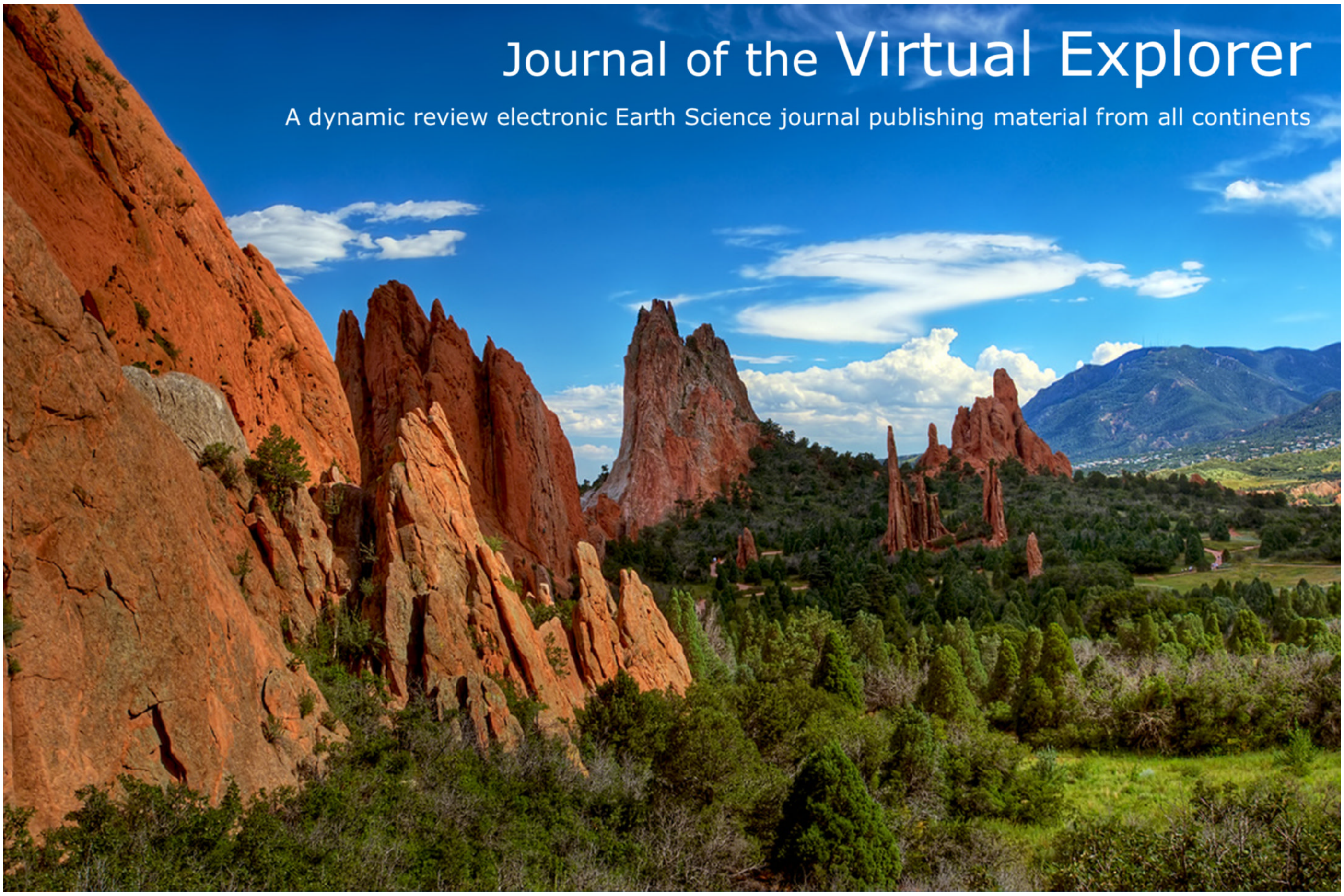



# Destruction of the North China Craton: evidence from the Bohai Bay Basin

*Guiting Hou, Mohan Yang, Weihou Yao*

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **31**, paper 2
In: (Eds.) Guiting Hou and Gideon Rosenbaum, General Contributions, 2009.


# Destruction of the North China Craton: evidence from the Bohai Bay Basin

*Guiting Hou, Mohan Yang, Weihou Yao*

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **31**, paper 2
In: (Eds.) Guiting Hou and Gideon Rosenbaum, General Contributions, 2009.

**Abstract**: The Bohai Bay Basin is a Late Mesozoic-Cenozoic feature of the basins-mountains system in the eastern North China craton. Five mountains around the basin are Yanshan, Taihangshan, Zhongtiaoshan, Taishan and Liaodong. They are block-faulting mountains, not typical orogenic mountains except intraplate orogenic Yanshan Mountain. These mountains constituted the Mesozoic plateau before the destruction of the North China craton. The basin resulted from extension of the North China craton; its formation signaled the destruction of the craton. Based on analysis of the growth indices and section balance for seismic sections from the offshore portion (Bohai Sea) of the Bohai Bay Basin, the growth faults controlled the sedimentation and the migration of the sedimentary depocenter. The depocenters of the basin moved from the margins of the basin to the center of Bohai Sea in the period from the Early Tertiary to the Late Tertiary. The construction of balanced cross-sections and determination of the extension factor ($\beta$) for four sections suggest that the extension factors for the offshore portion are higher than those for the onshore portion in the Mesozoic and Cenozoic. These lines of evidence suggest that the extension was greatest in the offshore parts of the craton. This is consistent with the thinnest crust occurring in the offshore portion. The onset of destruction of the craton resulted from the delamination and thinning of thick lithosphere of the plateau, which is evidenced by the presence of NW-trending grabens that occur in an en echelon arrangement on the west of Tanlu Fault Zone and NNE-trending grabens within the Tanlu Fault Zone. Extension-related destruction of the craton was largely dictated by the tectonic evolution of northeast Asia. The offshore (Bohai Sea) portion is the region of the North China craton that Cenozoic extension affected most severely.

http://virtualexplorer.com.au/article/2009/243/destruction-of-north-china-craton

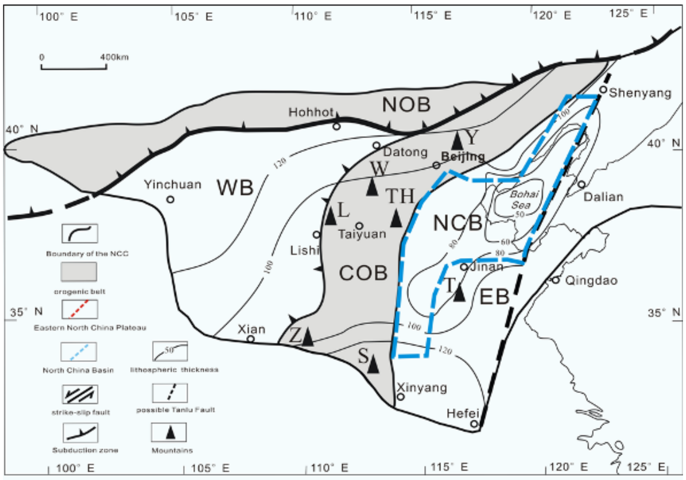
**Citation**: Hou, G., Yang, M., Yao, W. 2009. Destruction of the North China Craton: evidence from the Bohai Bay Basin. In: (Eds.) Guiting Hou and Gideon Rosenbaum, *Journal of the Virtual Explorer*, volume **31**, paper 2, doi: 10.3809/jvirtex.2009.00243

## Introduction

The Bohai Bay Basin is the largest of the Mesozoic and Cenozoic basins belonging to the North China craton (NC), a unique craton amongst the Earth's other stable cratons in that it has been tectonically active since the Mesozoic (~220 Ma) (Gao *et al.*, 2002). The destruction of the North China craton has aroused much interest within the international geological community in recent times.

