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RESEARCH ARTICLE

Mesozoic-Cenozoic extension of the Bohai Sea: contribution to the destruction of North China Craton

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Abstract The Bohai Sea is a Late Mesozoic-Cenozoic feature of the basin-mountain system located in eastern North China Craton (NCC). The Late Mesozoic thinning of the lithosphere signals the early destruction of the NCC. The onset of the destruction was due to the delamination of thick lithosphere of the craton, represented by the NW-trending grabens in an en-echelon arrangement west to Tanlu Fault, and by the NNE-trending grabens within the Tanlu Fault Zone. The Late Mesozoic NW-trending grabens are overprinted by structures related to the Cenozoic NE-trending pull-apart basin with very thick Mesozoic-Cenozoic sediments in the eastern NCC. *C*-frequency diagrams of growth faults and the extension factor (β) of four sections across the basin suggest that the extension migrated from the margin to the center of Bohai Sea, and that the Mesozoic and Cenozoic extension factors for Bohai Sea are higher than that of the margin. These evidences suggest that the greatest extension occurred in the center of Bohai Sea, which is consistent with the thinnest crust being found in the center of the sea. The extension ratios and tectonic evolution of the Bohai Sea suggest that it is the key region for the destruction of the NCC, as evidenced by the topography. However, the NCC experienced two stages of destruction with the late stage related to the tectonic regime of Northeast Asia.

Keywords Bohai Sea, extension, pull-apart, lithospheric thinning, destruction of craton

1 Introduction

The North China Craton (NCC), a stable craton from the Late Archean to the Mesozoic era, which stabilized during the Middle and Neo-Proterozoic eras, is covered by Paleozoic shallow marine sediments (Zhao et al., 2000; Kusky and Li, 2003; Qian, 2004; Zhai et al., 2005; Hou et al., 2006; Kusky et al., 2007; Kusky, 2011; Zhao and Zhai, 2013). The earliest horizontal platform-type Mesoproterozoic sedimentary rocks (Changcheng Group), found on Mt. Taihang, unconformably rest on the Archean crystalline basement of the central NCC. The flat topped mountains with horizontal Paleozoic strata in the western Shandong Province of the eastern NCC suggest that the NCC was stable in the Proterozoic and Paleozoic eras (Li, 1986; Hou et al., 2006).

The Bohai Sea, located in the offshore portion of the North China Basin, is in the thickest center of a Mesozoic and Cenozoic composite basin in the eastern NCC, surrounded by Wutai, Taihang, Luliang, Zhongtiao, Songshan, Taishan, and Yanshan Mountains (Fig. 1 and Fig. 2). These mountains, which constitute the Mesozoic Plateau before the destruction of the NCC, are typical block-faulting ranges, with the exception of Mt. Yanshan which is intraplate orogenic (Chen, 1998; Zhang et al., 2001a, b, c). The majority of the mountains located in the NCC are non-orogenic and develop almost-horizontal Proterozoic-Paleozoic strata which cover the basement of the NCC. Paleo-level surfaces are still preserved at the peaks of the five Wutai Mountains. These mountains and the basins which constitute the North China Basin-Range system are a result of the extension events representing the tectonic configuration of the destruction of the NCC during the Cenozoic era.

The lithospheric thickness of the NCC, where earthquakes and Cenozoic volcanoes extensively occurred, is less than 200 km. In the eastern NCC, where the late Mesozoic-Cenozoic North China Basin developed, the thickness is less than 100 km (Lin et al., 2005). The Precambrian lower crust of the NCC underwent a long history of geological evolution and was mostly replaced by the present lower crust in the Mesozoic era (Zhai et al.,

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2007; Zhao and Zhai, 2013). These evidences suggest that the NCC is a reactive craton that was destroyed during the Mesozoic era (~220 Ma) (Gao et al., 2002; Zhu et al., 2012). This destruction aroused great interest in the international geological community raising questions as to the geological time of destruction as well as the exact portion of the NCC involved. The intent of this paper is to answer these questions based on the structural analysis of the Mesozoic-Cenozoic North China Basin.

2 Mesozoic and Cenozoic basins in the eastern NCC

The NCC, China's oldest continental fragment, is composed of three main Archean elements: the Eastern Block, Western Block, and the intervening Central Orogenic Belt (Zhao et al., 2000; Kusky and Li, 2003; Zhai et al., 2005) (Fig. 1). The Eastern and Western Blocks of NCC experienced different evolution in the Mesozoic and Cenozoic with the development of shallow marine basins along the whole margin and terrestrial basins covering the major portion in the early Mesozoic. In the late Mesozoic and Cenozoic, the western NCC was uplifted to become a loess plateau, whereas in the eastern NCC, an extensional basin-range system developed (Zheng et al., 1988; Hou et al., 1998, 2001, 2003).

The North China Basin (also called Bohai Bay Basin), a tectonically active part of the NCC (Li, 1986; Liu, 1987; Hong, 1990; Tian et al., 1992; Hou et al., 2003; Shao et al., 2003; Zhou et al., 2012), is the largest of the Mesozoic and Cenozoic basins in the eastern NCC, and is comprised of a basin-range system located amidst Yanshan Mountain, Taihang Mountain, West Shandong uplift, Jiaodong uplift, and Liaodong uplift (Fig. 2). In order to understand the Mesozoic and Cenozoic evolution of the North China Basin, it is essential to assess and reconstruct destruction events that occurred during that time.

The Cenozoic evolution of the North China Basin has been studied extensively with the research mainly focused on the gravity field, high conductive asthenosphere, thermal history, stress field, onshore structures, and Cenozoic tectonism (Wang et al., 1985; Liu, 1987; Ye et al., 1987; Wang and Wang, 1988; Hong, 1990; Zhao and Windley, 1990; Allen et al., 1997; Hu et al., 2001; He and Wang, 2003; Zhao and Zheng, 2005; Hou et al., 2010; Li et

