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REVIEWS

Meso-Cenozoic Evolution of Earth Surface System under the East Asian Tectonic Superconvergence

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Abstract: The East Asian geological setting has a long duration related to the superconvergence of the Paleo-Asian, Tethyan and Paleo-Pacific tectonic domains. The Triassic Indosinian Movement contributed to an unified passive continental margin in East Asia. The later ophiolites and I-type granites associated with subduction of the Paleo-Pacific Plate in the Late Triassic, suggest a transition from passive to active continental margins. With the presence of the ongoing westward migration of the Paleo-Pacific Subduction Zone, the sinistral transpressional stress field could play an important role in the intraplate deformation in East Asia during the Late Triassic to Middle Jurassic, being characterized by the transition from the E-W-trending structural system controlled by the Tethys and Paleo-Asian oceans to the NE-trending structural system caused by the Paleo-Pacific Ocean subduction. The continuously westward migration of the subduction zones resulted in the transpressional stress field in East Asia marked by the emergence of the Eastern North China Plateau and the formation of the Andean-type active continental margin from late Late Jurassic to Early Cretaceous (160-135 Ma), accompanied by the development of a small amount of adakites. In the Late Cretaceous (135-90 Ma), due to the eastward retreat of the Paleo-Pacific Subduction Zone, the regional stress field was replaced from sinistral transpression to transtension. Since a large amount of late-stage adakites and metamorphic core complexes developed, the Andean-type active continental margin was destroyed and the Eastern North China Plateau started to collapse. In the Late Cretaceous, the extension in East Asia gradually decreased the eastward retreat of the Paleo-Pacific subduction zones. Futhermore, a significant topographic inversion had taken place during the Cenozoic that resulted from a rapid uplift of the Tibet Plateau resulting from the India-Eurasian collision and the formation of the Bohai Bay Basin and other basins in the East Asian continental margin. The inversion caused a remarkable eastward migration of deformation, basin formation and magmatism. Meanwhile, the basins that mainly developed in the Paleogene resulted in a three-step topography which typically appears to drop eastward in altitude. In the Neogene, the basins underwent a rapid subsidence in some depressions after basin-controlled faulting, as well as the intracontinental extensional events in East Asia, and are likely to be a contribution to the uplift of the Tibetan Plateau.

Key words: superconvergence, topographic inversion, Meso-Cenozoic, East Asia

1 Introduction

The Mesozoic and Cenozoic East Asian tectonic setting is under a background of change from a convergent-collisional dynamic system to an active continental margin dynamic system (Dong Shuwen et al., 2008), and is also within the combined action area of the Tethyan, the Paleo-Asian and the Paleo-Pacific (or the Pacific) tectonic domains, including orogenic belts, cratons, ocean-

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continent connection zones and other tectonic units.

In the Early Mesozoic, East Asia was entirely under a compressive stress control to form the Central China Orogen, the Andean-type orogenic belt on the eastern margin of East Asia, the Mongol-Okhotsk Orogenic Belt, and other Mesozoic orogenic belts (Dong Shuwen et al., 2007; Sun et al., 2007; Huang Shiqi et al., 2016; Li Sanzhong et al., 2017a), and within cratons, such as the North China and South China cratons, there are a strong Indosinian-Yanshanian intraplate thrusting, thickening of the crust, plateau uplifting, adakite formation, and other geological processes.

In the Late Mesozoic–Cenozoic, the Paleo-Pacific Plate continues to subduct under the East Asian Continent, and the large-scale NE–NNE-trending strike-slip fault system developed in the eastern margin and inner side of East Asia (Shao Ji'an and Tang Kedong, 1995). The deep and shallow parts of the North China Craton experienced strong tectonic superimposition and magmatic intrusions. Under the influence of underplating, delamination, and other possible deep mechanisms, the lithosphere of the North China Craton appeared to undergo large-scale destruction and loss, its thickness being reduced from an average of 200 km to about 100 km. The core or centre of the destruction is located in the Bohai Bay Basin, where the present-day thinned lithosphere thickness is 80 km (Li Sanzhong et al., 2011). Accompanied by formation of the rifted basins and metamorphic core complexes, the plateau in eastern North China under the influence of extension and detachment completely disappeared, it behaved as a plain in relief, the plateau formed as a remnant only in the Luxi region, western Shandong Province (Zhang Jian et al., 2017).The large-scale geomorphic reversal from the Mesozoic plateau to the Cenozoic plain in the eastern North China Craton (Cao Xianzhi et al., 2015; Xu Liqing et al., 2016) resulted in a huge transformation of the Earth surface system.

As the topography and geomorphology of the inner parts of East Asia were changing, the northward subduction of the Neo-Tethyan Ocean occurred along the southern margin of East Asia (Morley et al., 2008), the northward migration of the Indo-Australian Plate, a collision with the Eurasian Plate at 45 Ma (Wang Erqi, 2017), the Qinghai-Tibetan Plateau began to form and reached the peak plateau height after the Miocene, the surrounding blocks extruded and escaped to both the east and west sides. During the Mesozoic the Qinghai-Tibetan Plateau formed in a marine environment, but later in the Cenozoic began to rise as a huge reversal occurred.

On the whole, in the East Asia region with China as the core, during the Mesozoic and Cenozoic, the seesaw-type giant reversion of the relief and geomorphology of the east and west areas of China occurred. The Mesozoic relief was high in the east and low in the west, while the Cenozoic relief was high in the west and low in the east. The giant geomorphic changes are accompanied by changes of the river-lake system adjustment, source-channel-sink effect, biomes migration, ecosystem adjustment and other obvious changes in the Earth surface system.

What is the global tectonic background? What are the deep processes? What does it symbolize in the big scientific problems? Based on the analysis at different scales, some geoscientists emphasized that the superconvergence was synchronous with the initial break-up of Gondwana, others suggested that it was related to the subduction of the Pacific Plate, whereas some considered that the extinction of the Neo-Tethyan Ocean played the dominant role; not surprisingly, there is always a huge debate.

For this reason, based on Scotese's plate reconstruction and topographic reconstruction (Scotese, 2016), and on the long-term group research on the East Asian tectonics, this paper attempts to provide a profound overview of the evolution of the Earth surface system of East Asia at different times through the Mesozoic and Cenozoic, which can be used as background information for specialists in the different fields of sediment dynamics, basin dynamics, orogenic dynamics and structural kinetics and others.

2 Mesozoic East Asian Superconvergence and the Evolution of the Earth Surface System

The most northern part of East Asia is the Siberian Craton, the southernmost part is the Indian Plate, the Malaya Plate, the Indochina Block and the Kalimantan Block, the easternmost part is the Philippine Sea Plate and the Pacific Plate (Fig. 1).

The E-W-trending Central Asian Orogenic Belt between the Siberian Craton and the Amur Plate in the north of East Asia has an eastward extension, resulting from the subduction of the Paleo-Asian Ocean to the south and the block collision. The Paleo-Asian Ocean Basin initially closed in the Permian (Xiao Wenjiao et al., 2003; Li Jinyi, 2006), and then continued to be a deformed orocline, convex to the south.

The boundary between the Amur Plate and the North China Craton is the E–W-striking Solonkar- Moron-Changchun Suture. After experiencing a long-range block drifting from the low latitudes to the high latitudes, the North China Craton and the Amur Plate started a convergence and collided in the northern hemisphere during the Triassic (Osozawa, 1994; Shao Ji'an and Tang Kedong, 1995; Zhang Yueqiao et al., 2008). The Siberian

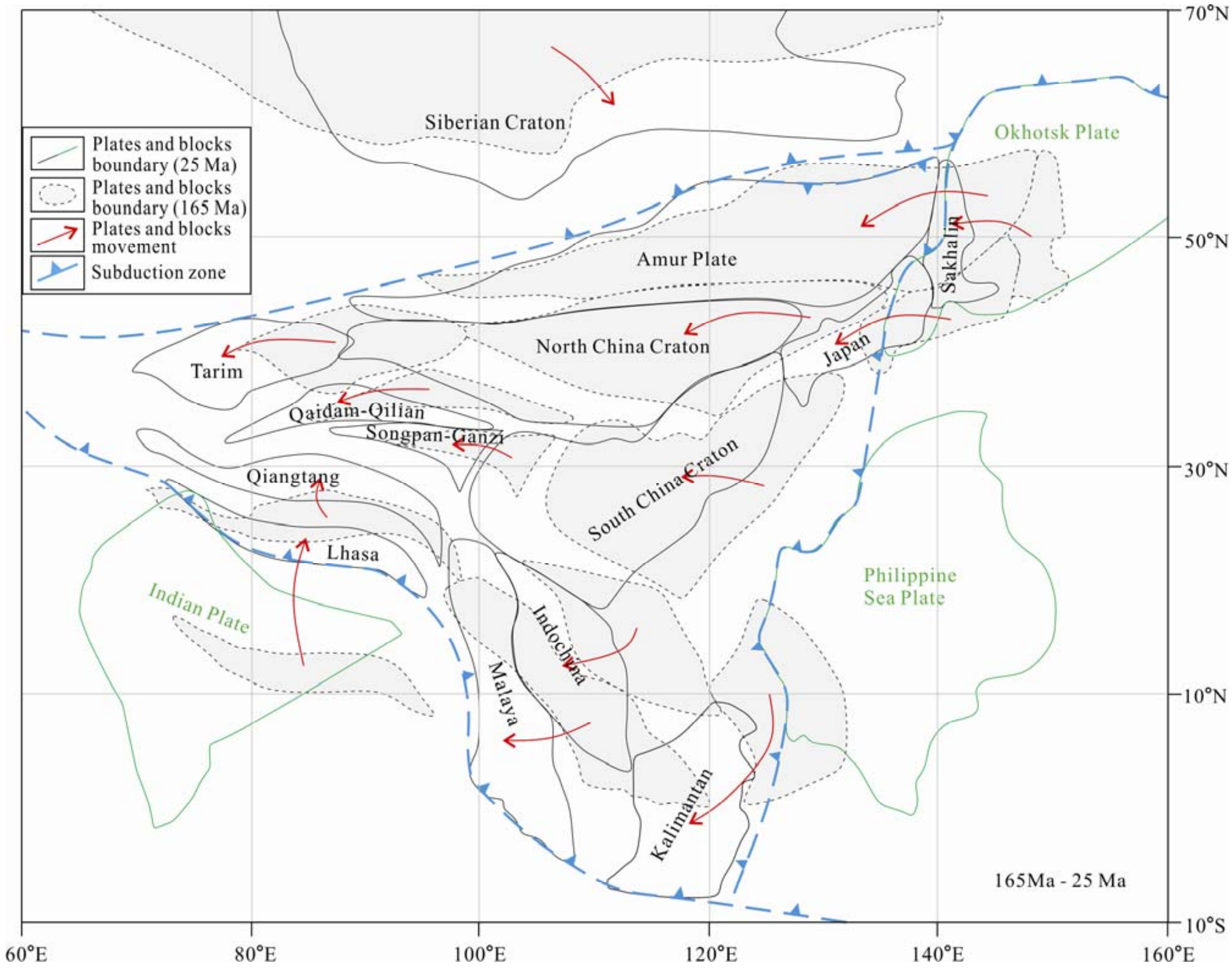

Fig. 1. Schematic tectonic map showing Mesozoic-Cenozoic blocks migration in East Asia.