The North China craton, China's oldest continental fragment, is composed of three main Archean elements: the Eastern Block, the Western Block, and the intervening Central Orogenic Belt (Zhao *et al.*, 2000; Kusky *et al.*, 2001; Li *et al.*, 2002; Zhai *et al.*, 2005) (Figure 1). The tectonic histories of the Eastern and Western Blocks diverge from the Mesozoic and Cenozoic. In the Mesozoic, the western NC developed a shallow marine basin and passive continental margin, while the eastern NC was uplifted to form the "Eastern North China Plateau" (Ren, 1999; Deng *et al.*, 2000; Dong *et al.*, 2000; Zhang *et al.*, 2001a, 2001b, 2001c) and, in the Cenozoic, the western NC was uplifted to form a loess plateau while the Eastern North China Plateau collapsed to develop an extensional basin-mountains system (Zheng *et al.*, 1988; Yan *et al.*, 1996; Hou *et al.*, 1998, 2001, 2003; Zhang *et al.*, 2001a, 2001b, 2001c).

**Figure 1. The Pre-Cambrian tectonic divisions and lithospheric thickness contours of the North China Craton**

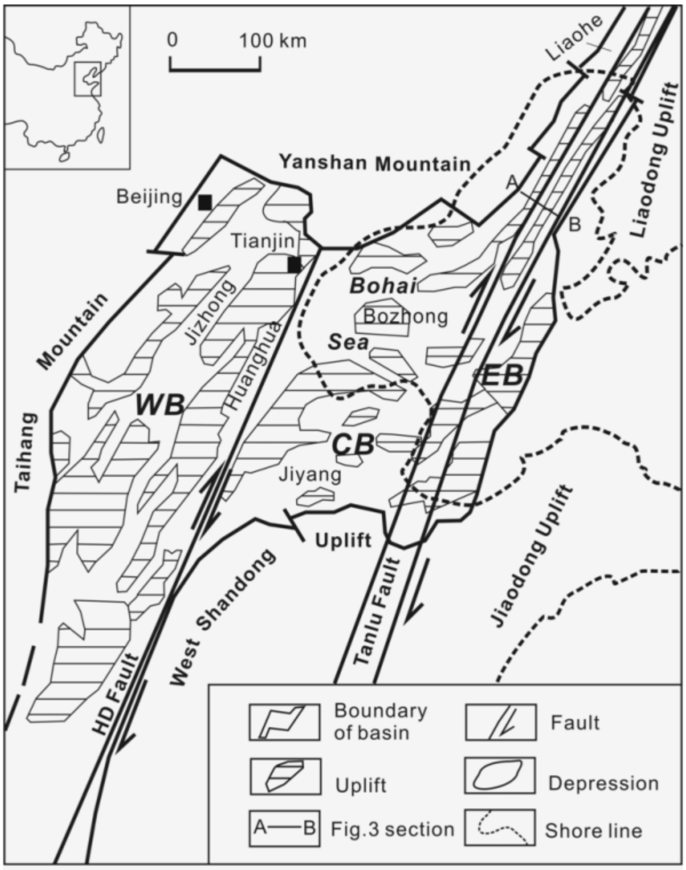



WB-West Block; COB-Central Orogenic Belt; EB-East Block; NOB-North Orogenic Belt; NCB-North China Basin Y-Mt.Yanshan; W-Mt.Wutai; TH-Mt.Taihang; L-Mt.Luliang; Z-Mt.Zhongtiao; S-Mt.Songshan; T-Mt.Taishan

(sources: Lin *et al.*, 2005; Hou *et al.*, 2006a,b)

The Bohai Bay Basin is located within the eastern NC (Figure 2) and represents one basin of the basins-mountains system, which also includes the North China Plain and Bohai Sea. The eastern parts of the NC host the components of the NC that were tectonically reworked in the Mesozoic-Cenozoic (Hong, 1989; Tian *et al.*, 1992; Liu, 1997; Hou *et al.*, 2003). The Bohai Bay Basin trends north-south, has a length of *c.* 1000 km and a total area of *c.* 200,000 km$^2$. Five mountains surround it, the Yanshan, Taihang, Taishan, Jiaodong and Liaodong (Ye *et al.*, 1985). The Bohai Bay Basin developed evidence for extension of the eastern NC in the Cenozoic, following destruction of the craton. Its exact timing and tectonic evolution of the eastern NC during the Mesozoic, prior to its destruction, are issues of importance if the tectonic development of the NC is to be better understood.

**Figure 2. Cenozoic tectonic divisions of the North China Basin**




HD Fault-Huanghua-Dongming strike-slip fault; WB-Western Basin; CB-Central Basin; EB-Eastern Basin

(modified after Hu *et al.*, 2001; Lu *et al.*, 1997)

The Cenozoic evolution of the Bohai Bay Basin has been well treated by a number of existing articles (Yin and Nie, 1996; Ren, 1999; Hsiao *et al.*, 2004). The majority of these works have focused on issues including the gravity field, highly conductive asthenosphere, thermal history, onshore structures and Cenozoic tectonism (Ye *et al.*, 1985; Wang *et al.*, 1985; Liu, 1987; Allen *et al.*, 1997; Wang and Wang, 1988; Hong, 1989; Zhao and Windley, 1990; Hu *et al.*, 2001; He and Wang, 2003; Zhao and Zheng, 2005). Inconsistencies in the conclusions of previous studies suggest that the Bohai Bay Basin experienced a complex development. The Cenozoic dynamics of the entire basin remains controversial due to lack of comprehensive research of the offshore (Bohai Sea) portion of the Bohai Bay Basin. The timing of the onset and the evolution of the destruction of the NC has been obscured by the lack of a complete understanding of the Mesozoic development of the Bohai Bay Basin.

## Geological setting

The NC was initially stabilized in the Middle Proterozoic and Neoproterozoic and was covered by Paleozoic shallow marine sediments (Qian *et al.*, 1986). The earliest platform-type sedimentary rocks belonging to the Mesoproterozoic Changcheng Group are preserved with an almost horizontal stratigraphy in the Mt. Taihang area and rest unconformably on the Archean crystalline basement of the central NC. Horizontal Paleozoic strata in the eastern NC commonly covered flat-topped (Karst-like) mountains of the western Shandong Province. These observations suggest that the NC was stable in the Proterozoic and Paleozoic (Li, 1998; Lin, 1985). The Cenozoic extensional basin, Bohai Bay Basin, is surrounded by the Wutai, Taihang, Luliang, Zhongtiao, Songshan, Taishan and Yanshan mountains. They are block-faulting mountains, not typical orogenic mountains except intraplate orogenic Yanshan mountain. Mt. Yanshan displays overthrusts and anticlines related to the final close of the Mongolian-Okhostk Ocean before the Late Jurassic (Chen, 1998). These mountains probably once formed an Early Mesozoic plateau, the Eastern North China Plateau. The mountains and Bohai Bay Basin together constitute the basins-mountains system which resulted from the extensional event associated with collapse of the plateau.

In the eastern NC, the Cenozoic Bohai Bay Basin was developed on the site of a Late Mesozoic basin (Hou *et al.*, 2001). The outline of the basin envelopes a rhomboidal central area with slender arms that extend to both the northeast and southwest (Figure 2) and, at the eastern edge of the basin, the well-known, north-northeast trending Tanlu strike-slip fault zone occurs (Xu, 1993; Xu *et al.*, 1993; Ross *et al.*, 1996). The basin consists of a series of uplifts and depressions containing numerous secondary uplifts and depressions. Six major depressions are recognized: the Jizhong, Huanghua, Liaohe, Bozhong, Jiyang and Linqing depressions (Ye *et al.*, 1985; Liu, 1987; Lu *et al.*, 1997). The offshore portion of the basin includes the Bozhong, southern Liaohe, eastern Huanghua and northern Jiyang depressions (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 is typically 4-7 km thick in the main depression, with a maximum thickness of more than 10 km at the depocenter of the Bozhong depression (Central Bohai Sea) (Ye *et al.*, 1985; Liu, 1987; Hu *et al.*, 2001). Lithologies are dominated by sandstone, mudstone and interbedded volcanic sedimentary rocks. The Cenozoic succession has been divided into six formations: the Kongdian (Ek), Shahejie (Es), Dongying (Ed), Guantao (Ng), Minghuazhen (Nm), and Pingyuan (Qp) Formations, which are further sub-divided into several members. The basin experienced two phases of rifting in Cenozoic times (Ye *et al.*, 1985; Hou *et al.*, 2001).