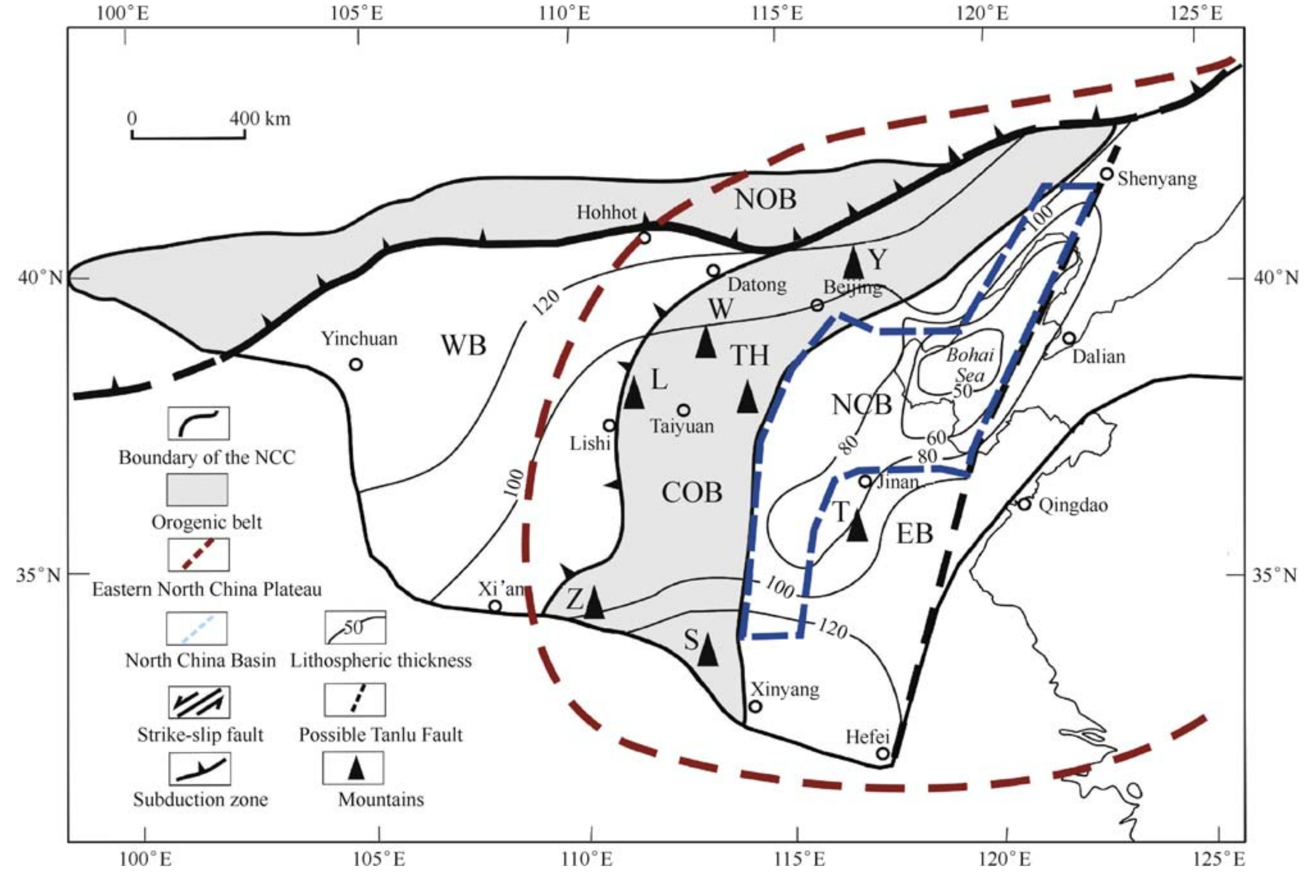

Fig. 1 Tectonic divisions of the North China Craton and the range of the Eastern North China Plateau (sources: Zhang et al, 2001a; Hou et al., 2006). WB, West Block; COB, Central Orogenic Belt; EB, East Block; Y, Mt. Yanshan; W, Mt. Wutai; TH, Mt.Taihang; L, Mt. Luliang; Z, Mt. Zhongtiao; S, Mt. Songshan; T, Mt. Taishan; LD, Mt. Liaodong; JD, Mt. Jiaodong.

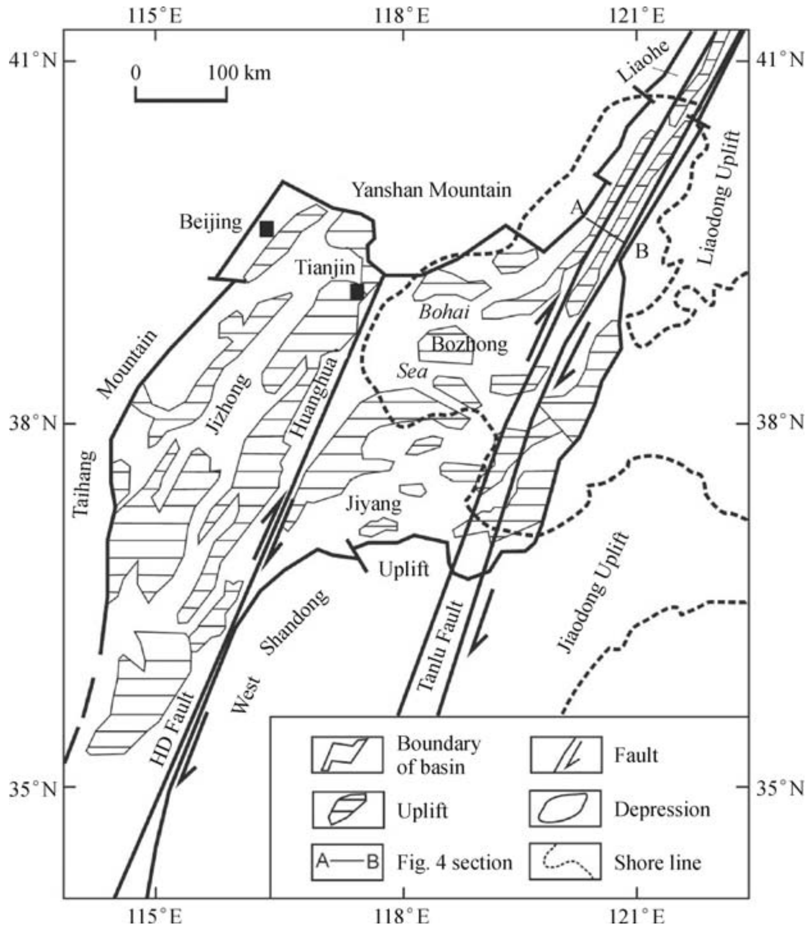

Fig. 2 Basin-range system of the North China Basin (modified after Hu et al., 2001). HD Fault, Huanghua, Dongming strike-slip fault.

al., 2012a, b; Zhou et al., 2012). However, there are many inconsistencies in the conclusions of previous studies which suggest that the North China Basin is complex. The geodynamics of the NCC destruction are still obscured due to limited studies of the Mesozoic geology of the Bohai Sea. The Mesozoic and Cenozoic dynamics of the Bozhong sag remains controversial due to the lack of detailed geological and geophysical data, thus obscuring interpretations of the exact geodynamics of the NCC destruction.

In recent years, the exploration of offshore oilfields generated numerous data and also highly sensitive seismic sections of Mesozoic-structures which prompted a number of comprehensive studies into the Mesozoic and Cenozoic extension of the Bohai Sea. In the present paper, using these data, we attempt to discuss the Mesozoic-Cenozoic tectonic configuration of the eastern NCC and the destruction events of the NCC in response to the tectonic regime of the Northeast Asia.

2.1 Mesozoic basins in the eastern NCC

In the past, oilfield exploration efforts within the Bohai Sea concentrated only on the Cenozoic parts of the basin with little attention given to the Mesozoic parts. Until recently, very few wells were drilled in the Mesozoic strata due to the poor quality of the seismic sections, thus the literature available on Mesozoic strata is very limited (Hou et al., 2001; Qi et al., 2003). As a result, the Mesozoic structural geology of the Bohai Sea has remained ambiguous. However, today many deep wells have been drilled into or through the Mesozoic strata and more sensitive reflection seismic sections have been constructed providing useful information on the Mesozoic basin structure and history.

In the NCC, the cratonic basement consists of Archean and Proterozoic metamorphic rocks that crop out in the west, north, and south of the North China basin. Pre-Mesozoic platform sedimentary rocks consist of stable Cambrian-Triassic strata including Cambrian-Ordovician carbonates and shales (shallow marine facies), and Permo-Carboniferous lake delta and limnic coal-bearing formations (Zhao et al., 2000; Kusky and Li, 2003). Triassic formations are comprised of red clastic fluvial and lacustrine deposits. The depositional environment of the NCC is stable and few volcanic rocks were developed during this period (Lu and Wang, 1997). Pre-Mesozoic structural trends in the craton are dominantly E-W (e.g., the axial orientations of folds) (Lu and Wang, 1997; Wan and Zeng, 2002).