Craton, the Amur Plate, and the Central Asian Orogenic Belt are the component of the Paleo-Asian Tectonic Domain.

The micro-continental blocks south of the North China Craton and the Tarim Block belong to the Tethyan Tectonic Domain, including the Qaidam-Qilian Block, Songpan-Ganzi Block, Qiangtang Block, South China Craton, and others. The Paleo-Luonan-Luanchuan, Longmu Co-Shuanghu, Bangong-Nujiang sutures and many other collisional zones developed between these micro-continental blocks. Among them, the Paleo-Luonan -Luanchuan Suture between the North China Craton and the Qaidam-Qilian Block represents the northern boundary of the Proto-Tethyan Ocean (Li Tao et al., 2015; Zhao Shujuan et al., 2016; Li Sanzhong et al., 2017b); the Longmu Co-Shuanghu Suture between the south and north Qiangtang blocks marked the southern boundary of the Proto-Tethyan Ocean (An Huiting et al., 2014; Li Sanzhong et al., 2017b).

The Mianlue Suture between the North China and South China cratons and the Bangong-Nujiang Suture between the Qiangtang and the Lhasa blocks represent the closing locations of the Paleo-Tethyan Ocean Basin in the Late Triassic (Pullen et al., 2008; Li Sanzhong et al., 2017b; Metcalfe, 2011).

The area to the south of the Qiangtang Block belongs to the Neo-Tethyan Tectonic Domain, including the Lhasa Block and the Indian Plate. In the beginning of the Late Jurassic, the Neo-Tethyan Ocean subducted beneath the East Asian Continent (Morley and Alvey, 2015). 45 Ma ago, the Neo-Tethyan Ocean disappeared, the Indian Plate collided with the East Asian Continent, and the Qinghai-Tibet Plateau began to form (Hall, 2012).

From the inner parts of East Asia, such as the Greater Khingan-Taihang-Xuefeng Mountains, in a seawards (easterly) direction, in accordance with the gravity gradient line, the crustal thickness decreases obviously (Jiang Suhua et al., 2017), the continental crust gradually transited into the oceanic crust, at the same time, the tectono-magmatic-sedimentary processes showed an obvious NE-NNE-trending distribution (Dmitrienko et al., 2016).

The eastern East Asian margin was a passive continental margin before the Triassic (Li Sanzhong et al., 2011), however, it was followed by the subduction of the Paleo-Pacific (Izanagi) Plate to East Asia after the Late Triassic. The eastern East Asian margin is under the transition of the E-W-trending Paleo-Asian Tectonic Domain into the NE-NNE-trending Paleo-Pacific Tectonic Domain (Cao Xianzhi et al., 2015; Ge Rongfeng et al., 2010), forming a broad NE-trending Andean-type continental margin (Honza and Fujioka, 2004; Müller et al., 2008). The Late Mesozoic-Cenozoic deformation and magmatism have a tendency to form a gradual change from west to east (Mao Jianren et al., 2009; Suo Yanhui et al., 2014, 2015). Due to the oblique subduction of the Paleo-Pacific Plate, a series of NE-NNE-striking sinistral transpressional faults developed in eastern East Asia from the Late Jurassic to the Early Cretaceous (Zhu Guang et al., 2001). Following the changing of the subduction direction of the Pacific Plate in the Cenozoic, the NNE-trending strike-slip faults in eastern East Asia had been converted to dextral strike-slip faults (Shao Ji'an and Tang Kedong, 1995; Suo et al., 2014), resulting in a large number of Cenozoic basins (Li Sanzhong et al., 2012; Cheng Shixiu et al, 2014).

2.1 Late Triassic - Middle Jurassic thrust system and the nature of Earth surface system (~160 Ma)

During the opening of the Paleo-Tethyan Ocean, several micro-blocks in East Asia successively drifted away from the northern margin of the Gondwana Continent. Subsequently, a series of orogens or high pressure/ultra-high pressure metamorphic belts had developed in the Indosinian, accompanied by long-term northward drifting. In the Late Triassic, a uniform Ocean–Continent Connection Zone (OCCZ) developed in East Asia (Guo Runhua et al., 2017a; Li Sanzhong et al., 2017a).

It is a controversial issue regarding the initial age of the Paleo-Pacific Plate subduction under the East Asian Continent, as well as when the passive continental margin converted to an active continental margin in East Asia. It is generally recognized that the Paleo-Pacific Plate began to subduct partly at the end of the Carboniferous (Isozaki et al., 2010) or Early or Middle Permian (Li Xianhua et al., 2000; Isozaki et al., 2010; Li Sanzhong et al., 2017a, b), subducting as a unified active continental margin in the Late Triassic (Li Sanzhong et al., 2011). Meanwhile, E–W-trending structures were overprinted by NE–NNE-trending structures in East Asia. Subsequently, the thrusting mechanism was replaced by an extensional mechanism with the significant changes of Earth surface system in the eastern East Asian continental margin.

(1) Northern East Asia

In this complex area, the northern segment of East Asia consists of the Central Asian Orogenic Belt (CAOB) and the Amur Plate (also called the Sino-Mongolia-Songnen Block), being bounded by the Siberian Craton to the north and the North China Craton to the South, respectively. The CAOB, a curved orogenic belt, which displays a NW-trending strike in the west part while the ENE-trending in the east part, has a shape with a southward convex (Fig. 2). As an accretionary collage of the last southward subduction of the Paleo-Asian Ocean (Coleman, 1989), the CAOB included several micro-blocks which collided eventually during the Late Permian (Xiao Wenjiao et al., 2003; Li Jinyi, 2006).

During the superconvergence in East Asia, the CAOB had been settled in a compressive regime. As a result, the broader intra-continental deformation took place in the Altay Mountains and Tianshan Mountains. Additionally, the Altay Mountains underwent uplifting since the Early Triassic to Late Jurassic. Especially in the eastern Altay area, the Kelameili Mountains uplifted rapidly since the Late Triassic to Early Jurassic interval, as interpreted by evidence from apatite fission track data. Intensive deformation took place in the Tianshan Orogen at the end of the Indosinian period. Specifically, the Tianshan Orogen experienced a fast-stage uplifting episode and the thrust-nappe belt formed along its southern and northern peripheries. Sedimentary strata underwent substantial erosion in the Junggar Basin because of significant uplifting (Zhang Chuanheng et al., 2005; Yan Shulan et al., 2008). Some strike-slip faults developed in the Junggar Basin, being characterized by northwestward divergence and southeastward convergence. The adjacent orogenic belts around the Junggar Basin had intraplate deformation during the Late Triassic to Middle Jurassic. The deposition center as well as the source rocks and petroleum reservoirs in the Junggar Basin migrated southward (Sun Wenjun et al., 2014; Wang Xuebin et al. 2014), which resulted from the southward thrusting (Yang Zhao et al., 2015).

To the east of northern East Asia, the Okhotsk Ocean lying between the Amur Plate and the Siberian Craton, started a gradual scissor-like closing from west to east, evolving eventually into the Okhotsk structural belt (Fig. 2). The age of the Sunwu Granite indicates that the Okhotsk Ocean closed before 170 Ma in the west of the Great Khingan Mountains (Li Yu et al., 2015), whereas the subduction continued to Early Cretaceous. The processes of continental collision affected almost the whole area. The Hailar Basin, located west of Great Khingan Mountains, characterised by a near-E–W-trending long-axis basin during the Late Triassic to Early–Middle Jurassic, was filled by clastic rocks interbedded with andesite, in an upward-fining grading molasses sequence (Dong Jing, 2009). The Songliao Basin, east of the Great

