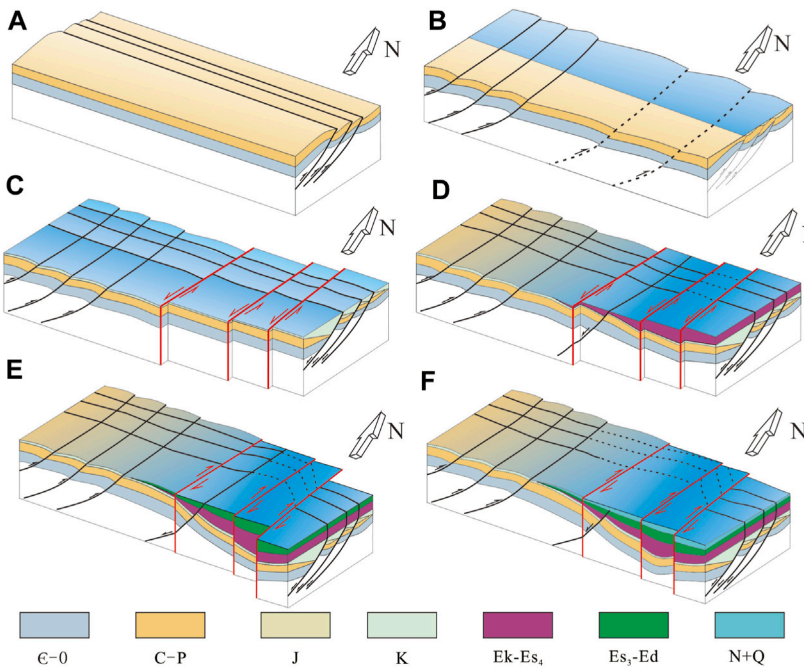

FIGURE 9 | The evolution pattern WNW-directed fault in the study area at different evolutionary stages. **(A)** The Late Triassic, **(B)** the Jurassic, **(C)** the Early Cretaceous, **(D)** the Paleocene and the Early Eocene, **(E)** the Middle Eocene-Oligocene, **(F)** the Neogene, and Quaternary.

background and shallow NNE-directed extension derived from the left-lateral movement of the TLFZ, the early WNW-directed faults were transformed into normal faults, with large amounts of displacement (**Figures 7**, **8F**, **9C**).

Thrusting Stage During the Late Cretaceous

During the Late Cretaceous (93.9–65 Ma), a new lithospheric mantle formed under the NCB (Wu et al., 2014). The gravitational influence of the newly formed lithosphere caused contraction of the shallow crust and thus superimposed the compression on the early extensional fault basin (Ying et al., 2006). At the same time, the Izanagi Plate in the Western Pacific Ocean was completely subducted under the Eurasian Plate in the Late Cretaceous (85 Ma), and the WNW-ward subduction of the Kula Plate (Zhang et al., 2008) caused the transformation of the regional stress field in the NCB into nearly NW-SE compression (Li S Z et al., 2005; Li W et al., 2005). Thus, the Early Cretaceous extensional fault basins were inverted under the regional contraction regime. A certain number of reverse faults and folds developed, such as the Chengbei-20 Fault in the Jiyang depression and Cangxian uplift in the Huanghua depression (Zhou et al., 2003; Li and Gao, 2010; Li et al., 2021a). In the study area, the WNW-directed faults ceased their normal faulting motions, and some local segments were transformed into thrust faults (**Figure 8E**). From a regional tectonics standpoint, this interpretation is also evidenced by a regional tectonic inversion event that occurred between 90 and 65 Ma in the Hailaer, Songliao, and Sanjiang Basins in Northeast China (Liu S et al., 2017; Liu et al., 2020). Meanwhile, this event is synchronous with the extensive fold development and striking angular unconformity within most of East Asia (Liu et al., 2020), which demonstrates an extensive compressional deformation history during the Late Cretaceous.

Reactivation and Extension Stage During the Cenozoic

During the Paleogene (66–23 Ma), deep mantle upwelling caused extension in the shallow crust, and the WNW-directed faults were reactivated locally.

During the depositional period of the Ek-Es4 sequence (e.g., Paleocene to Early Eocene), the motion along the TLFZ still consisted of sinistral shear (Hu et al., 2003). Some pre-existing WNW-directed faults were reactivated and controlled the lacustrine deposition (**Figures 7**, **8D**, **9D**), which indicates the inheritance of the Early Cretaceous tectonics (Hou and Hari, 2014). In addition, the main WNW-directed faults in the middle part of the BBB have similar characteristics, such as the Jiyang subbasin (Cheng et al., 2018; Liu et al., 2020), Chengbei subbasin (Liu L et al., 2019), and Huanghekou and Laizhouwan subbasins (Zhang et al., 2017), which reflect the prevalence of WNW-directed fault inheritance and reactivation during the Paleocene to early Eocene.