Depressions within the basin mostly take the form of half-grabens with the geometry of Cenozoic successions controlled by listric master faults (Ye *et al.*, 1985; Lu *et al.*, 1997). The Bohai Bay Basin is divided into three parts: the western, central and eastern parts (Figure 2). The dominant structures of the Bohai Bay Basin are WNW and E-W trending uplifts and depressions in the central basin, and NNE trending uplifts and depressions in the eastern and western parts. The Tanlu Fault Zone developed in the east of the basin, while Huanghua-Dongming Fault developed in the basin centre (Hou *et al.*, 2001; Hu *et al.*, 2001) (Figure 2). Syn-rift deposits rest on pre-rift basement and are covered by post-rift deposits. The Bohai Bay Basin experienced a typical rifting sequence from tectonic subsidence to thermal subsidence; however, the relationship between the Mesozoic and Cenozoic basins of the Bohai Bay Basin and their implications for the destruction of the NC remain ambiguous.

## Mesozoic configuration of the Bohai Bay Basin

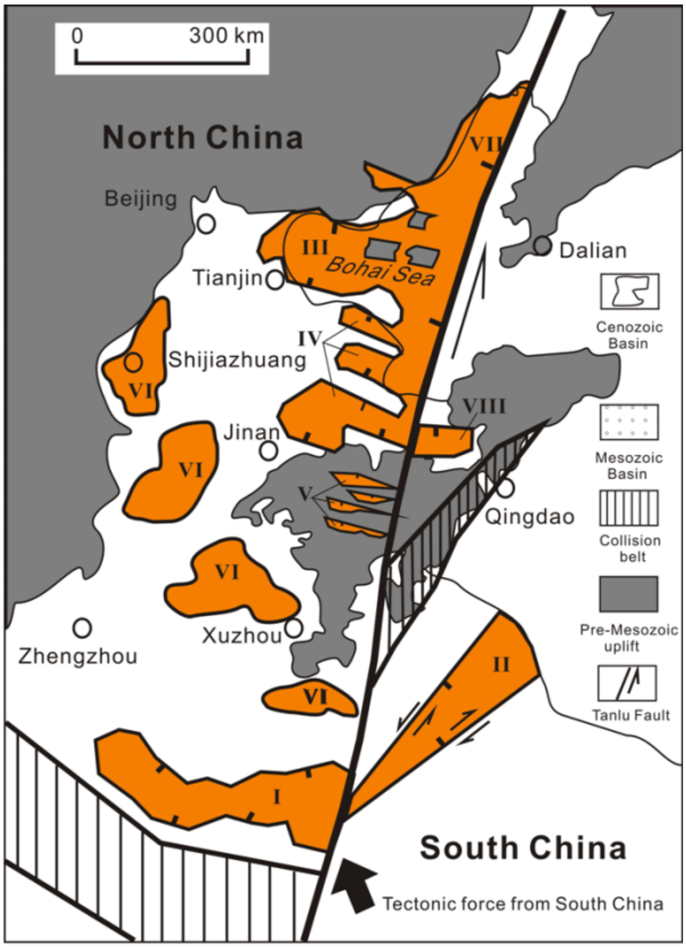
In the past, oilfield exploration efforts within the Bohai Bay Basin were concentrated on the Cenozoic parts of the basin and little attention has been directed toward the Mesozoic parts (Qi *et al.*, 2003; Hou *et al.*, 2001). Few articles in the literature discuss the Mesozoic basin because the majority of exploration wells were not drilled deep enough to penetrate the Mesozoic strata and because of the poor quality of seismic sections that display a Mesozoic component. Thus the geology of Mesozoic parts of the Bohai Bay Basin has remained ambiguous. However, more recently, deep wells have been drilled into or through the Mesozoic strata and more sensitive reflection seismic sections have been constructed for the Mesozoic sequences. These works have provided useful information to study the Mesozoic basin.

In the NC, the cratonic basement consists of Archean and Proterozoic metamorphic rocks that crop out in the west, north and south of the Bohai Bay Basin. Pre-Mesozoic platform sedimentary rocks consist of stable Cambrian-Triassic strata including shallow marine facies, Cambrian-Ordovician carbonates and shales, and Permo-Carboniferous lake delta and limnetic coal-bearing formations (Zhao *et al.*, 2000; Kuskey and Li, 2003). Triassic formations comprise red clastic fluvial and lacustrine deposits. The depositional environment of the NC was relatively stable and few volcanic rocks were developed in this period (Qian, 1986; Lu *et al.*, 1997). Pre-Mesozoic structural trends in the craton are dominantly east-west (Qian, 1986; Wan and Zeng, 2002; Lu *et al.*, 1997).

During the late Permian and early Triassic, the North China craton and South China craton (SC) began colliding, building the Qinling-Dabie-Sulu mountains. Convergence probably lasted to Middle Jurassic times. The eastern part of the NC experienced intra-continental deformation and uplift due to the convergence at the north and south margins in the Early Mesozoic and experienced widespread thermal activity in Late Mesozoic and Cenozoic, as indicated by the emplacement of voluminous late Mesozoic granites and extensive Cenozoic volcanism (Yin and Nie, 1996; Tian *et al.*, 1992; Hou *et al.*, 2003). During the Dabie orogenic episode, Late Triassic contractional foreland basins were developed in the south of the NC, for example the west-northwest trending Xinyang-Hefei Basin () on the north of the Dabie Orogen and northeast trending Subei Basin () on the south of the Sulu Orogen. These Late Triassic foreland basins were filled by red molasse formations (Lu *et al.*, 1997).

In the Late Jurassic and Early Cretaceous, the Tanlu Fault Zone was intensely active, and several late Mesozoic basins developed in the grabens within the Tanlu Fault Zone and on its two flanks (Figure 3). New sensitive reflection seismic sections have revealed the Mesozoic configuration of the Bohai Bay Basin (Figure 3 and 4).

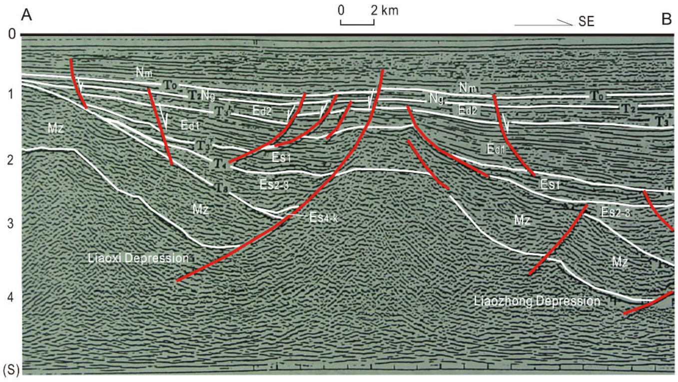
**Figure 3. Distribution of the Mesozoic basins in the North China**




-Xinyang-Hefei Basin; -Subei Basin; -Bohai Basin; -Jiyang Basin; -Luxi Grabens; -Xu-Shi Basin; -Liaohe Graben; -Jiaoliao Graben

(sources: Shandong Geological Map, 1990; Hou *et al.*, 2001; and new seismic sections from the offshore oilfield company, 2005)

**Figure 4. New seismic reflection section (AB) in the offshore of the North China Basin**




Location of section AB is shown in Fig.2 and Fig.5. Mz-Mesozoic Formation; Es4-k-Eocene Shahejie Formation 4 and Kongdian Formation; Es2-3-Eocene Shahejie Formation 2 and 3; Es1-Eocene Shahejie Formation 1; Ed1-Oligene Dongying Formation 1; Ed2-Oligene Dongying Formation 2; Ng-Miocene Guantao Formation; Nm-Miocene Minghuazhen Formation.