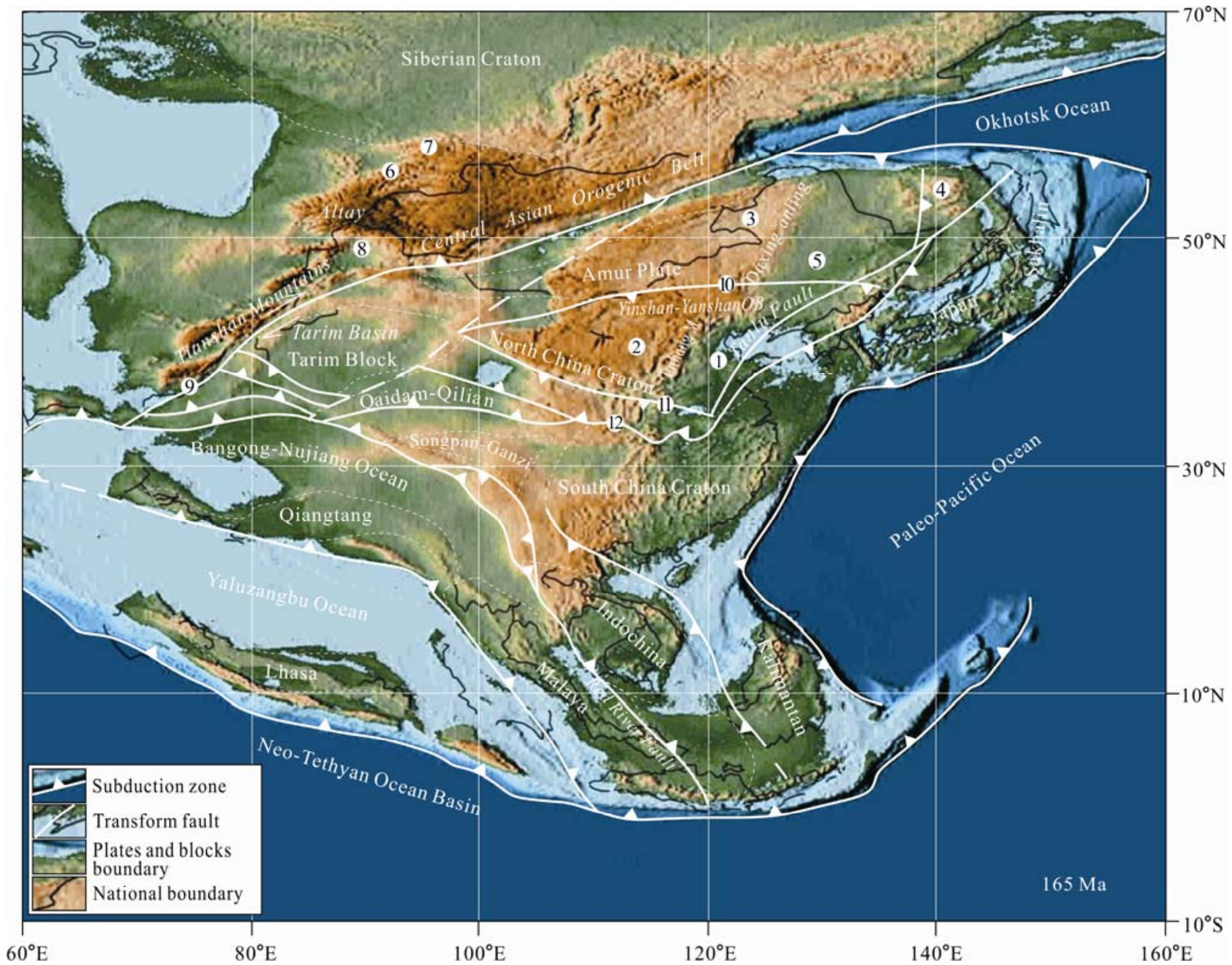

Fig. 2. Tectonic and geomorphological reconstruction of Jurassic East Asia at ca 165 Ma.
Abbreviations: M-Mountains; OB-Orogenic Belt. 1, Bohai Bay Basin; 2, Ordos Basin; 3, Hailar-Tamsag Basin; 4, Mongolian-Okhotsk Orogenic Belt; 5, Songliao Basin; 6, Western Sayan Mountains; 7, Eastern Sayan Mountains; 8, Junggar Basin; 9, Cherchen Fault Zone; 10, Solon-Xar Moron-Changchun Fault; 11, Lu'an-Hefei Fault; 12, Xiangfang-Guangji Fault.

Khingan Mountains, has similar features as those of the Hailar Basin, in which the Upper Triassic to Lower Jurassic strata underwent folding and thrusting as a response to the Early Yanshanian Movement at the end of Early Jurassic (Su Yushan et al., 2008).

In summary, the compressive tectonic mechanism dominates the northern East Asia region from Late Triassic to Middle Jurassic, which belongs to the Paleo-Asian Tectonic Domain and the Mongol-Okhotsk Tectonic Domain.

(2) Eastern East Asia

During Late Triassic to Middle Jurassic, the eastern margin of East Asia converted to an Andean-type continental margin related to a NNW-directed subduction of the Paleo-Pacific Plate beneath the East Asian Continent (Shao Ji'an and Tang Kedong, 1995). The Paleo-Pacific subduction zone possibly developed along the Sakhalin, Japanese Archipelago, southern Korea Peninsula, the Zhejiang-Fujian coastline, and the Kalimantan Block from north to south. The Paleo-Pacific subduction zone shaped in a "Ω" in conjunction with the eastern Okhotsk Ocean subduction zone to the north, and the Neo-Tethyan Ocean subduction zone to the south, respectively (Fig. 2). The subduction-related accretionary complexes that developed along the subduction zone comprise deep-sea sediments containing radiolaria, limestone, clastic successions, serpentinite and blueschist formed in the Late Triassic to Jurassic. Furthermore, the subduction complexes also mixed with the seamount rocks formed in Carboniferous to Triassic times, even the rocks with low-grade metamorphic matrix formed in the Late Jurassic to Early Cretaceous.

During Late Triassic to Middle Jurassic, the Paleo-Pacific subduction created the Nadanhada Accretionary Complex, the Wandashan Terrane and magmatic rocks in the Nadanhada Terrane located along the northern segment of eastern East Asia. The Nadanhada Accretionary Complex consists of the Yuejinshan and the Raohe complexes, which are dominated by limestone, bedded chert, basalt, meta-clastic rocks, and meta-mafic-ultramafic rocks (Zhou Jianbo et al., 2014). Geochemical data indicate that the Yuejinshan meta-basalts have an affinity of normal mid-ocean ridge basalt (N-MORB) formed in the Middle Jurassic (167 Ma) (Zhou Jianbo et al., 2014), whereas the Raohe basaltic pillow lavas have an affinity to ocean island basalts (OIB) formed at a similar age of 166±1 Ma (Zhang Qi et al., 2001; Cheng Ruiyu et al., 2006). The Wandashan Orogen, also known as the Nadanhada Terrane, is characterised by accretionary units upward younging (Kemkin et al., 2016). Under the Paleo-Pacific subduction, magmatic activity took place frequently, especially in the Khanka Terrane, located west of the Nadanhada Terrane during Late Triassic to Middle Jurassic times. Magmatic units clustered in the period 220–180 Ma and distributed in a S-N direction which is different from the E–W direction caused by the contemporary Okhotsk Ocean Subduction Zone (Wang Wei et al., 2015). Traditionally, the Nadanhada and the Khanka terranes contain a typical accretionary complex, ophiolite and magmatic rocks related to the subduction of the Paleo-Pacific Plate beneath the East Asian Continent.

In the middle part of the eastern East Asian Continent, some granites are exposed in northern Korea Peninsula (Zhai Mingguo, 2016) and South China (Li Zhengxiang and Li Xianhua, 2007) with intrusion ages of 225–184 Ma. The ages of granites tend to be younger westward parallel to strike of the subduction zone, which is interpreted as westward and forward subduction migration during the Late Triassic to Middle Jurassic. In the south part of the eastern East Asian Continent, the granites have ages of 170–160 Ma, while some granodiorites are concentrated at 170 Ma in the Dexing area of Jiangxi Province. As a magmatic arc in an Andean-type active continental margin, the magmatic belts are parallel to the restored Paleo-Pacific subduction zone (Fig. 2). Especially, the marble interbedded in the Tanan'ao Group in Taiwan is considered as fore-arc deposit, and its earlier metamorphic age of 166 Ma infers metamorphism related to the subduction.

(3) Southern East Asia

In this part, the southern East Asian Continent is composed of the Qiangtang, Malaya and Lhasa blocks, in a line shape with a NW direction, located south of the North China Craton, the Tarim Block, the South China Craton, the Qaidam-Qilian Block, the Songpan-Ganzi Block and the Indochina Block. After the Late Triassic, the active subduction zone along the southern East Asian Continent was situated south of the Qiangtang and Indochina blocks (Fig. 2). The Bangong-Nujiang Ocean, a northern branch of the Neo-Tethyan Ocean, originating from the break-up of Gondwana, had been eliminated along the northern of the Lhasa Block and the Malaysia Block. The Bangong-Nujiang Ocean occupied a relatively stable space with a northward ongoing subduction until the Early Cretaceous (Fig. 2). Subsequently, the Bangong–Nujiang Suture formed due to the last collision of the Malaysia Block, the Lhasa Block to the Qiangtang Block and the Indochina Block. The Neo-Tethyan Ocean, south of the Yarlung–Zangbo Suture, subducted northward beneath the Lhasa Block in a WNW direction, with the NE-directed extension eastward to the Malaysia Block, linking with the coeval Paleo-Pacific Subduction Zone.

(4) East Asian intra-continent

During the Late Triassic to Middle Jurassic, in the East Asian intra-continent, there were some triangular blocks, such as the North China Craton, the Tarim Block, the Qaidam-Qilian Block, the South China Craton, the Songpan-Ganzi Block and the Indochina Block. With the multidirectional subduction to the north, east and south, the triangular blocks under the transpressive stress field developed thrusting-related structures in the blocks and the escape of the blocks in the direction of low stress. The Alashan Block escaped to the ESE (Liu Shaofeng et al., 2005), and the thrust-nappes and uplifting developed in the front of the Helan Mountain. The southern parts of the North China and South China cratons developed some shrinked lacustrine basins, while the secondary triangular blocks to the east escaped to the NE or the SW. Meanwhile, the escape tectonics was controlled by the boundary of the Paleo-Pacific subduction. Because they were surrounded by multiple plates for a long time, the small- and medium-sized blocks inside the East Asian Continent had been adjusted, which resulted in the multi-stage assembly of continental blocks and the wide-range intra-continental orogeny (Zhang Guowei et al., 2013). And then there were formed polydirectional thrust-nappe structures, such as the NE-trending Longmengshan-Helan Mountain Belt, the WNW-trending Micang-Daba Mountain and Dabie Orogen, the E–W-trending Nanling Belt and so on. Those thrust-nappe structures can be subdivided into two types: subparallel to the Paleo-Pacific subduction zone and perpendicular to the Pacific subduction zone. It is difficult to explain them by the dynamic mechanism of a single plate margin.