Since the Middle Eocene (the depositional period of the Es3-Ed sequence), the subduction direction of the Pacific Plate changed to WNW-directed, and the motion of the TLFZ then transformed into dextral shear (Zhu et al., 2021), which was derived from NW-directed extension and NE-directed compression. Since the direction of the derived compression was vertical to the WNW-directed faults, the activity of the WNW-directed faults weakened and gradually stopped

(**Figures 7**, **8B**,**C**, **9E**). Instead, NNE-directed faults began to activate and became the main basin-controlling faults in the Liaodong Bay subbasin (Hu et al., 2003). Consequently, the NNE- and NE-directed faults cut across the WNW-directed faults and reconstructed the previous tectonic patterns (**Figure 9E**). Additionally, due to the right-lateral strike-slips of the NNE-directed faults, the strikes of the WNW-directed faults between the Lvda21 and Central Strike-slip faults changed in the N-S direction (**Figures 3** and **5**). Similar to the study area, in the Zhanhua subbasin and Chengbei subbasin in the southeastern BBB, the strikes of the Mesozoic basin-controlling WNW-directed faults also changed to the N-S direction due to the close distance to the TLFZ (Li et al., 2006; Cheng et al., 2015).

During the depositional period of the Neogene-Quaternary sequence (e.g., Miocene-Holocene), the Bohai Sea area entered a postrift thermal subsidence stage, and the subsidence center migrated to the Bozhong sag (**Figure 9F**). Since the depositional period of the upper Minghuazhen subsequence, regional N-S extension (Li L et al., 2012) caused the WNW-directed faults to reactivate (Suo et al., 2013), and the motion was extensional with a sinistral shear sense.

Implications for the Distribution of the WNW-Directed Fault System in the Northern Part of the NCB

When compared with the NNE- and NE-directed faults, WNW-directed faults are not obvious in eastern China and are generally distributed in a dispersed manner (Suo et al., 2013). Previous studies have suggested that a large-scale WNW-directed fault zone developed in the northern NCB, namely, the Zhangjiakou-Penglai Fault Zone (Gao et al., 2001; Xu et al., 2012; Suo et al., 2013) or Zhangjiakou-Bohai Fault Zone (Lai et al., 2004), which is composed of many NW-, WNW-, and nearly E-W-directed faults. These faults in the ZPFZ have mutual cutting relationships with the nearly N-S- and NNE-directed faults. The ZPFZ can be divided into an onshore part in the west and offshore part in the east. The onshore part includes the Zhangjiakou-HuaiLai section and Beijing-Tianjin section, and both of them are located south of the Shangyi-Chicheng-Chongli fault, which is the western section of the southern boundary fault of the YOB (Zhang et al., 2011) (**Figure 1**). The offshore part includes the Bohai section located in the Bohai Sea and Penglai-Weihai section located in the north part of the Shandong Peninsula, and the Bohai section is mainly composed of the Weibei fault, Sha'nan fault, Huanghekou fault, and Laibei fault, all of which are located in the middle of the Bohai Sea area (Gao et al., 2001).

The Liaodong Bay subbasin is in the northern Bohai Sea, while few studies have been conducted on the WNW-directed faults. Based on the regional geophysical data and the offset of the NNE- and NE-directed TLFZ, it is suggested that a WNW-directed fault zone may have developed between the Liaodong Bay subbasin and Bodong-Bozhong subbasin, which is called the Qinhuangdao-Lvshun fault zone (Qi et al., 2004; Li and Hou, 2019). Based on the analysis in this study, we speculate that the WNW-directed faults in the south part of the Liaodong Bay subbasin should extend westward to the YOB and connect inland with the Shangyi-Pingquan fault.