(source: Bohai Oilfield Company, China)

Aside from the foreland basins in the south of the NC, the basins located within the craton are extensional in origin and are of Late Mesozoic age, all occurring in the east of the craton. Four Late Mesozoic NW trending basins were identified on the west of Tanlu Fault Zone, from north to south, the Bohai Basin (), Jiyang Grabens (), Luxi Grabens () and Xu-Shi Basins (). Two late Mesozoic basins are identified on the east of the Tanlu Fault, one of which is the N-NE trending Liaohe Graben () within the Tanlu Fault Zone. The other is the E-W trending Jiaolai Graben () (Figure 3).

The Jiyang Grabens consists of three narrow grabens configured in an en echelon arrangement. The Luxi Grabens in the western Shandong Province consists of five narrow grabens in an en echelon arrangement. The Xu-Shi basins consist of four Late Mesozoic relic depressions from Xuzhou to Shijiazhuang in a northwest orientation, which were probably linked together to form one northwest trending basin before they were uplifted (Figure 3). The Late Mesozoic Tanlu Fault Zone is also a narrow rift, which consists of two grabens and an uplifted section (Xu, 1993). The northeast trending Subei basin developed on the east of the Tanlu Fault (Shang *et al.*, 2002).

The Mesozoic parts of the Bohai Bay Basin formed during the Late Jurassic and Early Cretaceous by the deposition of sedimentary and volcanic units in an intraplate rift environment. The Late Jurassic and Early Cretaceous volcanic rocks display NW orientations, controlled by NW-trending master faults on the west of Tanlu Fault Zone and NNE orientations within the Tanlu Fault Zone (Tian *et al.*, 1992; Hou *et al.*, 2003). These grabens were filled with Late Jurassic tuffaceous sandstones, brown mudstones and andesitic basalts that were deposited unconformably on pre-Mesozoic basement (pre-rift sediments) during the Late Jurassic. During the Early Cretaceous, the Qingshan Formation (Jq) was deposited in differentially subsiding grabens and half-grabens in the eastern NC, which consists of dark grey mudstones, grey-green muddy sandstones and brown-red sandy conglomerates interbeded with volcanics.

Yi and Hou (2002) proposed that master faults controlled the deposition of the Late Mesozoic sediments. These master faults are northwest trending, as revealed by highly sensitive seismic reflection sections and by the distribution of the Late Mesozoic sediments (Figure 3 and 4). They show syn-rift movement during the Late Mesozoic and are thus growth faults (Hou *et al.*, 2001).

Seismic sections from the Bohai Bay Basin show that the depocenters of the Mesozoic basins are not coincident with the Cenozoic basin depocenters. The Mesozoic basins appear to have been of greater lateral extent than the Paleocene basins, but smaller than the Oligocene and Miocene basins. The uniform Mesozoic basin is fragmented by Cenozoic basins (Figure 4) and the Cenozoic depressions rest on the Mesozoic depressions, giving the Bohai Bay Basin the structure of a superimposed basin.

The orientations of these basins, master faults and volcanic rocks suggest that these Mesozoic basins were induced by sinistral strike-slip movement within the Tanlu Fault Zone. The northwest trending Late Mesozoic basins have a structural orientation that is distinct from the northeast and east-west trending Cenozoic basins in the eastern NC. The differences between Mesozoic and Cenozoic basins result from their development in different tectonic settings related to the different strike-slip movements within the Tanlu Fault Zone (Figure 2 and 3).

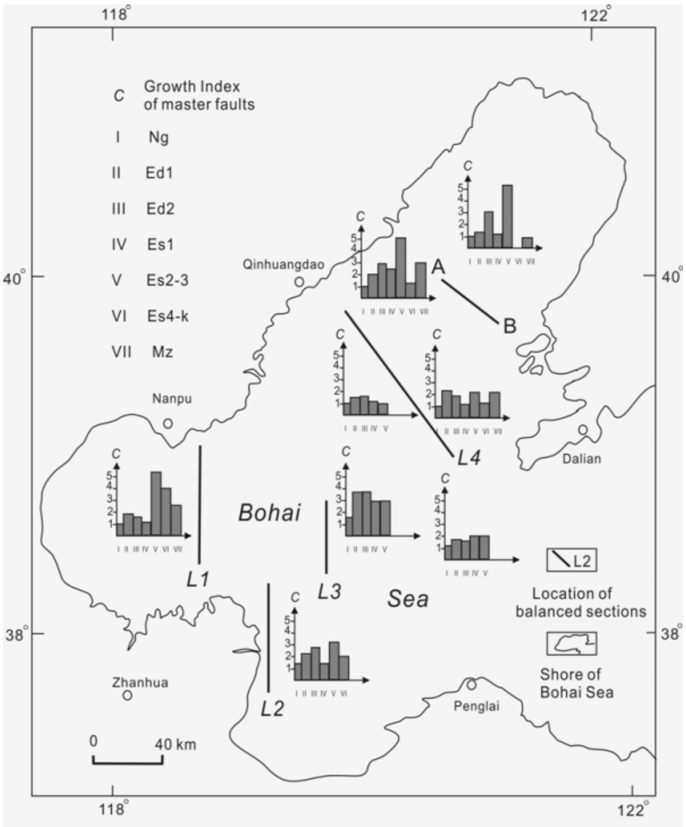
The Early Mesozoic collision between the NC and the SC caused intra-continental deformation (Zhao and Zheng, 2005; Yin and Nie, 1996). The pre-Mesozoic structural trends in the basement of the NC are dominantly east-west (Qian, 1986; Gong, 1987; Wang *et al.*, 2005). There is evidence for further convergence between two blocks accommodated by thrusting in the Dabie and Sulu Orogens during the Early Mesozoic (Okay and Sengör, 1992). The NC developed an orogenic belt along the southern margin of the craton, and intra-continental deformation shaped the Eastern North China Plateau by thickening of the lithosphere. The Tanlu Fault Zone accommodated sinistral strike-slip, and acted as a transfer zone between the thrust-dominated orogenic zones (Xu, 1993; Xu *et al.*, 1993; Ross *et al.*, 1996). The Late Mesozoic grabens on the two flanks of the Tanlu Fault Zone suggest that these grabens have their origins in a transtensional fault zone. The right-handed pattern of the en echelon grabens resulted from sinistral strike-slip within the fault zone and thus they developed under the same tectonic stress field (Figure 3). The Late Mesozoic extension and rifting of the eastern NC signalled the onset of the destruction of the NC. Mesozoic rifting stopped in the Late Cretaceous, allowing initiation of temperary uplift. The Bohai Bay Basin has experienced a newer phase of extension and rifting since the Paleocene.

## Mesozoic and Cenozoic extension in the offshore portion of the Bohai Bay Basin

Over the past two decades, a number of articles have addressed the Cenozoic evolution of the Bohai Bay Basin (Ye *et al.*, 1985; Wang *et al.*, 1985; Liu, 1987; Hong, 1989; Zhao and Windley, 1990; Allen *et al.*, 1997; Hu *et al.*, 2001; He and Wang, 2003; Zhao and Zheng, 2005). To date, attempts at a reconstruction of the Mesozoic basin have been limited. The crustal thickness of the offshore portion (Bohai Sea) of the Bohai Bay Basin is the thinnest within the NC, suggesting that the offshore portion of the basin is a region of importance in the destruction of the NC.