The NE–NNE-trending Early Mesozoic thrust faults widely developed inside the North China Craton, and they displayed wide intra-continental deformation under the compression. The range of deformation was as far west as the eastern margin of the Ordos Basin (Liao Changzhen et al., 2007), which was greater than 1000 km from the plate boundary. In the Taihang Mountains, there developed widely-spaced anticlines, duplex thrusts and imbricated faults (Wu Qi, 2012). In the Luxi Block, the faults changed from the imbricated to strike-slip and the extrusion-related half grabens. At the same time, the Jura-style folds changed from widely-spaced anticlines to widely-spaced synclines (Li Sanzhong et al., 2005). These structures were parallel to the Paleo-Pacific subduction zone, and may have been influenced by the far-field effect of plate margins. In Late Triassic-Middle Jurassic, there developed WNW-trending thrusts and large-scale vertical and lateral extrusion in the Qinling-Dabie Orogen (Hacker et al., 2000; Li Sanzhong et al., 2010, 2011, 2015), which was located to the south of the North China Craton. There developed E–W-trending thrust-fold belts in the Yinshan-Yanshan Orogen in the north of the South China Craton. These activities belonged to the deformation of the Early Yanshanian Movement, marked by an angular unconformity below the andesite of the Tiaojishan Formation. Its age has been determined as 175–160 Ma (Dong Shuwen et al., 2008) or 173–160 Ma (Hu Jiangmin et al., 2007). It indicates that in the Late Triassic-Middle Jurassic, the strikes of the deformation in the north and south of the North China Craton were perpendicular to the NE–NNE-trending thrusts and nappes inside the craton, and it was also perpendicular to the Paleo-Pacific subduction zone. At present, we didn't exclude that it was the far-field effect of the southward indentation of the Siberian Craton, which was caused by the opening of the Arctic Ocean.

Between west of Xuefeng Mountain and the Huanyingshan Fault in South China, there developed NE–NNE-trending westward thrusting during the Early Yanshanian (Jin Chong et al., 2009), with a combination of the widely-spaced anticlines and synclines. And the folding and thrusting were gradually younger from east to west. Inside the North China Craton, this change corresponded to the NE–NNE-trending structures, whose influence could have extended to the Ordos Basin. In the Middle and Lower Yangtze River, we also found a NE–NNE-trending thrust-and-fold belt, which developed in the Late Triassic-Middle Jurassic. And this deformation was superimposed on the early Indosinian tectonics (Li Haibin et al., 2011; Wang Pengcheng et al., 2012, 2015). In the east of the Dabie Mountains, the Indosinian high-pressure rocks were thrust to cover the coal-bearing strata of the Lower Jurassic (Dong Shuwen et al., 2011). According to the types, the strikes of basins located in the Lower Yangtze area were NE-striking during the Late Triassic-Middle Jurassic, and the type of basins was back-arc buckling foreland basin (Li Sanzhong et al., 2017a, b; Wang Pengcheng et al., 2012; Zhu Guang et al., 1998). The NE-NNE-trending thrust-fold structures were parallel to the Paleo-Pacific subduction zone and became gradually younger from east to west, which matched with the westward subduction of the Paleo-Pacific Ocean. Meanwhile, the E–W-trending structures may be related to the near-S–N-directed intra-continental compression, which was caused by the far-field effect of the subduction to the East Asian Continent of both the Okhostk Ocean to the north and the Neo-Tethyan Ocean to the south.

According to the analysis of sedimentary environments, the crust and lithosphere of the North China Craton were strongly thickened and uplifted, and then the crust was denuded, with the effect of the NE–NNE-trending and the near-E–W-trending thrust-fold deformation. The strata of the Lower–Middle Triassic were widely distributed in the North China Craton, corresponded to large-scale lacustrine basin sedimentation (Fig. 2). During the Late Triassic to Middle Jurassic, after the uplifting of the crust, the basins shrank westward, which corresponded to the distribution range of the strata of Upper Triassic moving toward the west. Therefore, at present, the strata of the Upper Jurassic are almost missing in the North China Plain. Then the basins shrank to the eastern margin of the Ordos Basin during the Late Jurassic (Zhao Zhongyuan, 1998; Li Zhenhong et al., 2014). According to the study of the Mesozoic igneous rocks in the North China Craton, Zhang Qi et al. (2008) proposed the concept of "C-type adakite", meaning that it came from the melting of mafic rocks in the thickened lower crust. Based on the age statistics of a large number of adakites, it reveals that there was a plateau in the eastern North China Craton in the Mesozoic. The adakites developed in Late Triassic-Middle Jurassic were mainly distributed in the northern Taihang Mountains area and the Yanshan Mountain area (Cao Xianzhi et al., 2015; Xu Liqing et al., 2016). There was relatively less distribution in the southern Taihang Mountains and the Luxi Block (Zhang Jian et al., 2017). The main body of the plateau appeared and formed a rudiment in the Late Triassic-Middle Jurassic interval. After the formation of the plateau, a great change had taken place in the biocoenosis, river system, climate system and so on. The distribution of dinosaurs indicated that the dinosaurs mainly lived in the northern North China Craton during the Middle Jurassic, while there was hardly any dinosaur in the Late Jurassic epoch (Zhang Qi et al., 2008).

2.2 Late Jurassic–early Early Cretaceous extension and Earth surface system evolution (160~135 Ma)

In the Late Jurassic–early Early Cretaceous, it continued to maintain the pattern of multidirectional tectonic convergence in East Asia. The Okhotsk Ocean north of East Asia subducted to both the north and south sides, and it was finally closed in the Late Cretaceous. And then, it resulted in the Mongo Okhotsk tectonic unit and the intensive deformation in the Yinshan-Yanshan Orogen. The subduction of the Paleo-Pacific Plate beneath the East Asian Continent caused the formation of an Andean-type active continental margin and the uplifting of onshore mountains. The northern segment of the continental margin was named the Sikhote-Alin Orogen, the middle segment corresponded to the continental margin of Southeast China, and the southern segment developed the Kalimantan Accretionary Orogenic Belt (Wang Pengcheng et al., 2016). The subduction resulted in the formation of abundant intermediate–acid igneous rocks. The continuously northward subduction of the Neo-Tethyan Ocean in southern East Asia caused the joining of the Lhasa and Qiangtang blocks, and the crust near the subduction zone was strongly uplifted (Fig. 3). The blocks inside the East Asian Continent, such as the North China Craton, the South China Craton and the Tarim Block, were strongly uplifted due to the effect of thrusting. At the center of the convergence, the plateau east of the Ordos Basin and the mountains along the eastern coast eventually formed, following the plateau rudiment in Late Triassic-Middle Jurassic (Fig. 3).

(1) North margin of East Asia

During the Late Jurassic–Early Cretaceous, the Siberian Craton rotated clockwise, while the Amur Plate rotated counterclockwise, causing the subduction and closure of the Okhotsk Ocean between the two blocks (Nie Shangyou et al., 1990; Oxman, 2003). And then there formed the Mongol-Okhotsk tectonic unit. In Middle to Late Jurassic, there developed intermediate and intermediate-basic volcanics in the Erguna Block. Those

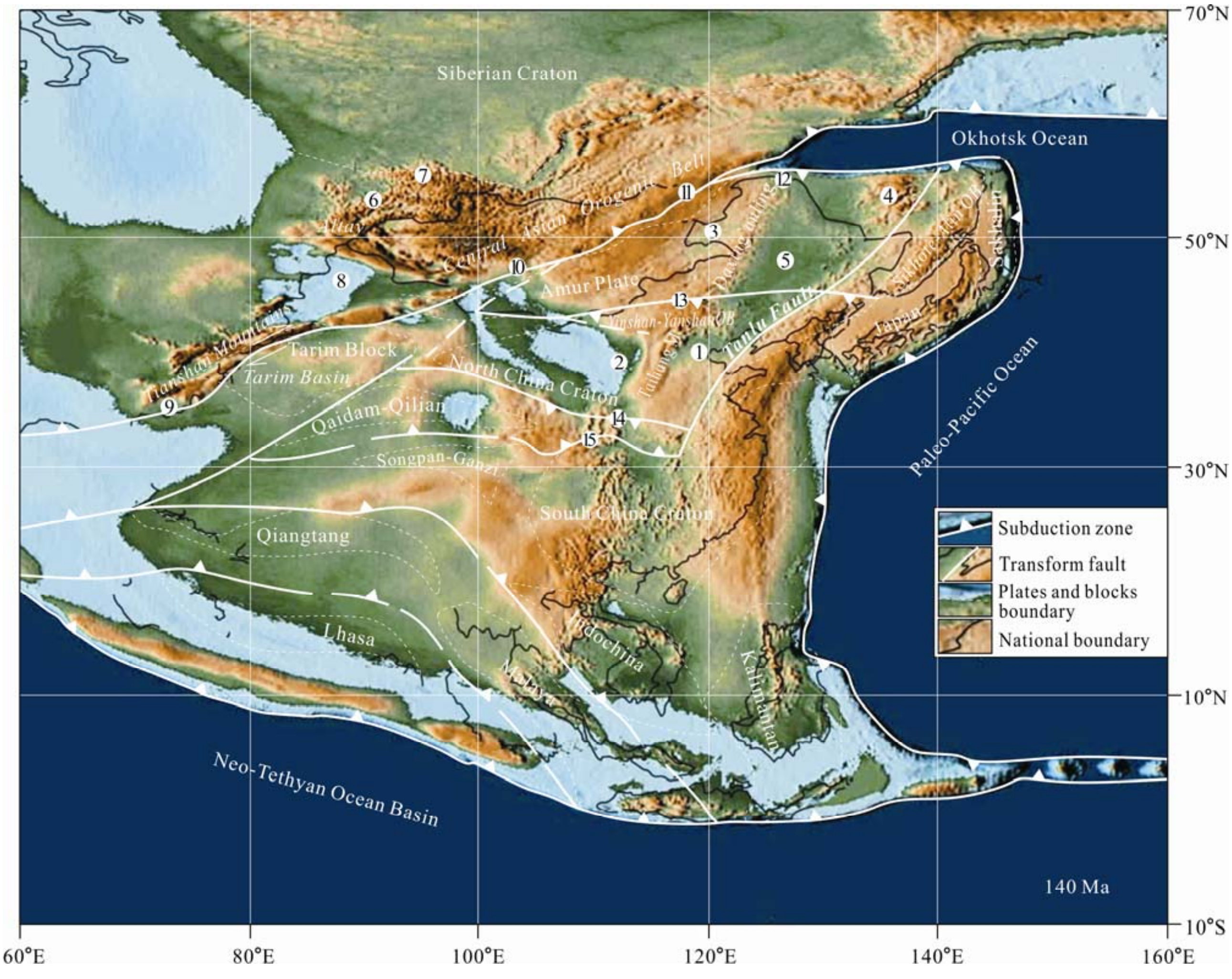

Fig. 3. Tectonic and geomorphological reconstruction of early Early Cretaceous East Asia at ca 140 Ma.
Abbreviations: M-Mountains; OB-Orogenic Belt. 1, Bohai Bay Basin; 2, Ordos Basin; 3, Hailar-Tamsag Basin; 4, Mongolian-Okhotsk Orogenic Belt; 5, Songliao Basin; 6, Western Sayan Mountains; 7, Eastern Sayan Mountains; 8, Junggar Basin; 9, Cherchen Fault Zone; 10, Gobi-Onon Fault; 11, Mongolian-Okhotsk Suture; 12, Mohe Basin; 13, Solon-Xar Moron-Changchun Fault; 14, Lu'an-Hefei Fault; 15, Xiangfang-Guangji Fault