However, the fault properties of the YOB are significantly different from the extensional deformations in the offshore basins. The nearly E-W- and WNW-directed faults in the YOB are generally considered to be reverse faults (Davis et al., 2001; Zhang et al., 2001; Zhang et al., 2011; Cope et al., 2007), while the Liaodong Bay subbasin is typically considered to be a strike-slip and extensional basin (e.g., Wenxian). The differences in the tectonic properties led to a lack of attention to the WNW-directed faults in the study area. In this study, we find that although the WNW-directed faults in the Liaodong Bay subbasin were mainly extensional and strike-slip in the Cenozoic, they had been reversed faults during the Late Triassic and Jurassic (**Figures 7**, **8G**,H), which are consistent with the nearly E-W- and WNW-directed faults in the YOB. The nearly E-W- and WNW-directed reverse faults in the YOB mainly acted during the Mesozoic (Davis et al., 2001; Zhang et al., 2001; Cope et al., 2007; Zhang et al., 2011) and being affected by continuous uplift during the Cenozoic, these faults ceased being active. Based on the above analysis, we speculate that the formation mechanism and evolution of the WNW-directed faults in the Liaodong Bay subbasin are similar to those in the YOB. In addition to the ZPFZ, another nearly WNW-directed fault zone should be present in the northern NCB along Jining-Shangyi-Pingquan and Qinhuangdao-Lvshun.

Implications for Hydrocarbon Exploration in the Southern Liaodong Bay Subbasin

Previous exploration efforts have confirmed the potential for oil and gas accumulations in the southern Liaodong Bay subbasin (Jia et al., 2018). The oil-source correlation analysis shows that these oils were derived from the source rocks of the Es1 and Ed3 strata. Hydrocarbon migration and accumulation primarily occurred during the depositional period of the Ed and N + Q sequences (Xu et al., 2011; Wang et al., 2014; Teng et al., 2016). As one of the hydrocarbon-rich depressions in the Bohai Sea, the Liaodong Bay subbasin has witnessed discoveries of several large and medium oil and gas fields, such as LD27, LD21, and LD16. After decades of exploration, the level of oil and gas exploration of the Paleogene reservoir in the Bohai Sea has been relatively high, and the pre-Paleogene reservoir is now the focus and hotspot of exploration in the BBB (Tong et al., 2012; Zhao et al., 2015; Xu et al., 2019). To date, hydrocarbon accumulations in the volcanic rocks of the Mesozoic and carbonates in the Paleozoic have been found in the Liaodong Bay subbasin, north of the BBB. However, until now, only 10 buried hill reservoirs have been discovered in the Bohai Sea (Deng, 2015), and the degree of exploration is significantly lower than that of the Cenozoic.

In this study, the WNW-directed faults that formed in the Mesozoic were discovered south of the Liaodong Bay subbasin. In addition, the residual strata of the Mesozoic and Paleozoic were revealed based on their seismic reflection characteristics. Thus, we speculate that the southern Liaodong Bay subbasin has a stratigraphic basis for the formation of buried hills. Moreover,

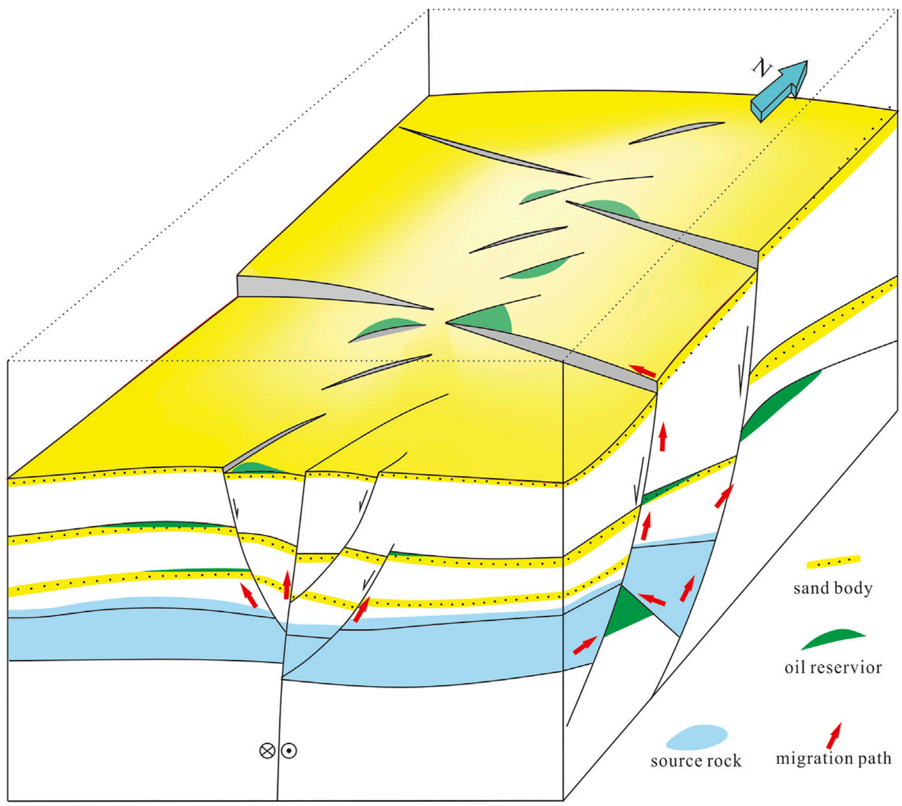

FIGURE10 | Diagram showing the hydrocarbon accumulation under the control of newly identified WNW-directed faults in the southern Liaodong Bay Depression.