Collision of the NCC and the South China Craton (SCC) in the late Triassic period resulted in the formation of the Qinling-Dabie-Sulu Orogens with the major convergence lasting into the Middle Jurassic period (Yin and Nie, 1996; Meng and Zhang, 1999). The eastern portion of the NCC experienced intra-continental deformation and uplift due to the convergence from the north and south margins during the Early Mesozoic. During the Late Mesozoic and Cenozoic periods, widespread tectonic-thermal activity occurred, which is evidenced by the emplacement of voluminous Late Mesozoic granites and extensive Cenozoic volcanism (Tian et al., 1992; Yin and Nie, 1996; Hou et al., 2003). During the Qinling-Dabie orogenic episode, Late Triassic-Early Jurassic contractional foreland basins were developed in the south of the NCC. For instance, the west-northwest trending Xinyang-Hefei Basin (I) north of the Dabie Orogen and northeast trending Subei Basin (II) and south of the Sulu Orogen, were formed during this period. These Late Triassic-Early Jurassic foreland basins were filled by red molasse formations (Lu and Wang, 1997; Zhu et al., 2005) (Fig. 3).

In the Late Jurassic and Early Cretaceous periods, the Tanlu Fault Zone was very active and several late Mesozoic basins were developed in grabens within the Tanlu Fault Zone and also on its two flanks (Fig. 3). The Mesozoic configuration of the Bohai Sea deciphered from the deep drilling data and new reflection seismic sections are depicted in Fig. 3 and Fig. 4.

Except for the foreland basins in the south of the NCC, the basins located within the east of the craton are of an extensional origin and of Late Mesozoic age. Four Late Mesozoic NW-trending basins (from north to south) were identified west to the Tanlu Fault Zone based on the distribution of the Mesozoic sediments and the orientations of the Mesozoic major faults: the Bohai Sea Basin (III), Jiyang Grabens (IV), Luxi Grabens (V), and Xu-Shi Basins (VI) (Fig. 3). Xu-Shi basins include four sub-basins which would be related to one greater basin. Two identified late Mesozoic basins are the NNE-trending Liaohe Graben (VII) within the Tanlu Fault Zone, and the NE-trending Jiaolai Graben (VIII) east to Tanlu Fault (Fig. 3).

The Jiyang Grabens consist of three narrow grabens and the Luxi Grabens in the western Shandong Province consist of four narrow grabens configured in an en-echelon pattern. The Xu-Shi basins consist of four Late Mesozoic relic depressions from Xuzhou to Shijiazhuang in north-

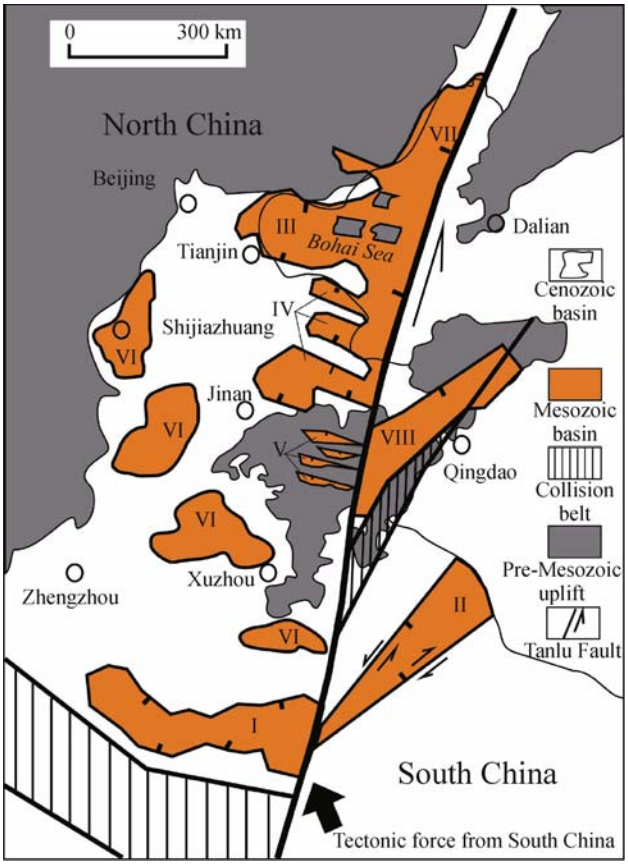

Fig. 3 The distribution of the Mesozoic basins in North China (sources: Hou et al., 2001; and new seismic sections from the offshore oilfield company, 2005). I, Xinyang-Hefei Basin; II, Subei Basin; III, Bohai Sea Basin; IV, Jiyang Grabens; V, Luxi Grabens; VI, Xu-Shi Basins; VII, Liaohe Graben; VIII, Jiaolai Graben.

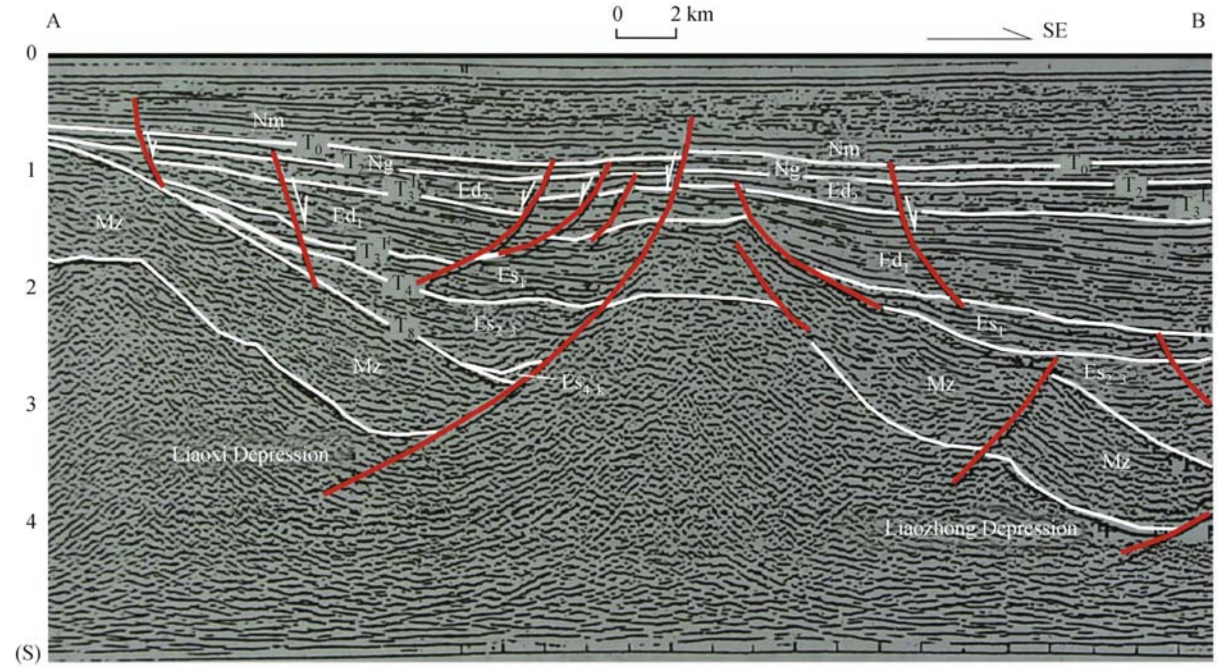

Fig. 4 New seismic reflection section (AB) in the Bohai Sea (source: Bohai Oilfield Company, China).

west orientation and were linked together properly to form one NW-trending basin before the upliftment (Fig. 3). The Late Mesozoic Tanlu Fault Zone is a narrow rift that consists of two grabens and an uplifted section (Xu, 1993; Hsiao et al., 2004) with the NE-trending Subei basin east to Tanlu Fault (Shang et al., 2002) (Fig. 3).