volcanics included rhyolite, andesite with acid ignimbrite and terrestrial clastic rocks (Chen Zhiguang, 2006). The subduction of the Okhotsk Ocean was "scissor-type", which was earlier to the east than to the west. The eastern Okhotsk Ocean located in the eastern Greater Khingan Mountains closed before the Middle Jurassic to develop S-type granites (Li Yu et al., 2015; Tang Jie et al., 2015; Zhao Pan et al., 2017), high-K calc-alkaline rocks and adakites (Wang Tao et al., 2011). The western Okhotsk Ocean located in the western Greater Khingan Mountains closed later, and remained open in the Early Cretaceous (Zonenshain et al., 1990; Parfenov et al., 2010). With the subduction of the Okhotsk Ocean, the extension at the trailing edge of the subduction zone controlled the formation of the basins in Late Jurassic-early Early Cretaceous. It was characterized by a low topography (Fig. 3). The northward subduction of the basins controlled the development of the Baikal Graben (162–151 Ma) (Donskaya et al., 2013). And the southward subduction controlled the development of the Mohe Basin, the Hailaer -Tamtsag Basin and the Songliao Basin (Tang Jie et al., 2015). According to the analysis of the pollen assemblages (Huang Qinghua et al., 2011) and the detrital zircon U-Pb spectrum (Ren Jianye et al., 2002), the ages of the andesites of the Taonan Formation in the Songliao Basin was identified as 146–148 Ma. They revealed some local extensional events in the Songliao Basin in the Early Cretaceous.

In the closing process of the Okhotsk Ocean, the collision between the Siberian Craton and the Amur Plate caused the surrounding micro-blocks to be under a compressional environment as a whole. The collisional zone was shortened in the S–N direction, while the micro-blocks escaped eastward or westward (Ren Jianye et al., 2002). Between the Central Asian Orogenic Belt and the Amur Plate, there developed enormous dextral strike-slip faults, such as the Cherchen Fault, the Gobi-Onon Fault and other faults. These faults extended from the western margin of the Tarim Basin to the Mohe Basin (Fig. 3). To the northwest of the faults is the Central Asian Orogenic Belt, and to the southwest and southeast of the faults are the Tarim Block and Amur Block, repsectively. The large-scale sinistral strike-slip displacement occurred along the NE–SW-trending Cherchen Fault during the Late Jurassic-Early Cretaceous, which caused both the Altay Mountains and the Tianshan Mountains to be in an extrusion state. The results of the apatite and zircon fission tracks revealed that the rapid extrusion-uplifting events developed in both the Altay Mountains and the Tianshan Mountains in 153–143 Ma (Guo Zhaojie et al., 2006). Owing to the extrusion of the two mountains, the Junggar Basin was extruded westward. In the northern part of the Junggar Basin, there developed top-to-the south thrusts and the basement-involved thrust-nappe structures, which gradually became younger from north to south. In the southern part there developed top-to-the north thrust-nappe structures (Li Sanzhong et al., 2015; Zhao Shujuan et al., 2014).

(2) Eastern margin of East Asia

The data from tectonics, magmatism and paleogeography have revealed that the eastern margin of East Asia was an Andean-type active continental margin in the Late Jurassic–early Early Cretaceous (160–135 Ma) interval. At that time the subduction zone of the Paleo-Pacific Plate migrated westward. Under this influence, the East Asian Continent underwent transpression and thrusting (Müller et al., 2008; Kemkin et al., 2016), resulting in a rise of the ocean-continent connection zone from oceanic trench to internal zone with a width of more than 1000 km and the banded mountains (Fig. 3). In addition, due to NNW-directed oblique subduction of the Paleo-Pacific Plate, the eastern margin and internal East Asia were controlled by a sinistral transpressional stress field. Furthermore, a series of NNE–NE-trending sinistral strike-slip faults formed. Along these faults, some small pull-apart basins also developed.

At this time, due to the accretion of the subducting Paleo-Pacific Plate, some terranes formed in the northern segment of the eastern East Asian continental margin, including the Nadanhada Complex, the Sikhote-Alin Terrane, the Mino-Tamba-Ashio Terrane and so on, composing a unified superterrane (Zhang and Shijino, 2004). In the Nadanhada Complex, the Yuejinshan Complex formed at 210–180 Ma, but probably was connected with the closure of the Paleo-Tethyan Ocean (Li Sanzhong et al., 2017a). The Raohe Complex formed during the early Early Cretaceous–Late Cretaceous (170–137 Ma) interval (Zhou Jianbo and Li Long, 2017) with a final accretion at 137–130 Ma. In general, the accreted terranes became younger from west to east, and all were connected with the accretion of the Paleo-Pacific Plate. During the Late Jurassic–early Early Cretaceous, the igneous activities along the eastern margin of East Asia were mainly distributed in the Greater Khingan (Xing'an), the Zhangguangcai Range and the Lesser Khingan. According to the lithological and geochemical characteristics, the magmatic activities were separated into the eastern and western parts: the western part included the Songliao Basin and the Greater Khingan Mountain, consisting of bimodal volcanic rocks which could be post-orogenic volcanic rocks related to the Okhotsk Ocean; the volcanic rocks in the eastern part were mainly intermediate-acid volcanics which are related to back-arc extension relative to the subduction of the Paleo-Pacific

Plate (Xu Wenliang et al., 2012,2013). Due to oblique subduction of the Paleo-Pacific Plate, the NE-NNE-trending strike-slip faults in the northern segment of the eastern margin of East Asia included the Yilan-Yitong Fault, the Dunhua-Mishan Fault, the Yuejinshan Fault and so on. Among these faults, the Yilan-Yitong Fault is an important branch of the Tanlu Fault as its northern extension. It shows a distinct sinistral strike-slip movement which was limited at 160–126 Ma by Zircon U-Pb dating (Gu Chengchuan et al., 2016). The Dunhua-Mishan Fault was another important branch of the Tanlu Fault, and underwent multi-stage activities. During Late Jurassic- Early Cretaceous, a sinistral displacement of this fault could have been up to 200 km (Zhou Liyun et al., 2015). In addition, the age of mylonite in the fault zone was dated to 161 Ma by K-Ar dating (Sun Xiaomeng et al., 2008).

In the southern segment of the east margin of East Asia, the continental margin of Southeast China developed a series of NE-NNE-trending transpressional faults, including the Chenzhou-Linwu Fault, the Hepu-Beiliu Fault, the Yangjiang-Heyuan Fault, the Lishui-Haifeng Fault, the Changle-Nanao Fault, the Binhai Fault, from land to ocean, respectively. At 145–137 Ma, the Changle-Nanao Fault suffered from transpression with high greenschist-facies metamorphism in the shallow structural level and low amphibolite-facies metamorphism in the mid-deep structural level. During the Late Jurassic- early Early Cretaceous interval, the continental margin of Southeast China was under a compressional stress, which has many geological responses, including rapid crustal uplift, weathering and erosion, the omission of Middle Jurassic strata (175–161 Ma), widespread and strong thrust-related structures in northern Fujian that resulted in Jurassic coal-bearing stratum forced under a Caledonian Pluton, confirmed by drilling (Li Huantong, 2014) and a series of NE-trending metamorphic belts in the northeastern Fujian exhumed area. Li Huantong (2014) revealed that this thrust event corresponded to the Andean-type continental margin of the eastern margin of East Asia (Fig. 3). Meanwhile, the subduction of the Paleo-Pacific Plate was undergoing “forward subduction”. In the southeast continental margin, Late Jurassic–Early Cretaceous plutons mainly showed a NE-SW-trending distribution, as a belt shape. On the west side the plutons are connected with an Early-Middle Jurassic magmatic zone separated by the Zhenghe-Dapu Fault to the west. On the east side they are connected with the Changle–Nan’ao ductile shear zone along which developed high-K calc-alkaline granites dated at 140–125 Ma (Mao Jianren et al., 2013).

(3) Southern margin of East Asia

In Late Jurassic–Early Cretaceous, the Bangong-Nujiang Ocean to the southern margin of East Asia subducted beneath the north Qiangtang Block. The subduction started in the Permian, and switched into bilateral subduction at 160–108 Ma (Wang Baodi et al., 2016). Some researchers believed that the subduction began at 160–130 Ma (Liu Yiming et al., 2017; Liu Yiming et al., 2017) mainly with accretion, and the Andean-type continental margin formed at 130-110 Ma. In addition, the ocean basin was closed at 110–100 Ma or 135–125 Ma (Hu Peiyun et al., 2017), forming the collisional orogenic belt. The closure of the Bangong-Nujiang Ocean was in a scissor-like pattern that closed from east to west (Yan Maodu et al., 2016). The subduction of the Bangong-Nujiang Ocean and the collision between the Lhasa Block and the Qiangtang Block resulted in the uplift of the Qiangtang Block and removal of some covering strata (Jolivet et al., 2010). This event probably influenced the erosion of the Tianshan rocks of northern East Asia and clastic sedimentation in the Junggar, Turpan and Tarim basins (Dumitru et al., 2001; Glorie et al., 2010).