the multistage reverse movements along the WNW-directed faults caused the formation of multiple angular unconformities during the uplift and erosion stages, which significantly improved the physical reservoir properties (Tian and Jiang, 2008). These tectonic activities simultaneously resulted in the formation of effective traps (**Figures 4** and **10**). In terms of hydrocarbon migration, the unconformities provide long-term continuous migration pathways (Zhao et al., 2015). Oil and gas can migrate from the hydrocarbon generation centers to the highpoints of the buried hills through extensional faults and these key unconformities. In addition, the late, active NNE-directed strike-slip faults can effectively seal the oil and gas accumulations. Based on the aforementioned analysis, buried Mesozoic and Paleozoic hills can be the subsequent exploration domain in the future (**Figure 10**).

Another issue worthy of attention is the distribution of oil and gas in the study area. At present, it is believed that oil and gas accumulations are abundant along the TLFZ, which has been confirmed by the exploration results (Gong et al., 2007; Zhu et al., 2019). However, drilling failures occurred during the exploration of structural traps along the TLFZ. Previous research has revealed the superior genetic potential of the source rocks in the southern part of the LBD (Huang et al., 2013). The key factor for hydrocarbon accumulations is whether there are effective traps and sealing faults. The NNE-directed strike-slip faults in the southern part of the LBD did not have a simple linear distribution but were slightly bending (**Figures 3** and **5**). The Late Paleogene to Neogene was a key period for oil accumulation. When the NNE-directed strike-slip faults mainly exhibited dextral shear, the WNW-directed faults exhibited sinistral shear (Suo et al., 2013; Peng et al., 2018). These two sets of strike-slip faults with conjugate strikes and opposite patterns simultaneously formed a conjugate strike-slip transition zone (**Figure 10**). Both the bending and the conjugation of the main strike-slip faults could result in local extension and compression, between which compression was conducive to the formation of fault gouges, so the permeabilities were lower, which contributed to the preservation of oil and gas (Wang et al., 2016). Previous studies have suggested that compressional strike-slip transfer zones or strike-slip derived structures are favorable locations for hydrocarbon accumulations and could therefore easily form large- and medium-sized oil and gas reservoirs (Xu, 2016). Therefore, in future exploration efforts, not only fine-scale seismic interpretations but also local stress field analyses are required, especially in the locations of extensional and compressional zones, which should be specified.

CONCLUSION

1) Four WNW-directed faults developed south of the Liaodong Bay subbasin and are mainly distributed on both sides of

NNE-directed strike-slip faults, with poor continuity and parallel orientations and controlled the deposition of the Jurassic and Lower Cretaceous strata of the Mesozoic and Ek-Es4 of the Cenozoic. Between the two NNE-directed strike-slip faults, the faults controlling the Mesozoic and Ek-Es4 are nearly N-S-directed instead of WNW-directed.

2) The WNW-directed faults in the south part of the Liaodong Bay subbasin initially were reverse faults beginning in the Late Triassic. During the Jurassic, these reverse WNW-directed faults became less active. The WNW-directed faults transformed into normal faults in the Early Cretaceous with intensive activity. During the Cenozoic, the WNW-directed faults were reactivated as normal faults during the depositional period of the Ek-Es4 sequence and then gradually became inactive.
3) The formation mechanism and evolution of the WNW-directed faults in the Liaodong Bay subbasin are similar to those in the YOB. In addition to the ZPFZ, another nearly E-W- and WNW-directed fault zone should be developed in the northern part of the NCB along Jining-Shangyi-Pingquan and Qinhuangdao-Lvshun.
4) The development of WNW-directed faults in the southern Liaodong Bay subbasin is conducive to the formation of buried Mesozoic and Paleozoic hills and hydrocarbon accumulations. In addition, we suggest that the compressional segment of the conjugated strike-slip transition zone that formed by the interaction of the WNW- and NNE-directed strike-slip faults is conducive to hydrocarbon accumulations.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

W.L.: Conceptualization, methodology, writing-original draft; M.M. and T.Z.: Methodology, software, writing-reviewing and editing; X.C., Y.L., and D.W.: Revising the manuscript critically for important intellectual content; C.N. and H.Y.: Acquisition of data; supervision.

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Conflict of Interest: Author ZT, NC and YH are employed by CNOOC.

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