Since the Late Mesozoic period, the eastern NCC has tectonically been very active with widespread volcanism, lithosphere thinning, and the formation of large sedimentary basins (Hou et al., 2003; Zhai et al., 2007; Liu et al., 2008). The Mesozoic parts of the Bohai Sea Basin which were formed during the Late Jurassic and Early Cretaceous periods were characterized by the deposition of sedimentary and volcanic units in an intra-plate rift environment. The Late Jurassic and Early Cretaceous volcanic rocks were controlled by NW-trending major faults west to Tanlu Fault Zone, and by the NNE-trending major faults within the Tanlu Fault Zone (Tian et al., 1992; Hou et al., 2003). These grabens were filled with Late Jurassic tuffaceous sandstone, brown mudstone, and andesitic basalt that were deposited unconformably on the pre-Mesozoic basement (pre-rift sediments). During the Early Cretaceous era, in the eastern NCC, the Qingshan Formation (Kq), consisting of dark gray mudstone, green-gray muddy sandstone, and brownish red sandy conglomerates, interbedded with volcanic rocks and were deposited in differentially subsiding grabens and half-grabens.

Yi and Hou (2002) proposed that Mesozoic major faults controlled the deposition of the Late Mesozoic sediments. These major faults are growth faults which indicate the syn-rift faulting during the Late Mesozoic era (Hou et al., 2001), and are revealed by highly sensitive seismic reflection sections and the distribution pattern of the Late Mesozoic sediments (Fig. 3 and Fig. 4).

It can be seen from the seismic sections of the Bohai Sea that the depocenters of the Mesozoic basins do not fit the Cenozoic basin depocenters. The Mesozoic basins appear to have been of greater lateral extent than the Paleocene basins, but are smaller than the Oligocene and Miocene basins. The Mesozoic basins are seen to have been fragmented by the Cenozoic basins (Fig. 4), thus it can be confirmed that the North China Basin is a superimposed Mesozoic-Cenozoic basin (Fig. 2 and Fig. 3). The NW-trending Late Mesozoic basins have a structural orientation that is distinct from the NE-NEE trending Cenozoic basins of the eastern NCC. The differences between Mesozoic and Cenozoic basins resulted from their development in different tectonic settings and are related to the strike-slip of the Tanlu Fault Zone (Fig. 2 and Fig. 3).

The Early Mesozoic collision between the NCC and the SCC caused intra-continental deformation in the NCC (Yin and Nie, 1996; Zhao and Zheng, 2005). The pre-Mesozoic structural trends in the basement of the NCC are dominantly east-west (Gong et al., 1987; Wang et al., 2005) which is evidence for further convergence between the two cratons accommodated by thrusting in the Dabie and Sulu Orogens during the Early Mesozoic era (Zhang et al., 1989). An orogenic belt developed along the margins of the NCC accompanied by intra-continental deformation. The Tanlu Fault Zone, which moved in a sinistral strike slip for 550 km in the Late Mesozoic era, acted as a transfer zone between these thrust zones (Xu, 1993; Xu et al., 1993;

Ross et al., 1996; Zhu et al., 2005). These Late Mesozoic grabens on the two flanks of the Tanlu Fault Zone suggest that these grabens originated in a transtensional fault zone. The right-handed pattern of the en-echelon grabens west to the Tanlu Fault resulted from the strong sinistral strike-slip of the fault zone, thus, it can be assumed that they were formed in the same tectonic stress field (Fig. 3). Zhu et al. (2012) concluded that the Tanlu fault had played an important role in the destruction of the NCC during the Mesozoic period. The Late Mesozoic extension and rifting of the eastern NCC signaled the onset of the destruction of the NCC.

During the Late Cretaceous period, the Mesozoic rifting stopped, a temporary uplift began, and the North China Basin started experiencing a new phase of extension and rifting since the Paleocene (Hou et al., 2001).

2.2 Cenozoic configuration of North China Basin

The Cenozoic North China Basin developed in the eastern section of the NCC on the site of a Late Mesozoic basin (Hou et al., 2001) with a rhomboidal central area and slender arms that extended to the northeast and southwest areas. This basin is ~1,000 km long with an areal extension of ~200,000 km^2 surrounded by five mountain ranges, namely the Yanshan, Taihang, Zhongtiaoshan, Taishan, and Liaodong (Ye et al., 1987) (Fig. 2). The well-known Tanlu strike-slip fault zone, with its NNE trend, traverses through the eastern edge of the basin (Xu, 1993; Xu et al., 1993; Ross et al., 1996; Hsiao et al., 2004). The basin consists of a series of primary and secondary uplifts and depressions which are comprised of six major depressions, namely the Jizhong, Huanghua, Liaohe, Bozhong, Jiyang, and Linqing (Fig. 2) (Ye et al., 1987; Lu and Wang, 1997). The Bohai Sea comprises the Bozhong depression, southern part of Liaohe depression, eastern part of Huanghua depression, and the northern part of the Jiyang depression (Fig. 2) (Gong et al., 1987; Hou et al., 2003). Tertiary strata rest unconformably on a variety of older pre-rift strata and are covered conformably or unconformably by Quaternary sediments. This succession, comprised of sandstone, mudstone, and interbedded volcanic sedimentary rocks, has a thickness of 4–7 km in the main depression, whereas in the depocenter of the Bozhong depression (Central Bohai Sea), the thickness exceeds 10 km (Liu, 1987; Ye et al., 1987; Hu et al., 2001). The Cenozoic succession has been divided into six formations: namely the Kongdian (Ek), Shahejie (Es), Dongying (Ed), Guantao (Ng), Minghuazhen (Nm), and Pingyuan (Qp) which are further sub-divided into several members.

Depressions within the basin typically take on the form of half-grabens. The geometry of Cenozoic successions is controlled by the listric-normal major faults (Ye et al., 1987; Lu and Wang, 1997). The dominant structures of the North China Basin are the WNW and E-W trending uplifts and depressions in the central basin and the NNE-trending uplifts and depressions in the eastern and western parts of the basin. The important faults in this basin include the Tanlu Fault Zone in the eastern part and the Huanghua-Dongming Fault in the center (Hou et al., 2001; Hu et al., 2001) (Fig. 2). The dextral strike-slip motion of the Tanlu Fault Zone and Huanghua-Dongming Fault formed a typical pull-apart basin. The dextral strike-slip Tanlu Fault Zone developed two sags and one uplift in the Bohai Sea and cut deep into lithosphere (Zhu et al., 2005; Qi et al., 2008, 2010; Li et al., 2012a, b).

Syn-rift deposits rest on the pre-rift basement and are covered by the post-rift deposition. The North China Basin experienced a typical rifting sequence from tectonic subsidence to thermal subsidence (Hou et al., 2001; Kusky et al., 2007; Kusky, 2011).

3 Mesozoic-Cenozoic extension of the Bohai Sea

During the past two decades, the Cenozoic evolution of the North China Basin has been discussed by many researchers, primarily in regard to the regional geology of the onshore portion of the basin (Wang et al., 1985; Ye et al., 1987; Hong, 1990; Zhao and Windley, 1990; Allen et al., 1997; Hou et al., 2001, 2010; Hu et al., 2001; He and Wang, 2003; Zhao and Zheng, 2005; Qi et al., 2008, 2010; Li et al., 2012a, b). The thin crustal thickness of the offshore portion (Bohai Sea) of the basin in the NCC suggests that this section played an important role in the destruction of the NCC.