(4) Interior of East Asia

In Late Jurassic-early Early Cretaceous, the compression within East Asia may have limited some processes at depth. Then, some intra-continental blocks with a different rigidity sufferred from thrusting, strike-slip movement and extrusion, separately. Under this complete readjustment, a series of NNE-NE-trending tranpressional strike-slip faults developed, including the Lanliao Fault, the Taihang Mountain Front Fault, the Cangdong Fault, the Tanlu Fault, the Ganjiang Fault, the Hepu-Beiliu Fault, the Wuchuan-Sihui Fault, and the Yangjiang-Heyuan Fault from northwest to southeast. These strike-slip faults cut through the North China and South China cratons and adjacent blocks into several triangular blocks. The complicated intra-continental deformation among these blocks controlled the development of contemporary multi-type basins. For example, under the control of the sinistral Tanlu Fault and the dextral Xiangfan-Guangji Fault, the indentation of the middle and lower Yangtze blocks to the Dabies Orogen formed the top-to-the southeast massive thrusts (Dong Shuwen et al., 2007). Meanwhile, the middle and lower Yangtze blocks escaped to the southwest and the northeast, respectively. In North China, the Tanlu Fault showed a strong sinistral offset in early Early Cretaceous, corresponding to the Phase B of the Yanshanian Movement (Zhu Guang et al., 2016). Geochronological data revealed that the activity time of the Feidong segment of the Tanlu Fault was at 143–130 Ma (Zhu Guang et al., 2005), and the compressional activity time of the Jimo-Muping Fault, the branch of the Tanlu Fault in the Jiaodong Peninsula, is at 160–150 Ma (Zhang Yueqiao et al., 2009).

In the interior of the North China and South China cratons, a series of NE-NNE-trending thrusts developed, superposing and reforming the Indosinian structures and early Yanshanian thrusts (Zhang Yueqiao et al., 2009; Wang Pengcheng et al., 2015; Li Sanzhong et al., 2005). In the western part of the North China Craton, the western Ordos Basin developed NE-NNE-trending thrust-and-fold structures in the Late Jurassic (Zhang Yueqiao et al., 2012). Previous researchers did apatite fission track and zircon geochronology of the surrounding strata of the Ordos Basin and found that a rapid uplift of this area was no earlier than 150-140 Ma. In the northern part of the North China Craton, the Yinshan-Yanshan Orogen developed the second-phase deformation of the Yanshanian Movement in the Late Jurassic- Early Cretaceous interval with a nearly E-W strike. Intense thrusting resulted in coarse clastic deposits of the Tuchengzi and Houcheng formations with ages ranging from 156 to 139Ma (Zhao Yue et al., 2004). The tuff and andesite of the Tuchengzi Formation (152–137 Ma) was related to the thrusting (Cope et al., 2007; Zhang Hong et al., 2009). Similarly, in the southern part of the North China Craton, the Dabie Orogen showed extrusion and thrusting in the Late Jurassic - early Early Cretaceous (Dong Shuwen et al., 2005; Zhang Qi et al., 2009). Inside the South China Craton, Jin Chong et al. (2009) studied the Xuefeng Mountain and revealed that the Yanshanian deformation in the South China Craton became younger from east to west. In addition, the newest deformed strata are Early Cretaceous strata in the eastern Sichuan Basin near the Huaying Mountain.

The compressive structures resulted in the strong crustal thickening and formed the plateau in eastern North China. The adakites are distributed in many areas and had different ages in eastern North China, the oldest is about 160 Ma in the Shandong Province, via 157–132 Ma in the Liaodong Peninsula to 130 Ma in the Hebei Province. This westward younging age distribution shows that the eastern North China Plateau extending from northeast to southwest, with a core in the Bohai Bay area, that resulted from the dynamics to the east. In addition, the final plateau developed in the early Early Cretaceous (around 135 Ma). The ages of adakites exposed in orogenic belts around the eastern North China Plateau were divided into two groups: 170–132 Ma and mainly 131–125 Ma. This probably represents two stages of delamination and different products in the evolution of the plateau. The former (170–132 Ma) could represent the adult stage of the plateau with a limited spatial distribution, and the latter (130–125 Ma) could represent the true transition from thrusting or contraction to extension with a large-scale range. In the South China Craton, the plutons are dominated by S-type and I-type granites related to the formation of nickel ores in the Late Jurassic- early Early Cretaceous. They are distributed in the Jiangnan Orogen or the Qinhang Metallogenic Belt and mainly aged from 160–150 Ma. Some 150–135 Ma plutons are mainly high-K calc-alkaline plutons (Zhou Taofa et al., 2008) and distributed in the middle-lower Yangtze area, corresponding to the formation of Cu-Au ore deposits. They also had adakite characteristics, probably corresponding to the mid-ocean ridge subduction (Sun Weidong et al., 2007) or delamination of the thickened lower crust (Liu Dongying et al., 2010). The 150–135 Ma plutons represent a key time of transition from contraction to extension.

2.3 Late Early Cretaceous-early Late Cretaceous extension and Earth surface system evolution (135–90 Ma)

The Okhotsk Ocean was closed completely at the end of Early Cretaceous, and the northern East Asia transited into intra-continental evolution. Meanwhile, the influenced range of the Paleo-Pacific Tectonic Domain extended northward as the Paleo-Pacific subduction zone developed northward (Fig. 4). New studies reveal that the eastward roll-back and subduction of the Paleo-Pacific Plate began at 135 Ma, and the subduction angles might become steeper gradually (Hou Fanghui, 2014). The stress field the Paleo-Pacific Plate changed from transpression to transtension gradually, which controlled the development of the eastern East Asian continental margin and the intracontinental tectonic units. At that time, the East China Sea Shelf Basin and the Zhejiang-Fujian region belong to the same fore-arc region, which was controlled by the compressional stress field, while the intra-continental area belonged to the back-arc region, developing a strong extension. And the Andean-type active continental margin, formed in the Late Jurassic to Early Cretaceous, was destroyed gradually. In addition, the mountains disappeared, the eastern North China Plateau began to collapse little by little (Fig. 4). The NE–NNE-trending transpressional fault system formed in the Late Jurassic to Early Cretaceous (160–135 Ma transited into the sinistral transtensional fault system in the Late Cretaceous (135–90 Ma). The time of the fault activity becomes younger, as well as metamorphism and magmatism, from west to east, or from land to sea. The Sikhote-Alin Orogen in the northern East Asia, the southeast China coastal range, as well as the Kalimantan volcanic–intrusive rock belt are related to the subduction of the Paleo-Pacific Plate and the

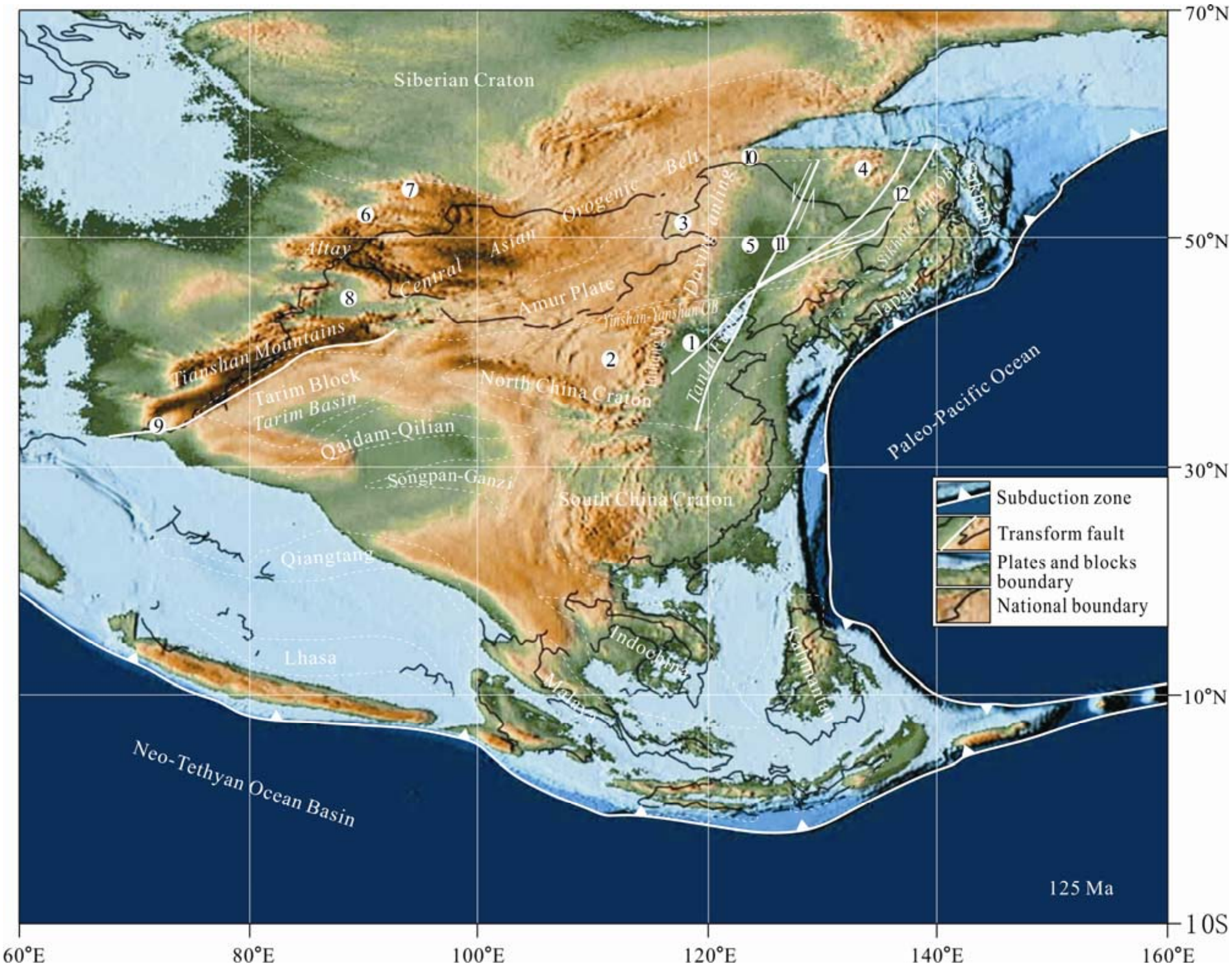

Fig. 4. Tectonic and geomorphological reconstruction of late Early Cretaceous East Asia at ca 125 Ma.
Abbreviations: M-Mountains; OB-Orogenic Belt. 1, Bohai Bay Basin; 2, Ordos Basin; 3, Hailar-Tamsag Basin; 4, Mongolian-Okhotsk Orogenic Belt; 5, Songliao Basin; 6, Western Sayan Mountains; 7, Eastern Sayan Mountains; 8, Junggar Basin; 9, Cherchen Fault Zone; 10, Mohe Basin; 11, Ilan-Yitong Fault; 12, Dunhua-Mishan Fault

late extension of the continental crust (Ren Jianye et al., 2002; Tao Kuiyuan, 1990). The lithospheric extension caused by the subduction of the Paleo-Pacific Plate had jumped from the intra-continental basins, about 1000 km distant from the trench to the back-arc basins, East China (Dmitrienko et al., 2016). It shows, obviously, a basin-mountain geomorphological boundary in the eastern areas along the Greater Khingan-Taihang Mountain-Xuefengshan north–south line (Fig. 4). However, the Qinghai-Tibet Plateau in West China had not yet uplifted, and was still an epicontinental sea environment.