The growth faults that define the depression boundaries of the basin are major extensional structures. The growth faults controlled sedimentation and the migration of the depositional depocenter. The depocenters of the Bohai Bay Basin moved from the margins of the basin to the center of Bohai Sea in the period from the Early Tertiary to the Late Tertiary. *C*-frequency (*C* being the thickness ratio of a layer in the hanging wall to the same layer in the foot wall for master fault) diagrams of growth faults were constructed from local seismic sections from the Bohai Sea. The *C*-frequency diagrams (Figure 5) further indicate that, in the Oligocene and Miocene, the growth faults in the center and east of the sea were more active than the faults near the margins of Bohai Sea (Figure 5), an observation consistent with migration of the depocenters from the margins to the center with continued extension.

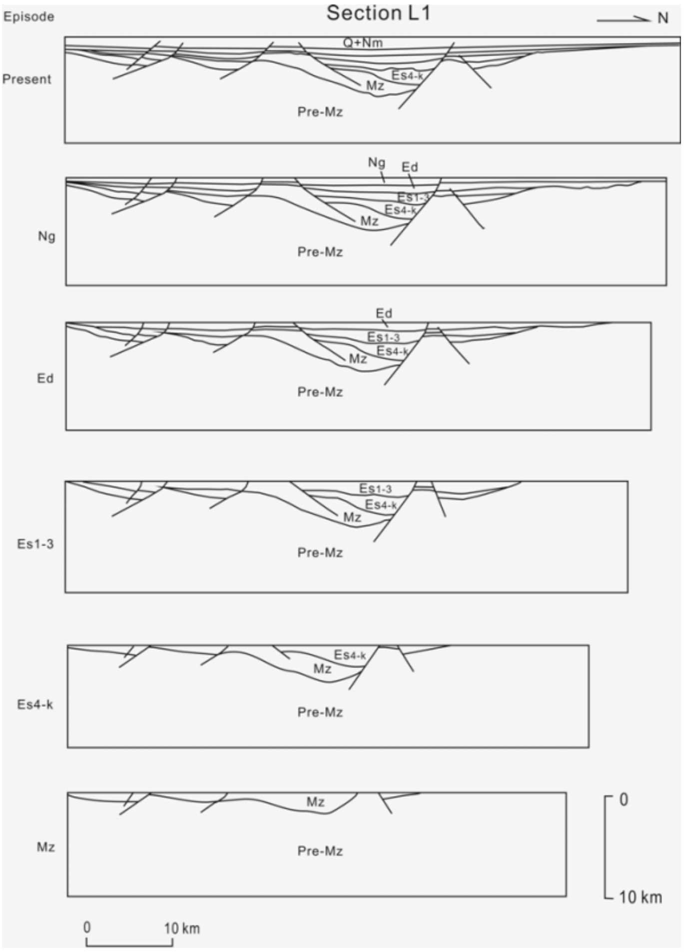
**Figure 5. Locations of C-frequency diagrams and the balanced-cross sections in the offshore portion of the North China Basin**




C is thickness ratio of a layer in the hanging wall to the same layer in the footwall for master fault; Mz-Mesozoic Formation; Es4-k-Eocene Shahejie Formation 4 and Kongdian Formation; Es2-3-Eocene Shahejie Formation 2 and 3; Es1-Eocene Shahejie Formation 1; Ed1-Oligene Dongying Formation 1; Ed2-Oligene Dongying Formation 2; Ng-Miocene Guantao Formation; Nm-Miocene Minghuazhen Formation.

We chose four representative interpreted seismic sections (*L*1, *L*2, *L*3and *L*4) that cross the orientation of the master faults in Bohai Sea, the offshore portion of the Bohai Bay Basin (Figure 5). Balanced cross-sections were analyzed following correction for the compaction curves and thermal subsidence based on the well data and an interpreted thermal history, with the depth (*c.* 12.6 km) of detachment for the basement faulting calculated from earthquake source depths (Ma and Liu, 1986). The method of Gibbs (1983) was used for construction of the balanced cross-sections. A representative balanced cross-section is shown in Figure 6. Extension estimates for four sections in different periods are presented in Table 1 and indicate the relative intensity of extension in the Mesozoic and Cenozoic. One section gives an extension estimate of 13.7% for the Late Mesozoic time, which is similar to the magnitude of extension in the Late Eocene and Oligocene ($Es_{1-3}$ and $E_d$). This suggests that the offshore portion of the basin witnessed major extension in the Late Jurassic and Early Cretaceous.

**Figure 6. Evolution of an offshore balanced section (L1)**




Pre-Mz-Pre-Mesozoic Basement; Mz-Mesozoic Formation; Es4-k-Eocene Shahejie Formation 4 and Kongdian Formation; Es2-3-Eocene Shahejie Formation 2 and 3; Es1-Eocene Shahejie Formation 1; Ed1-Oligene Dongying Formation 1; Ed2-Oligene Dongying Formation 2; Ng-Miocene Guantao Formation; Nm-Miocene Minghuazhen Formation; Q-.

**Table 1. The extension calculation of four balanced cross-sections in the offshore portion of the Bohai Bay Basin.**

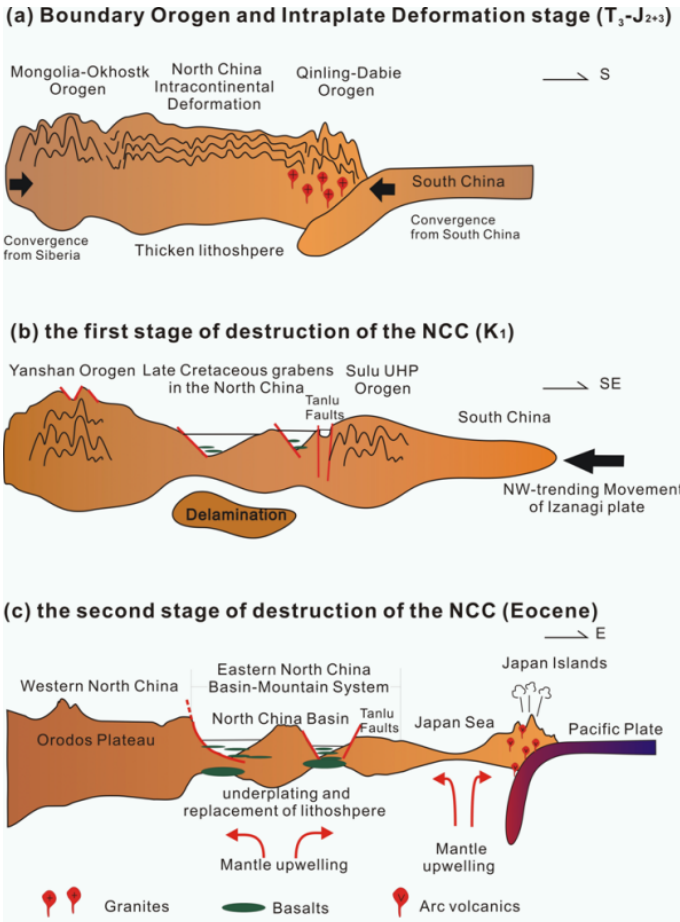
| **Balanced cross-sections** | **Periods** | **Length of sections (km)** | | **Extension in each period** | **Extension ratio in each period (%)** | **Accumulated extension** | **Accumulated extension ratio (%)** | **Extension factor (β)** |
|---|---|---|---|---|---|---|---|---|
| | Formations | Before extension | After extension | | | | | |
| | 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 | |
| *L*1 | 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 | |
| | $Es_4$-Ek | 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 | |
| | | | | | | | | |
| | 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 | |
| *L*2 | Ed | 44 | 54 | 10 | 21.7 | 20.3 | 60.2 | |
| | $Es_{1-3}$ | 36.7 | 44 | 7.3 | 19.9 | 10.3 | 30.5 | |
| | $Es_4$-Ek | 33.7 | 36.7 | 3 | 8.9 | 3 | 8.9 | |
| | | | | | | | | |
| | 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 | |
| *L*3 | 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 | |
| | $Es_4$-Ek | 24.6 | 26.1 | 1.5 | 6.2 | 1.5 | 6.2 | |
| | | | | | | | | |
| | 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 | |
| *L*4 | 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 | |
| | $Es_4$-Ek | 69 | 71.5 | 2.5 | 3.6 | 2.5 | 3.58 | |