The growth faults are the major extension structures that controlled the depression boundaries of the basin, as well as the sedimentation and the migration of the depocenters (Hou et al., 1998, 2001; Yi and Hou, 2002). The transposition of the depocenters of the Bohai Sea from the margins to the center from the Early to the Late Tertiary is an important geological event in the NCC. The C-frequency diagrams of the growth faults were calculated from the local seismic sections in the Bohai Sea where C, the growth index of the growth fault, is the thickness ratio of a layer in the hanging wall to the same layer in the foot wall for the master fault. C indicates the activeness of the fault; the higher the C value, the greater the activity. The C-frequency diagrams shown in Fig. 5 indicate that the C value of the growth faults in the center of the Bohai Sea is higher than that near the margins. The C values of Mesozoic faults are higher than those of the Miocene faults, both located in the margins of the Bohai Sea (Fig. 5). The C values of the growth faults of the Bohai Sea are consistent with the migration of the depocenters from the margins to the center from Mesozoic to Cenozoic (Fig. 5). These evidences suggest that the center of the Bohai Sea is the epicenter of destruction of the NCC in the Cenozoic time.

For further detailed investigations, we have chosen four

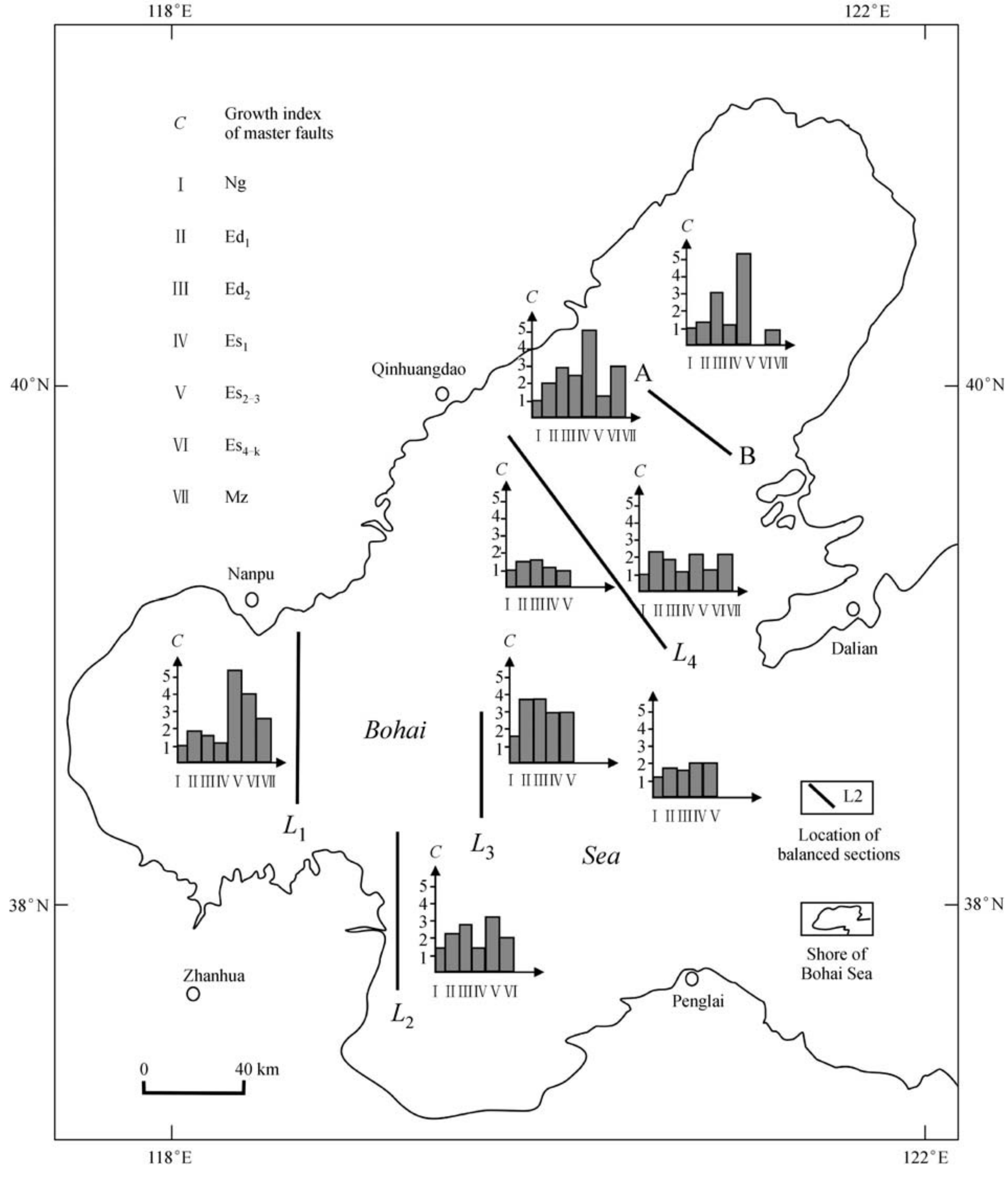

Fig. 5 Locations of *C*-frequency diagrams and balanced-across sections in the Bohai Sea. *C* is the thickness ratio of a layer in the hanging wall to the same layer in the footwall for master fault.

representative seismic sections (L_1, L_2, L_3, and L_4) across the orientation of the major faults in the Bohai Sea (Fig. 5). The evolution of the Bohai Sea area is reconstructed by these balanced-cross sections after sedimentary compaction and thermal subsidence correction. The depth of the basement faulting detachment (~12.6 km) was calculated from the earthquake depth (Liu, 1987). We have used the method for the reconstruction of balanced-cross-sections which was introduced by Gibbs (1983). One (L_1) of the four balanced-cross sections is shown in Fig. 6. Extension estimates of four sections in different periods (Table 1) indicate the intensity of extension during the Mesozoic and

Table 1 The extension calculation of four balanced-cross sections in the offshore portion of the North China Basin

Balanced-across sections	Periods and formations	Length of sections/km		Extension in each period	Extension ratio in each period /%	Accumulated extension	Accumulated extension ratio/%	Extension factor (β)
		Before extension	After extension					
L_1	Q + Nm	63.9	65.5	1.6	2.6	18.7	39.8	1.4
	Ng	62.2	63.9	1.7	2.7	17	36.3	
	Ed	59.6	62.2	2.5	4.3	15.3	32.7	
	Es$_{1-3}$	55.7	59.6	4	7	12.8	27.3	
	Es$_{4-k}$	53.3	55.7	2.4	4.5	8.8	18.8	
	Mz	46.8	53.3	6.4	13.7	6.4	13.7	
L_2	Q + Nm	55.8	57.7	1.9	3.4	24	71.2	1.71
	Ng	54	55.8	1.8	3.3	22.1	65.5	
	Ed	44	54	10	21.7	20.3	60.2	
	Es$_{1-3}$	36.7	44	7.3	19.9	10.3	30.5	
	Es$_{4-k}$	33.7	36.7	3	8.9	3	8.9	
L_3	Q + Nm	38	38.9	0.9	2.4	14.3	58.4	1.58
	Ng	37.1	38	0.9	2.4	13.4	54.8	
	Ed	35	37.1	2.2	6.2	12.6	51.2	
	Es$_{1-3}$	26.1	35	8.9	31.7	10.4	42.4	
	Es$_{4-k}$	24.6	26.1	1.5	6.2	1.5	6.2	
L_4	Q + Nm	98.8	104	5.2	5.2	35	50.6	1.51
	Ng	93.7	98.8	5.2	5.5	29.8	43.1	
	Ed	81.4	93.7	12.3	15.1	24.6	35.7	
	Es$_{1-3}$	71.5	81.4	9.9	13.9	12.4	17.9	
	Es$_{4-k}$	69	71.5	2.5	3.6	2.5	3.58	

Cenozoic periods. The extension ratios of the Late Eocene (Es$_{1-3}$) range from 7% to 32% with a mean of 18.1%. The extension ratios of the Oligocene (Ed) range from 4% to 22% with a mean of 12.1%. The dominant extension ratios of the other periods range from 2% to 9% with a mean of 4.2% (Table 1). The extension ratios of four representative balanced-cross sections suggest that the Late Eocence (Es$_{1-3}$) and Oligocene (Ed) periods were the strongest with much higher extension ratios than other periods. The extension estimate of the Late Mesozoic era is about 13.7% which is similar to the major extension in the Late Eocene and Oligocene (Es$_{1-3}$ and Ed). This comparison suggests that the Late Jurassic–Early Cretaceous periods also witnessed major extension in the basin and that the greatest destruction in the NCC occurred during the Late Mesozoic and Early Cenozoic periods.