(1) Northern margin of East Asia

During the late Early Cretaceous to early Late Cretaceous, the Okhotsk Ocean was closed completely in the northern margin of East Asia, resulting in the Mongol-Okhotsk Orogen, where the tectonism and magmatism were controlled completely by the westward subduction of the Paleo-Pacific Plate to the East Asian Continent at the beginning. A series of faulted basins and metamorphic core complexes developed under the back-arc extension resulted from an eastward retreat of the subduction (Wang Tao et al., 2011; Zorin et al., 1999; Meng Fanchao et al., 2014).

The late Early Cretaceous-early Late Cretaceous igneous rocks are widely distributed in Northeast China. Near the Paleo-Pacific subduction zone, the eastern Jilin-Heilongjiang provinces developed calc-alkaline igneous assemblages. In contrast, slightly away from the subduction zone, the Songliao Basin and the Greater Khingan Range developed bimodal volcanic rocks and A-type granites. The former marks the subduction of the Paleo-Pacific Plate, and the latter is related to the delamination of the early thickened continental crust or the extensional environment similar to the back-arc setting (Xu Wenliang et al, 2012, 2013). The U-Pb dating results show that the ages of the Early Cretaceous volcanic rocks range from 142 to 120 Ma (Cao Huahua, 2013; Zhao Lei et al., 2013), which is earlier than the transition time (135 Ma) from contraction to extension related to the Paleo-Pacific subduction. Affected by the extension after the formation of the Okhotsk Orogen during the late Jurassic to the early Early Cretaceous, the main magmatism of late Early Cretaceous-early Late Cretaceous has become younger from west to east.

The Songliao Basin was in a faulted depression period in the Early Cretaceous and developed regional extension and large-scale rifting, forming a syn-rift volcanic-sedimentary sequence, under the extension after the Okhotsk Ocean closure and back-arc extension of the Paleo-Pacific Ocean subduction (Wang Pujun et al., 2015). The faulted depression period could be further divided into two extensional stages. In the early stage, the graben-horst structures developed, being controlled by multi-directional normal faulting and accompanied by multi-stage volcanic activities (Ge Rongfeng et al., 2010). The Huoshiling and Shahezi formations developed mainly intermediate-basic eruptive rocks, and a large number of metamorphic core complexes developed simultaneously. In the late stage, the half-graben rifts with normal faults to the east and overlapping to the west were widespread, controlled by the low-angle listric-shaped normal faults. It may be related to a unilateral asymmetric dynamic system caused by the disappearance of the north-side dynamics. The volcanic sediments of the Yingcheng Formation in the faulted depression are mainly intermediate-acidic volcanic rocks (Ge Rongfeng et al., 2010), corresponding to an active event of the NE–NNE-trending faults.

The geochronological data indicate that the volcanic rocks of the Huoshiling Formation developed in 133–129 Ma or 133–125 Ma (Xu Yan, 2010), and that of the Yingcheng Formation developed in 110–119 Ma (Pei Fuping et al., 2008) or 113–111 Ma (Zhang Fengqi et al., 2007). Based on structural analysis, Chen Dongxu (2016) revealed that two periods of faulting and sedimentation happened in the Sanjiang and Jixi basins east of the Songliao Basin in the late Early Cretaceous. The sedimentary strata are divided into the Didao Formation (133–117 Ma), the Chengzihe Formation (116–110 Ma), the Muling Formation (110–101 Ma), as well as the Dongshan Formation (101 Ma). The lower Didao Formation and the others correspond to two periods of faulting and sedimentation in the Songliao Basin in the late Early Cretaceous, respectively.

The basin-controlling faults in the Songliao Basin in the Early Cretaceous are NNE-NE- trending and the Nenjiang -Balihan Fault is its western boundary. The $^{40}Ar/^{39}Ar$ age for muscovite and structural analysis reveal that the south-central segment of the fault developed sinistral transtensional deformation at 130 Ma and 124.4±0.9 Ma (Zheng Changqing et al., 2015), and the $^{40}Ar/^{39}Ar$ age for biotite is 123±0.7 Ma (Zheng Changqing et al., 2015). During the formation of the Songliao and Sanjiang basins, the development of the metamorphic core complexes was accompanied by transtensional faults. There are metamorphic core complexes in the central basement uplift of the northern Songliao Basin, and the age of the mylonite near the top of the detachment fault was 126.7±1.54 Ma, corresponding to the formation age of the extensional faulted depression at 133~120 Ma (Zhang Xiaodong et al., 2000). The $^{40}Ar/^{39}Ar$ dating results of muscovite in the Yiwulv Mountain reveal that the contraction occurred in the late Late Jurassic-early Early Cretaceous, while the extension occurred in the late Early Cretaceous (134–117 Ma) (Li Gang, 2013).

(2) Eastern margin of East Asia

In the late Early Cretaceous, the Paleo-Pacific subduction zone in eastern East Asia retreated eastward, and the Andean-type continental margin was destroyed, the mountains disappeared gradually under back-arc extension (Fig. 4). In addition, the NNE–NE-trending strike-slip faults were converted into sinistral transtensional faults, such as the Lishui-Haifeng Fault, the Changle-Nan'ao Fault and the Binhai Fault, and their activity time became younger seaward (Suo Yanhui et al., 2014). Geochronological data and microstructural analysis reveal that the Changle-Nan'ao Fault was a sinistral strike-slip fault, having experienced two-stage late Early Cretaceous strike-slip movement at 121.5 Ma and 109 Ma respectively (Du Jiyu et al., 2012), which corresponds to the $^{40}Ar/^{39}Ar$ dating results that the faulting could be divided into two stages at 132–110 Ma and 110–84 Ma, respectively (Chen Wenshan et al., 2002).

The late Early Cretaceous magmatism intensively happened in the southeast continental margin, northern East Asia. A NE-trending volcanic- intrusive belt, 400 km in width and 2000 km in length, was located in the coastal range of Zhejiang, Fujian and Guangdong provinces. To the east of the Lishui–Haifeng (Zhenghe–Dapu) Fault, the volcanic rocks, mainly constituted acid–intermediate acidic high-K calc-alkaline volcanic rocks, that almost completely covered the basement and developed as bi-modal volcanic rocks (Mao Jianren et al., 2013). Meanwhile, the distribution of A-type granites from 139 to 123 Ma extends westward across the Lishui-Haifeng Fault (Wang Qiang et al., 2007), while the corresponding A-type granites in the Late Cretaceous are mainly distributed in the coastal range of the Zhejiang and Fujian provinces. The magmatic activity in the late Early Cretaceous is widely distributed in the middle and lower Yangtze River. And the volcanic rocks mainly consist of shoshonite and intermediate-basic volcanic rocks during 135–125 Ma (Wang Qiang et al., 2007), while A-type granites and bi-modal volcanic rocks were emplaced after 125 Ma (Xing Fengming and Xu Xiang, 1994; Fan Yu et al., 2008).

(3) Southern margin of East Asia

The Lhasa and the Qiangtang blocks collaged and became a part of the East Asian continent. The Neo-Tethyan Ocean subducted northward and the subduction-related magmatic rocks were mainly located in the Gangdese Orogen, south of the Bangong Co-Nujiang Suture. The Gangdese Orogen refers to the E-W-trending panhandle between the Yarlung Zangbo Suture and the Bangong Co-Nujiang Suture, located in the Lhasa Block. The magmatic rocks formed in 130–120 Ma and might have extended to the Late Cretaceous, and the magmatism in the central and northern Gangdese are the most intensive. The volcanic rocks in the Central Gangdese are different from the traditional island-arc volcanic ones, while those in the North Gangdese are calc-alkaline volcanic rocks similar to the traditional island-arc volcanics (Zhu Dicheng et al., 2006). With the Neo-Tethyan Ocean subduction and the uplift of the Gangdese Orogen, the South China Craton and the Songpan-Ganzi Block uplifted and resulted in tectonic extrusion in the Early Cretaceous (Fig. 4). Furthermore, apatite fission track data reveals that the tectonic uplifting of the Qaidam Basin in the northern margin of the Tibet Plateau in 109–97 Ma (Zhu Dicheng et al., 2006) might be related to the activity of the southern Tethyan Tectonic Domain.

(4) Interior of East Asia

The transtension that controlled the tectonic evolution inside East Asia since the late Early Cretaceous (135 Ma), and developed the rifting and intensive volcanism (Ren Jianye et al., 2002), resulted in lots of intra-continental rifts or basins, with the Bohai Bay Basin being the largest (Fig. 4). The NNE-NE-trending faults were changed into transtensional faults. The sinistral transtensional ductile Tanlu Fault through the eastern North China Craton cooled in 120 Ma based on the $^{40}Ar/^{39}Ar$ dating, which indicates that strike slip faulting occurred in 120 Ma at the latest (Zhu Guang et al., 2001). Further research reveals that the active age is 133–122 Ma (Shi Yonghong et al., 2016). The high-precision dating results of the intrusive rocks associated with the faulting show that the sinistral transtension of the Jimo-Muping Fault occurred in 123–106 Ma (Zhang Yueqiao et al., 2007).