The extension factors (β) for four sections were calculated by the construction of the balanced cross-sections. Cenozoic extension factors for the offshore portion of the Bohai Bay Basin, as calculated from the four balanced cross-sections, range from 1.4 to 1.7 with a mean of 1.6 (Table 1). Cenozoic extension factors for the onshore portion in the Bohai Bay Basin range from 1.1 to 1.4 with a mean of 1.3 (Allen *et al.*, 1997). Thus, the extension factors for the offshore portion are higher than those for the onshore portion, suggesting that the greatest extension occurred in the offshore (Bohai Sea) portion of the basin. This is consistent with the thinnest crust being found in the offshore portion: 28 km compared with a maximum of 36-42 km at basin margins (Liu, 1987). Hu *et al.* (2001) proposed that a small amount of tectonic subsidence was superimposed on the post-rift thermal subsidence from about 2 Ma in the offshore portion but not the onshore portion. This suggests that extension of the offshore (Bohai Sea) portion persisted to 2 Ma though the extension was weaker in the Neogene than the Oligocene. Obviously, the Eocene and Oligocene represent the most significant periods of extension (rifting) for the offshore portion of the Bohai Bay Basin.

## Events contributing to the destruction of the North China craton

The NC and SC initially collided in the Early Mesozoic and collision probably lasted to Middle Jurassic time (Yin and Nie, 1993; Zhang, 1997). The NC experienced intra-plate deformation during which folds with east-west trending axes formed (Wang *et al.*, 2005). This intra-plate deformation was responsible for the construction of the North China Plateau (Zhang *et al.*, 2001a, 2001b, 2001c; Shao *et al.*, 2003). In the Late Mesozoic, the Kula plate was quickly moving north-northwest and was subducting beneath the Eurasian continent (Hilde *et al.*, 1977). Subduction led to mantle upwelling and widespread magmatic activity in eastern China (including the eastern NC). The lithosphere of the Eastern North China Plateau had been thinned by intense extension and several Late Mesozoic rifts developed in the Eastern North China Plateau under a transtensional stress field also responsible for the northwest trending en echelon arrangement of grabens on the west of the Tanlu Fault Zone (Figure 7a). The Mesozoic rifting ended in the Late Cretaceous and was followed by temporary uplift and erosion.

**Figure 7. Mesozoic-Cenozoic evolution of the Northeast Asia**




Mesozoic-Cenozoic evolution of the Northeast Asia

The Pacific plate moved northward and subducted beneath the Eurasian plate since 53 Ma at the average rate of about 25 mm/yr (Parés and Moore, 2005). This led to a sinistral strike-slip reactivation of the Tanlu Fault Zone. The northwest-trending, en echelon-arranged narrow grabens that developed in the extensional stress field were Paleocene to Early Eocene in age and were filled by the pre-rift sediments. At the same time, the Japanese arc belonged to the part of the northeast Asian marginal zone, the Okhotsk-Chukotka volcanic zone, which also experienced sinistral strike-slip movement within the northeast trending Sikhote-Alin Fault Zone (Lallemand and Jolivet, 1986; Jolivet *et al.*, 1988, 1994; Liu *et al.*, 2001).

The Pacific plate has moved in a west-northwest direction instead of a northward direction since 42 Ma at an average rate of 32 mm/yr (Parés and Moore, 2005). This has led to dextral strike-slip motion instead of the former sinistral strike-slip motion within the Tanlu Fault Zone. The change in motion triggered upper mantle upwelling and intense volcanic activity as the Bohai Bay Basin entered a new stage in its tectonic development. A late Eocene and Oligocene transtensional basin was created in the offshore portion of the Bohai Bay Basin (Figure 7b) while the Japanese arc began to separate from the northeast Asian margin (Lallemand and Jolivet, 1986; Jolivet *et al.*, 1994) and northeast Asia, as a whole, experienced lithospheric thinning.

The late Oligocene (32-25 Ma) was the first stage of the Japan Sea opening. During this period, the Japan Sea was a pull-apart basin between two dextral strike-slip faults and transition from continental to oceanic rifting occurred (Jolivet *et al.*, 1994). The regional compressive stress was northeast-southwest in northeast Asia and the Tanlu Fault Zone was reactivated within the new stress field. The Bohai Bay Basin developed intense volcanics and wider transtensional basin under the same stress regime as the Japan Sea (Figure 7c) and, in this period, the Korean peninsula moved anticlockwise, breaking away from the Chinese mainland (Qian, 2004). The motion of the Pacific plate coupled with the coeval Indian-Eurasian collision intensified extension in northeast Asia and the Bohai Bay Basin experienced a second stage of extension in response to opening of the Japan Sea.

In the Miocene (25-12 Ma), the Japan Sea continued to open and was transformed from pull-apart basin to back-arc spreading centre, triggering the onset of oceanic crust formation. The spreading ridge in the Japan Sea ran approximately north-south (Jolivet *et al.*, 1994; Itoh, 2001). The principal compressive stress was approximate E-W in the Northeast Asia due to the interaction between the Indian, Eurasian and Pacific plates and the southwest of Japan developed inversion structures in this period (Itoh, 2001). The Bohai Bay Basin stopped rifting in this compressive stress field and the basin, as a whole, experienced thermal subsidence. The Tanlu Fault Zone became a transpressive dextral strike-slip zone (Xu, 1993) while the Bohai Bay Basin experienced inversion deformation (Figure 7d) (Zhao and Zheng, 2005; Zhao and Windley, 1990).

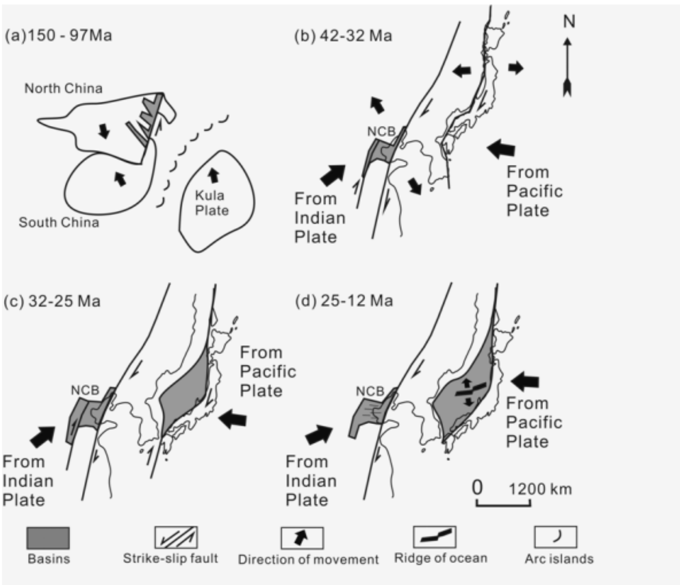
Northeast Asia was still in the E-W trending compressive regime in the Pliocene (12-2 Ma). The Japan Sea stopped opening, and rifting within the Bohai Bay Basin was reduced as the region entered a post-rift stage and experienced thermal subsidence. From 2 Ma, the compressive stress changed to a northeast-southwest orientation in northeast Asia (Huang *et al.*, 1996) and tectonic subsidence was superimposed on the offshore portion of the basin (Hu *et al.*, 2001) (Table1).