The extension factors (β) for the four sections were calculated by the reconstruction of the balanced-cross sections. The extension factors (β) for the Bohai Sea range from 1.4 to 1.7, with a mean of 1.6 (Table 1), whereas the extension factors (β) for the margins of the sea range from 1.1 to 1.4, with a mean of 1.3 (Allen et al., 1997). The higher extension factors for the Bohai Sea vs. those for the margins of the sea are consistent with the thinnest crust (28 km) found in the sea compared to the thicker crusts (36–42 km) found at its margins (Liu, 1987). The lithosphere in the Bohai Sea, with a thickness of 50 km, is much thinner than at its margins and in other parts of the NCC where the thickness is 100–200 km (Fig. 1) (Lin et al., 2005). It can therefore be inferred, from the above findings and interpretations that the Late Eocene and Oligocene represent the major extension (rifting) periods for the Bohai Sea in the Cenozoic era.

The Bohai Sea exhibits local geology that is distinct from its margins. The Late Mesozoic strata were better developed in the center of the sea than in its margins due to the sinistral strike-slip motion of the Tanlu Fault Zone. The depositional depocenter of the basin migrated from the west to the east during the Paleocene to the Quaternary (53 Ma to present). The composite basin is made of a thick Cenozoic basin resting on the thick Mesozoic basin in the Bohai Sea (Hou et al., 1998, 2001). The Oligocene (Ed) depression conformably rests on the Late Eocene (Es$_{1-3}$) depression in the Cenozoic basin. A conspicuous characteristic of this composite basin is that the east-west trending wide Cenozoic grabens are superimposed on the northwest-southeast trending narrow Mesozoic grabens. These structural and sedimentary evidences suggest that

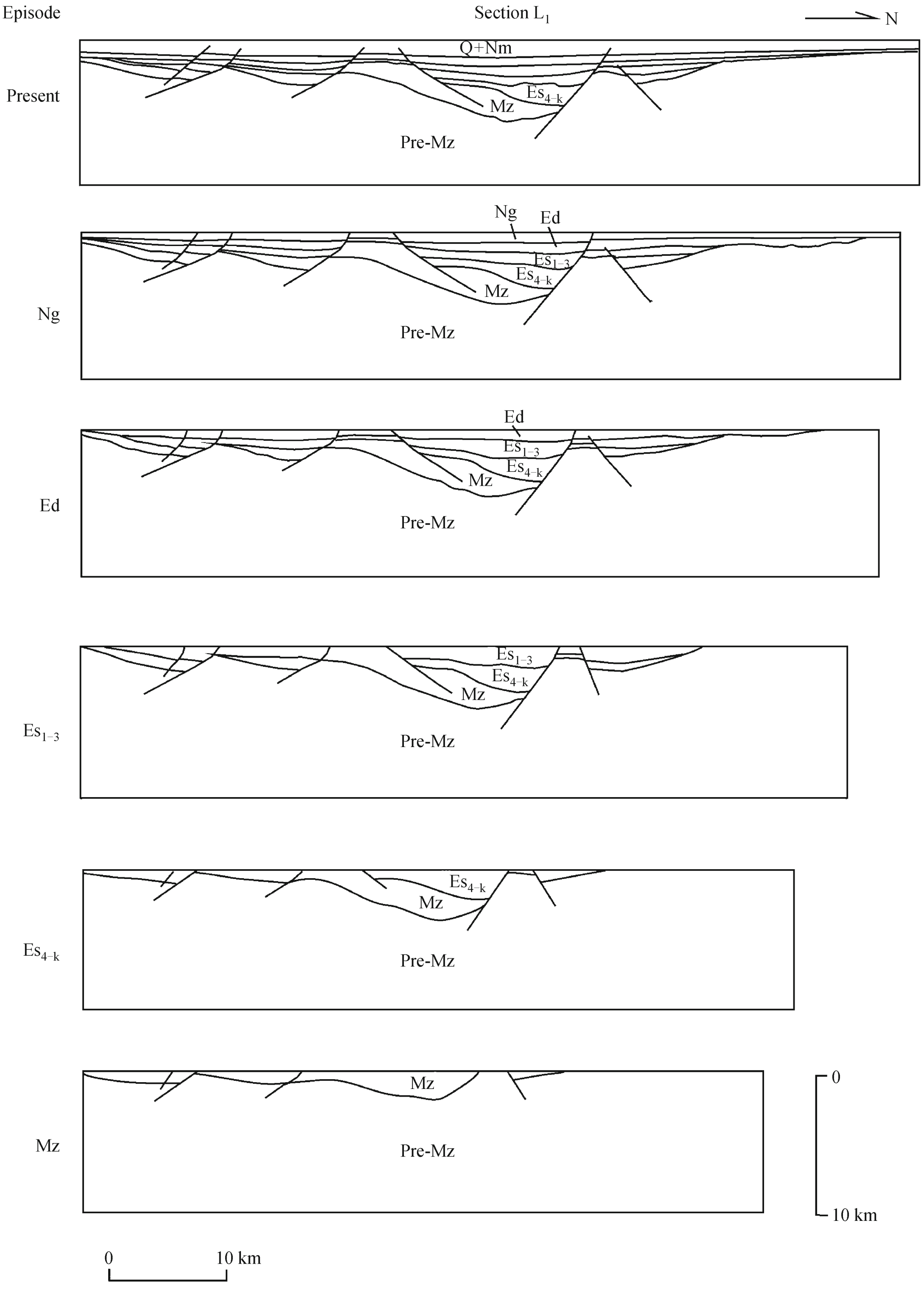

Fig. 6 The evolution of an offshore balanced section (L_1) across the Bohai Sea.

the destruction of the craton mainly concentrated on the Bohai Sea where the Cenozoic basin superimposed on the Late Mesozoic basin with the development of thick Mesozoic-Cenozoic sediments in the eastern NCC. Based on the growth indices (C) and extension factors (β), it can be interpreted that during the Late Eocene and Oligocene periods, the Bohai Sea portion of the NCC experienced maximum destruction related to dextral strike-slip motion of the Tanlu Fault Zone across the Bohai Sea. The present-day thickness of the lithosphere ranges from 50 km in the eastern NCC to 120 km in the western NCC. The lithospheric thickness contour pattern of 80 km is seen to have a perfect fit with the rhomboidal pattern of the Cenozoic North China Basin (Fig. 1). These above-mentioned evidences suggest that the Bohai Sea was the most active region responsible for the destruction of the NCC.

4 The evolution history for the destruction of the North China Craton

The major record of destruction of the NCC is the lithospheric thinning that resulted from the delamination, thermal erosion, or replacement of the lithospheric mantle (Kusky et al., 2007; Zhu et al., 2012). The destruction took place in the eastern NCC, which can be correlated with the East Asian tectonic regime, such as the collision between North and South China along the Qinling-Dabie orogenic belt, the collision between Siberia and North China during the Permian-Middle Triassic (Li, 2006, and ending with the final closure of the Okhotsk Ocean during the Middle Jurassic period (~170–150 Ma) (Jolivet et al., 1988) (Fig. 7 (a)). The subduction of the Paleo-Pacific Plate (i.e., Kula or Izanagi) also contributed to the Mesozoic tectonic regime of the eastern NCC (Fig. 7(a)). The interactions with the surrounding geological terranes strongly influenced the NCC in the Mesozoic era, with widespread intra-plate deformation in the early Mesozoic, constructing the Mesozoic North China Plateau (Zhang et al., 2001a, b, c; Zhai et al., 2007) (Fig. 7(a)).

The transition from marine to terrestrial deposit in the NCC and the SCC suggests that the two cratons finally collided along the Qinling-Dabie Zone during Late Triassic era (Zhang, 1997; Meng and Zhang, 1999; Dong et al., 2000; Wan and Zeng, 2002). The SCC subducted to 100 km or more depth and underwent UHP metamorphism beneath the NCC by the collision (Zhang et al., 1989; Li et al., 1993). These collisional events caused thickening of the lithosphere, which in some areas exceeded 200 km (Dong et al., 2000; Zhang et al., 2001a, b, c) (Fig. 7a). At about 160–150 Ma (Late Jurassic), drastic thinning and collapsing of the lithosphere occurred in the eastern NCC due to the delamination of cold and heavy lithosphere (Dong et al., 2000). The delamination led to the upwelling of asthenosphere with the formation of a great amount of

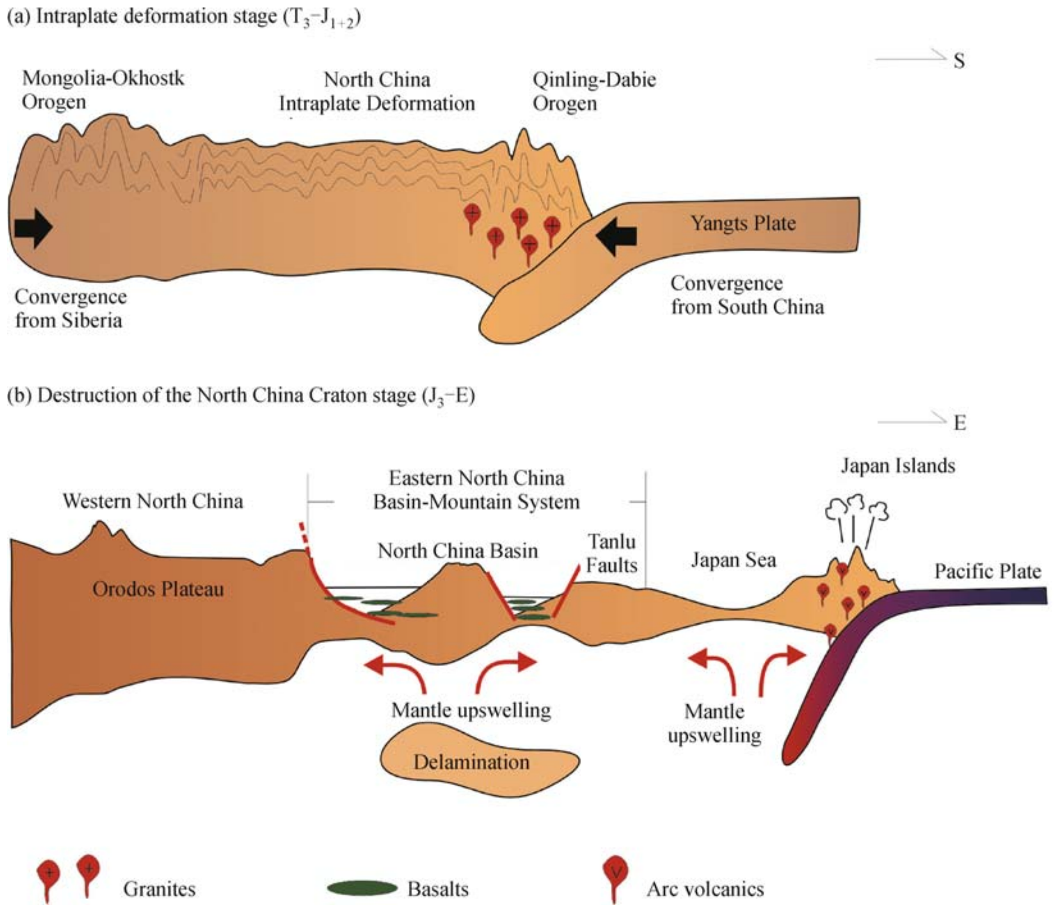

Fig. 7 The origin and destruction of the North China Plateau in the eastern NCC. (a) Origin of the North China Plateau in the Mesozoic time; (b) destruction of the North China Plateau by the extension of the North China Basin.

volcanic and granite belts in the eastern NCC (Dong et al., 2000; Hou et al., 2003; Wang et al., 2005). The subsequent event after delamination was replacement of the mantle, with subsequent thinning of lithosphere that led to the initial extension in the eastern NCC, beginning in the Late Jurassic and Early Cretaceous (Zheng et al., 1988; Zhu et al., 2012). During Eocene, strong extension occurred and an extensional basin-range system developed in the eastern NCC (Ma et al., 1983; Zheng et al., 1988; Hou et al., 2001) (Fig. 7(b)).

A key question typically asked is whether or not the tectonic processes are involved in transforming NCC from a reactive block in the Early Mesozoic intra-plate deformation regime to the Cenozoic basin-range system. The destruction events of the NCC coincided with the development of the large Mesozoic-Cenozoic basins in the eastern NCC. The basins were formed in two episodes during the Mesozoic-Cenozoic time, i.e., the first in Late Jurassic–Early Cretaceous eras and the second during the Eocene (Liu, 1987; Hou et al., 1998, 2001, 2010). It means that the destruction of the NCC not only occurred in Mesozoic, but also in Cenozoic.