The intensity of Cenozoic extension in the Bohai Bay Basin suggests that the destruction of the NC occurred mainly in the east of the craton during the Cenozoic. The destruction of the craton was concentrated in the offshore portion of the Bohai Bay Basin.

## Conclusions

At the Late Triassic, the North China craton and South China craton collided at the Qinling-Dabie Orogen and resulted in the thickening of the lithosphere in the North China craton (Figure 8a). At about 160-150 Ma (Late Jurassic), drastic thinning and collapse of the lithosphere occurred in the eastern NC due to delamination of the cold and heavy lithosphere (Deng *et al.*, 2000; Zhang *et al.*, 2001a, 2001b, 2001c; Gao *et al.*, 2002). The delamination led to upwelling of the asthenosphere, volcanism and the production of granite belts in the eastern NC (Dong *et al.*, 2000; Hou *et al.*, 2003). Following delamination, thinning of the lithosphere and collapse of the plateau occurred. The initial extension and collapse of the Eastern North China Plateau began in the Late Jurassic and Early Cretaceous. The extensive collapse of the plateau happened predominantly in the Eocene and caused development of the extensional basins-mountains system (Ma *et al.*, 1983; Zheng *et al.*, 1988; Hou *et al.*, 2001; Wang *et al.*, 2005). The destruction of the NC finally produces the thinnest lithosphere of the eastern China (Figure 8b and 8c).

**Figure 8. The destruction history of the North China Craton**




(a) Intra-plate deformation of the North China Craton; (b) the first stage of destruction of the NCC (delamination of lower crust); (c) the second stage of destruction of the NCC (underplating and replacement of lithoshpere).

The above-discussed tectonics of the Bohai Bay Basin suggests that the basin experienced a complex evolution in the Mesozoic and Cenozoic. The evolution of the basin spans from the Late Jurassic to the Neogene, and discrete, Late Jurassic-Early Cretaceous and Eogene-Neogene rifting cycles are distinguished on the basis of differing basin orientations. Extension and thermal subsidence of the basin is related to rifting events triggered by the response of the Eurasian plate to movement of the Kula and Pacific plates.

The Eastern North China Plateau resulted from Early Mesozoic convergence between the NC and the SC. Evidence for the onset of the destruction of the NC, triggered by the delamination of thick lithosphere of the eastern NC, is preserved in the NW-trending grabens which form an en echelon arrangement on the west of Tanlu Fault Zone and the NNE-trending grabens within the Tanlu Fault Zone (especially in the offshore portion of the Bohai Bay Basin). The extensive destruction of the craton was associated with the broader extensional environment of northeast Asia. The offshore (Bohai Sea) portion is the region that best preserves the evidence of the destruction of the NC. The NC represents a non-typical craton unique with respect to the Earth’s other stable cratons.

## Acknowledgements

Thanks to Daniel R. Viete (Australia) for assistance in editing and to Prof. Gordon S. Lister (ANU Research School of Earth Sciences). Thanks to Chief Geologist Cai Dongsheng for providing seismic sections for the Shengli, Liaohe and Bohai oilfields. Research for this paper was funded by NSFC (Nos. 40772121, 40172066 and 40314141) and the National 973 Project (2009CB219302).

## References

Allen, M.B., Macdonald, D.I.M., Zhao, X., Vincent, S.J., and Brouet-Menzies, C., 1997. Early Cenozoic two-phase extension and late Cenozoic thermal subsidence inversion of the Bohai Basin, northern China. Marine and Petroleum Geology, 14: 951-972. 10.1016/S0264-8172(97)00027-5

Chen, A., 1998. Geometric and kinematic evolution of basement-cored structures: intraplate orogenesis within the Yanshan Orogen, northern China. Tectonophysics, 292: 17-42. 10.1016/S0040-1951(98)00062-6

Dong, S., Wu, X., Wu, Z., Deng, J., Gao, R., and Wang, C., 2000. On tectonic seesawing of the East Asia continent: global implication of the Yanshanian Movement. Geological Review, 46(1): 8-13 (in Chinese with English abstract).

Fu, Z., Liu, J., Liu, G. 2004. On the long-term seismic hazard analysis in the Zhangjiakou-Penglai seismotectonic zone, China. Tectonophysics 390, 75-83. 10.1016/j.tecto.2004.03.021

Gao, S., Rudnick, R.L., Carlson, R.W., McDonough, W.F., and Liu, Y.S. 2002. Re-Os evidence for replacement of ancient mantle lithosphere beneath the NC. Earth and Planetary Science Letters, 6: 135, 1-15.

Gibbs, A.D., 1983. Balanced cross-section construction from seismic sections in areas of extensional tectonics. Journal of Structural Geology, 5: 153-160. 10.1016/0191-8141(83)90040-8

Gong, Z., Wang, S., and Mao, X. 1987. Petroleum area in the offshore and adjacent regions. Petroleum Geology of China. Beijing: Petroleum Press, Vol. 16: 258pp (in Chinese).

He, L., Wang, J., 2003. Cenozoic thermal history of the Bohai Bay Basin: constraints from heat flow and coupled basin-mountain modeling. Physics and Chemistry of the Earth, 28: 421-429.

Hong, H., 1989. Crustal stretching instability and formation of the Cenozoic basin in the North China Plain. Physics and Chemistry of the Earth, 17: 169-177. 10.1016/0079-1946(89)90022-0

Hou, G., Qian, X., and Cai, D., 2001. The tectonic evolution of Bohai Basin in Mesozoic and Cenozoic time. Acta Scientiarum Naturalium Universitatis Pekinensis, 37: 845-851 (in Chinese with English abstract).

Hou, G., Qian, X., and Cai, D., 2003. Cretaceous-Paleogene rifting in the Bohai Sea and Western Shandong: geochemical evidence from volcanic rocks. Chinese Journal of Geology, 38: 13-21 (in Chinese with English abstract).

Hsiao, L.Y., Graham, S.A., and Tilander, N., 2004, Seismic reflection imaging of a major strike-slip fault zone in a rift system: Paleogene structure and evolution of the Tan-Lu fault system, Liaodong Bay, Bohai, offshore China, AAPG Bulletin, 88: 71-97. 10.1306/09090302019

Hu, S., O'Sullivan, P.B., Raza, A., and Kohn, B.P., 2001. Thermal history and tectonic subsidence of the Bohai Basin, northern China: a Cenozoic rifted and local pull-apart basin. Physics of the Earth and Planetary Interior, 126: 221-235. 10.1016/S0031-9201(01)00257-6

Huang, W., Gao, W., and Ding, G., 1996. Neogene volcanism and Holocene earthquakes in the Tanlu fault zone, eastern China. Tectonophysics, 260: 259-270. 10.1016/0040-1951(95)00195-6

Jolivet, L., Cadet, J.P., and Lalevee, F., 1988. Meozoic evolution of Northeast Asia and the collision of the Okhotsk microcontinent. Tectonophysics, 149: 89-109. 10.1016/0040-1951(88)90120-5

Jolivet, L., Tamaki, K., and Fournier, M., 1994. Japan Sea, opening history and mechanism: A synthesis. Journal of Geophysics Research, 99: 22, 237-259.

Kusky, T.M., and Li, J.H., 2003. Paleoproterozoic tectonic evolution of the NC. Journal of Asian Earth Science, 22: 383-397. 10.1016/S1367-9120(03)00071-3

Lallemand, S., and Jolivet, L. 1986. Japan Sea: a pull-apart basin? Earth and Planetary Science Letters, 76: 375-389. 10.1016/0012-821X(86)90088-9

Li, D.S., 1986. The compounded geological characteristics of the Bohai Bay Basin. China Petroleum (summer), 20-31 (in Chinese with English abstract).

Li, R.Q., 1998. Revisit for the leveling surface of the Mt. Wutai. Shanxi Seismology, 93(2): 29-49.