The NCC and SCC collided in the Late Triassic and likely continued up to Middle Jurassic era (Yin and Nie, 1996; Zhang, 1997; Meng and Zhang, 1999). The intra-plate deformation in the NCC gave rise to folding with east-west trends (Wang et al., 2005). In the Late Mesozoic, the Izanagi plate, which was quickly moving in a north-northwest direction, began subduction beneath the Eurasian Continent (Jolivet et al., 1994), which led to mantle upwelling and widespread magmatic activity in eastern China (including the eastern NCC). Further, the collision between the NCC and SCC gave rise to the synorogenic sinistral strike slip of the Tanlu Fault Zone with a 350 km offset in the Late Triassic and Early Jurassic periods (Zhu et al., 2005). As a result, the Tanlu Fault Zone extended further north with left-lateral displacements of 200 km due to the northwest motion of the Izanagi plate in the Late Jurassic and Early Cretaceous (Zhu et al., 2005). Northwest trending en-echelon arrangements of grabens west to the Tanlu Fault Zone were developed by the thinning of the lithosphere of NCC by the 550 km long sinistral strike slip of Tanlu Fault Zone. The initial extension of the lithosphere in the Late Jurassic and Early Cretaceous triggered the destruction of the NCC and the formation of an unstable craton (Fig. 8(a)). The Pacific plate moved in a west-northwest direction instead of northward since 42 Ma with an average speed of 32 mm/yr (Parés and Moore, 2005). This transformation of plate movement led to dextral strike-slip motion, instead of the already existing sinistral strike-slip motion of the Tanlu Fault Zone. This motion also led to upper mantle upwelling and intense volcanic activity at which time the North China Basin entered into a new stage (Hou et al., 2003). During the Late Eocene (42–32 Ma), the North China Basin developed the first stage of a pull-apart basin (Fig. 8(b)) and during this period, Japan began to separate from the northeast Asian margin (Lallemand and Jolivet, 1986; Jolivet et al., 1994; Liu et al., 2001) with strong lithospheric thinning in all of northeast Asia. The late Oligocene (32–25 Ma) witnessed the first stage of a Japan Sea opening; a pull-apart basin between two dextral strike-slip faults which was transferred from the continental rift to the oceanic rift (Jolivet et al., 1994; Liu et al., 2001). In the North China Basin, intense volcanism and a wider pull-apart basin also developed with the same tectonic setting as that of the Japan Sea (Fig. 8(c)). During this period, the anticlockwise movement of the Korean peninsula broke this landmass away from the Chinese mainland (Qian, 2004). The motion of the Pacific plate and the coeval Indian-Eurasian collision strengthened the extension event in northeast Asia and strengthened the destruction of the NCC. The opening of the Japan Sea triggered a second stage of extension in North China. Thus, our research concludes that the Late Eocene (42–32 Ma) and Late Oligocene (32–25 Ma) can be considered as the periods of strong destruction of the NCC on the basis of the C and β indices of the growth faults in the Bohai Sea.

During the Miocene period (25–12 Ma), the Japan Sea continued to open in an approximate E-W direction (Jolivet et al., 1994; Itoh, 2001; Liu et al., 2001), and was transformed from a pull-apart basin to a back-arc, triggering the onset of an oceanic crust formation. During this period, the principle compressive stress was approximately E-W in Northeast Asia due to the interaction between the Indian, Eurasian, and Pacific plates. Itoh (2001) pointed out that during this period, the southwest of Japan developed inversion structures. Due to this compressive strength, rifting in the North China Basin ceased with thermal subsidence throughout the basin (Fig. 8(d)) (Zhao and Windley, 1990; Zhao and Zheng, 2005). During the Late Cenozoic era, the destruction of the NCC stopped (Zhu et al., 2012).

5 Conclusions

The NCC experienced two stages of destruction: 1) the Late Jurassic-Early Cretaceous destruction was triggered by the sinistral strike-slip Tanlu Fault due to the northwest motion of the Kula plate; and 2) the Eocene-Oligocene pull-apart extension of the North China Basin experienced the strongest destruction caused by the dextral strike-slip Tanlu Fault and the opening of the Japan Sea. The destruction of the NCC is characterized by the early delamination and subsequent thinning of the lithosphere due to the widespread extension.

The calculated extension factors (β) for the Bohai Sea are higher than that of the margins of the sea, suggesting that the greatest extension occurred within the sea. The late

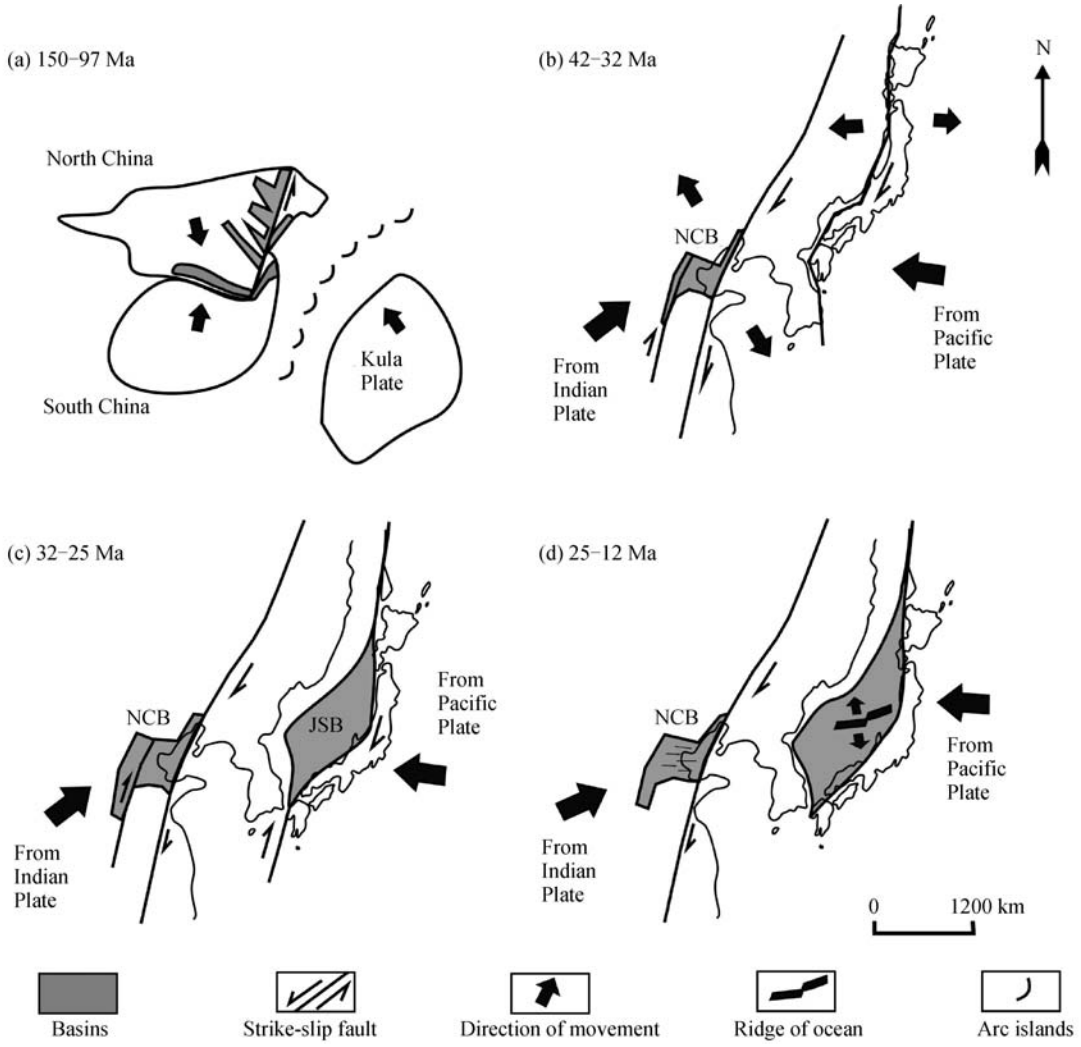

Fig. 8 Tectonic evolution for the Cenozoic North China Basin in the Northeast Asia. NCB, North China Basin; JSB, Japanese Sea Basin.

Mesozoic NW-trending grabens, which are superimposed by the Cenozoic NE-trending pull-apart basin in the Bohai Sea, developed very thick Mesozoic-Cenozoic sediments in the eastern NCC. The *C* index values of the Bohai Sea growth faults are consistent with the migration of the depocenters from the margins to the center of the sea. These evidences suggest that the Bohai Sea was the strongest site for destruction of NCC. The destruction in the eastern NCC during the Eocene-Oligocene periods was stronger than that of the Mesozoic period. The NCC has become a non-typical craton since late Mesozoic time.

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