Lin, C.Y., 1985. Quaternary glacial debris in the peak of the Mt.Wutai. Bulletin of Tianjin Geological Research Institute, 9: 599-614 (in Chinese with English abstract).

Liu, G., 1997. The Cenozoic rift system of the North China Plain and the deep internal process. Tectonophysics, 133: 277-285. 10.1016/0040-1951(87)90270-8

Liu, J., Han, J., and Fyfe, W., 2001. Cenozoic episodic volcanism and continental rifting in northeast China and possible link to Japan Sea development as revealed from K-Ar geochronology. Tectonophysics, 339: 385-401. 10.1016/S0040-1951(01)00132-9

Lu, K., Qi, J., and Tong, H., 1997. The tectonic mode of the Cenozoic Petroleum Bohai Bay Basin. Beijing: Geological Publication House, 356 pp (in Chinese).

Ma, X., Liu, H., Wang, W., and Wang, Y., 1983. The Mesozoic and Cenozoic rifting and extension structures in the Eastern China. Acta Geologica Sinica (English edition), 57(1): 22-31.

Parés, J.M., and Moore, T.C. 2005. New evidence for the Hawaiian hotspot plume motion since the Eocene. Earth and Planetary Science Letters, 237: 951-959. 10.1016/j.epsl.2005.06.012

Qi, J.F., YU, F.S., Lu, K.Z., Zhou, J.X., Wan, G.Z., and Yan, G.Q., 2003. Conspectus on Mesozoic basins in Bohai Bay province. Earth Science Frontiers, 10:199-126 (in Chinese with English abstract).

Qian, X., 1986. The tectonics of the North China craton. In: Zhang, W. (Ed.), The tectonics of Chinese continent, offshore and adjacent region. Beijing: Science Publication, 575 (in Chinese with English abstracts).

Qian, X., 2004. On the basic features of the regional geological tectonics of China –The key to understanding of the Cenozoic intra-plate orogeny. Earth Science Frontier, 11: 221-225 (in Chinese with English abstract).

Ross, J.V., Mercier, J., and Xu, Y., 1996. Diffusion creep in the upper mantle: an example from the Tanlu Fault, northeastern China. Tectonophysics, 261: 315-329. 10.1016/0040-1951(95)00158-1

Shang, Y.J., Yue, Z.Q., Xia, B.D., Lin, H.M., and Li, G.H., 2002. A tectonic escape model for the formation of sedimentary basins in the Yangzhou block of the Lower Yangtze Region, Eastern China. Journal of Asian Earth Science, 20: 105-117. 10.1016/S1367-9120(01)00026-8

Shao, J., Zhang, C., Zhang, L., and Zhang, Y., 2003. Disscussion on the Basin-Mountains model of the North China. Progress in Nature Science, 13: 218-224.

Tian, Z.Y, Han, Ping., and Ding, X.K., 1992. The Mesozoic-Cenozoic East China rift system. Tectonophysics, 208,: 341-363. 10.1016/0040-1951(92)90354-9

Wan, T.F., and Zeng, H.L., 2002. The distinctive characteristics of the Sino-Korean and the Yangtze plates. Journal of Asian Earth Science, 20: 881-888. 10.1016/S1367-9120(01)00068-2

Wang, J.Y., Chen, M., Wang, J.A., and Deng, X., 1985. On the evolution of the geothermal regime of the BOHAI BAY BASIN. Journal of Geodynamics, 4: 133-148.

Wang, J.Y., and Wang, J.A., 1988. Thermal structure of the crust and upper mantle of the Liaohe Rift Basin, North China. Tectonophysics, 145: 293-304. 10.1016/0040-1951(88)90201-6

Wang, Y., Houseman, G.A., Lin, G., Guo, F., Wang, Y., Fan, W., and Chang, X., 2005. Mesozoic lithospheric deoformation in the NC: Numerical simulation of evolution from orogenic belt to extensional basin system. Tectonophysics, 405: 47-63. 10.1016/j.tecto.2005.05.012

Xu, J., 1993. Basic characteristics and evolution of the Tancheng-Lujiang Fault Zone. In: Xu, J. (Ed.), The Tancheng-Lujiang Wrench Fault System Wiley, Chichester, 17-50.

Xu, Y. G., Ross, J.V., and Mercier, J., 1993. The upper mantle beneath the continental rift of Tanlu, Eastern China: evidence for the intra-lithospheric shear zones. Tectonopysics, 225: 337-360. 10.1016/0040-1951(93)90304-3

Yasuto Itoh, 2001. A Miocene pull-apart deformation zone at the western margin of the Japan Sea back-arc basin: implications for the back-arc opening mode. Tectonophysics, 334: 235-244. 10.1016/S0040-1951(01)00068-3

Ye, H., Zhang, B., and Mao, F., 1985. The Cenozoic tectonic evolution of the Great North China: two types of rifting and crustal necking in the Great North China and their tectonic implications. Tectonophysics, 133: 217-227. 10.1016/0040-1951(87)90265-4

Yi, X., and Hou, G., 2002. A study of intensity of the faults activity in Jiyang Depression in Mesozoic and Cenozoic. Acta Scientiarum Naturalium Universitatis Pekinensis, 38: 504-509 (in Chinese with English abstract).

Yin, A., and Nie, S. Y., 1996. Phanerozoic palinspastic reconstruction of China and its neighboring regions. In: Yin, A., Harrison, T.M. (Eds.), The Tectonic Evolution of Asia, London: Cambridge University Press. pp. 442-485.

Zhang, K., 1997. North and South China collision along the eastern and southern North China margins. Tectonophysics, 270: 145-156. 10.1016/S0040-1951(96)00208-9

Zhang Qi, Qian Qing, and Wang Erqi. 2001a. Existence of East China Plateau in mid-late Yanshan Period: implication from adakites. Scientia Geologica Sinica, 36 (2): 248 - 255 (in Chinese with English abstract).

Zhang Qi, Wang Yan, Qian Qing, Yang JH, Wang YL, Zhao TP, and Guo GJ. 2001b. The characteristics and tectonic- metallogenic significance of the adakites in Yanshan Period from eastern China. Acta Petrologica Sinica, 17 (2): 236 - 244 (in Chinese with English abstract).

Zhang Qi, Wang Y, and Wang YL. 2001c. Preliminary study on the components of the lower crust in east China Plateau during Yanshanian Period: constraints on Sr and Nd isotopic compositions of adakite-like rocks. Acta Petrologica Sinica, 17 (4):505 - 513 (in Chinese with English abstract)

Zhai, M.G., Guo, J.H., Liu, and W.J., 2005. NeoArchaean to PalaeoProterozoic continental evolution and tectonic history of the NC: a review. Journal of Asian Earth Science, 24: 547-561. 10.1016/j.jseaes.2004.01.018

Zhao, G.C., Cawood, P.A., Wilde, S.A., and Lu, L.Z., 2000. Metamorphism of basement rocks in the Central Zone of the NC: implications for Paleoproterozoic tectonic evolution. Precambrian Research, 103: 55-88. 10.1016/S0301-9268(00)00076-0

Zhao, L., and Zheng, T., 2005. Seismic structure of the Bohai Bay Basin, northern China: Implications for basin evolution. Earth and Planetary Science Letters, 271: 9-22. 10.1016/j.epsl.2004.12.028

Zhao, Z., and Windley, B.F., 1990. Cenozoic tectonic extension and inversion of the Jizhong Basin, Hebei, northern China. Tectonophysics, 185: 83-89. 10.1016/0040-1951(90)90406-X

Zheng, Y., Wang, Y., Liu, R., and Shao, J., 1988. Sliding-thrusting tectonics caused by thermal uplift in the Yunmeng Mountains, Beijing, China. Journal of Structural Geology, 10(2): 135-144. 10.1016/0191-8141(88)90111-3