A series of faulted basins were produced in the fault zone or on its two sides during the activities of the Tanlu Fault and its branch faults. And the rifted basins were generated in the fault zone while the strike-slip pull-apart basins were generated on both sides, such as the Jiaolai Basin, the South Yellow Sea Basin and others (Zhao Shujuan et al., 2017). The Jiaolai Basin experienced two-stage extension in the late Early Cretaceous: 135–120 Ma and 120–100 Ma, respectively. The former is characterized by normal faulting and rapid subsidence caused by the NE-SW-directed extension. The latter appeared as a narrow rift and produced bimodal volcanic rocks, which are mainly distributed in the inner fault zone caused by S–N-directed extension (Zhang Yueqiao and Dong Shuwen, 2008). During the formation of faults and basins, two magmatic events developed in the Jiaodong area. The first stage is distributed mainly along the faults at 135–125 Ma and the latter in 125–105 Ma is not confined. In the South China Craton, a series of red sediment filled basins and volcanic basins developed, controlled by the NE–NNE-trending faults. The high-precision geochronology of the volcanic rocks shows that the basins occurred at about 130 Ma. Obviously, with the formation of the strike-slip faults and basins, a large number of metamorphic core complexes developed in East Asia. The North Dabie metamorphic core complex formed at 142 Ma, and the Hohhot at 137–119 Ma, the Daqing Shan at 129 Ma, the Xiaoqinling at 127 Ma, the Guojialing at 130–120 Ma, the Yunmengshan at 126 Ma, the Lushan at 126 Ma, the South Liaoning at 125 Ma, the South Liaoning-Wanfu at 130-113 Ma, the Wulian at 135–122 Ma, the Queshan at 118 Ma (Liu Junlai et al., 2005, 2006, 2011, 2013; Ni Jinlong et al., 2014; Ji Mo et al., 2015).

The extension in the Late Jurassic-Early Cretaceous caused the plateau in the eastern North China to stretch and collapse. The adakitic rocks of 124–113 Ma developed in the Sulu Orogen, Shandong Peninsula and Liaodong Peninsula. And the zircon isotope data shows that the crustal thinning in the Dabie area is at 127 Ma (Xie Zhi et al., 2006). The development of post-orogenic granitoids in Liaodong Peninsula (126 Ma) (Yang Jinhui et al., 2006), the Dabie Orogen (127 Ma) (Qian Cunchao et al., 2004), Shandong Peninsula (113–111 Ma) and Suzhou (113–111 Ma) (Zhao Guangtao et al., 1997) indicates contemporaneous magmatic events with the collapse of the eastern North China Plateau. Based on the study of deformation in the Zhangjiakou area, it indicates that the plateau range began to shrink obviously from outer to inner at 132 Ma. Until 125–127 Ma, the plateau almost disappeared (Yang Jinhui et al., 2006; Zhang Hong et al., 2005; Zhang Qi et al., 2008; Niu Baogui et al., 2003).

2.4 Late Cretaceous transition between continental marginal and intra-continental deformation and evolution of the Earth surface system (90–65 Ma)

At this time, the whole East Asian Continent may have retreated about 1000 km to the east following the eastward retreating subduction of the Paleo-Pacific Plate, and it just coincided with the geographic coordinates today after increasing 10 degrees longitude in Fig. 5. Of course, this may involve a plate reconstruction problem, requiring further test in the future. The tectonism-magmatism-mineralization in East Asia became younger gradually from west to east. From the late Early Cretaceous to early Late Cretaceous (90±5 Ma), the position of the subduction zone may be located in the east of the East China Sea (ECS) Shelf Basin (Fig. 5), the core of the back-arc extensional zone is located in the ESC Shelf Basin, while the extensional basins or rifts west of the ECS Shelf Basin such as the Songliao Basin, the Jiaolai Basin, the South Yellow Sea Basin and the Yishu Rift, had stopped their extensional activities. All the extensional basins or rifts changed from faulted depression to thermal depression. The transtensional faults in the Songliao Basin, the Jiaolai Basin and the other early basins show an inversion tectonics under the control of the westward compressional stress field by the rifting of the ECS Shelf Basin, and the age of this inversion became younger from east to west (Suo Yanhui et al., 2017). There is an unconformity between the Lower Cretaceous and the Upper Cretaceous of the basins (Hou Fanghui, 2014; Zhang Yueqiao et al., 2003). In Late Cretaceous, the Paleo-Pacific Plate subducted continuously under the East Asian Continent, and the intra-continent moved gradually away from the effected area of subduction with the retreat of the subduction zone.

(1)Northern margin of East Asia

In Late Cretaceous, the northern margin of East Asia had been subjected to intense compression, and the rifted basins began inversion. The Songliao Basin is characterized by a thermal subsidence dish-like basin, in which the sedimentary thickness was about 3000–4500 m. The Sanjiang Basin had a half-graben structure, and the

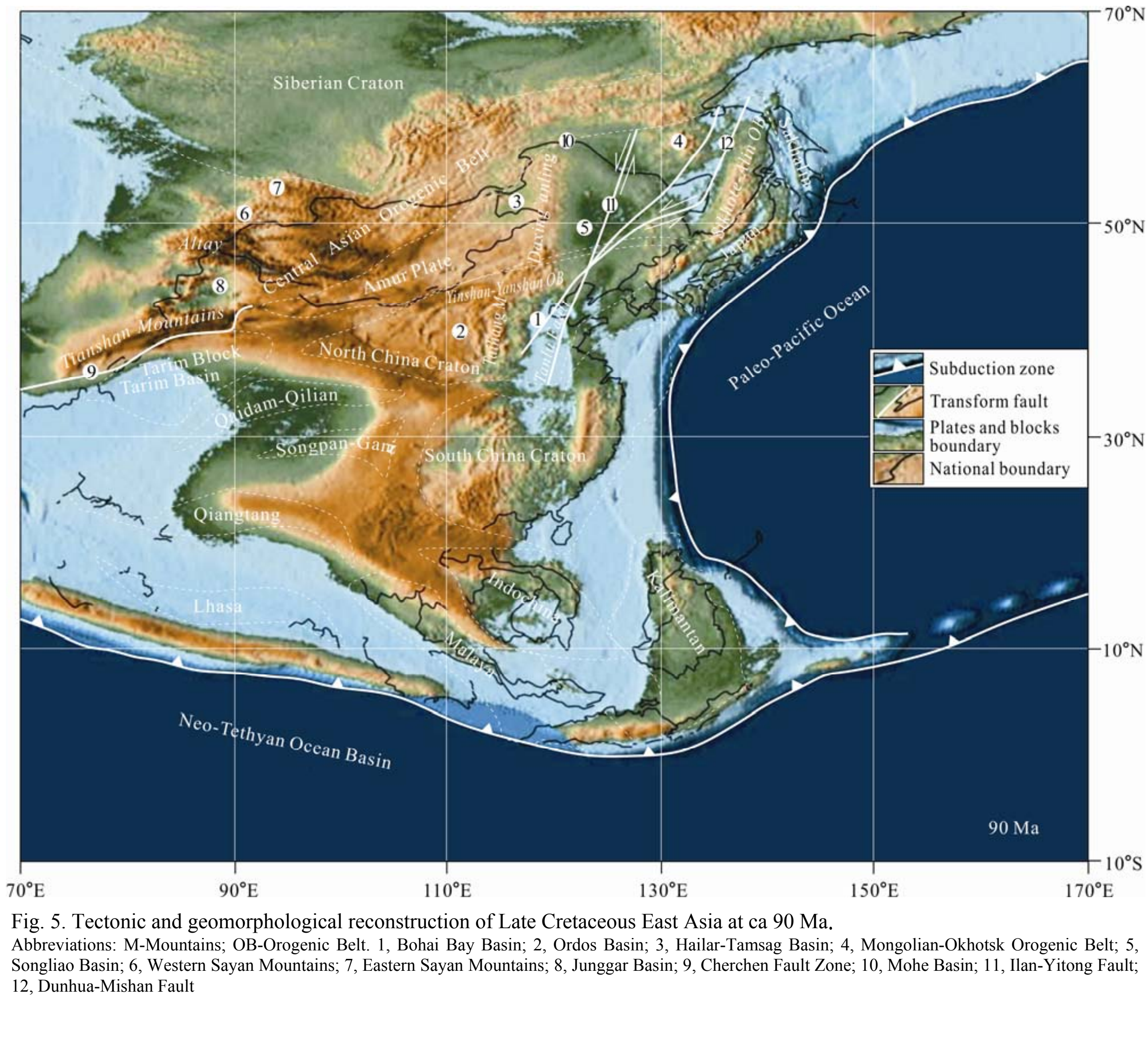

Fig. 5. Tectonic and geomorphological reconstruction of Late Cretaceous East Asia at ca 90 Ma.
Abbreviations: M-Mountains; OB-Orogenic Belt. 1, Bohai Bay Basin; 2, Ordos Basin; 3, Hailar-Tamsag Basin; 4, Mongolian-Okhotsk Orogenic Belt; 5, Songliao Basin; 6, Western Sayan Mountains; 7, Eastern Sayan Mountains; 8, Junggar Basin; 9, Cherchen Fault Zone; 10, Mohe Basin; 11, Ilan-Yitong Fault; 12, Dunhua-Mishan Fault

basin inversion is characterized by the emergence of a NNE-trending thrust-and-fold belt, which developed a series of top-to-the-west dipping strata and formed a narrow molasse accumulation. The structural inversion was a contractional process from east to west, so the age of this inversion became younger from east to west. The structural inversion and rapid uplift of the eastern Heilongjiang Province occurred in 90–70 Ma, while the Songliao Basin happened in 70–65 Ma (Chen Dongxu et al., 2016). Further research reveals that the Songliao Basin in the Late Cretaceous period (100–65 Ma) suffered gradually from the enhanced compressional stress from its east side (Song Ying, 2010). It has undergone at least four stages of tectonic inversion: the first stage (the end of the Qingshankou Formation at ~88.5 Ma) of regional deformation produced some NNE-trending open and gentle folds with slight uplift; the second stage (the end of the second period of the Nenjiang Formation at ~77 Ma) is characterized by the contracted uplift of its eastern strata; the third stage occurred at the end of the Nenjiang Formation at ~73 Ma; and the fourth stage from ~65 Ma to Cenozoic is characterized by the intensive uplifting of the eastern basin. Meanwhile, the normal faults converted into thrust faults, and the strata were strongly eroded. Ren Jianye et al. (2002) and Song Ying et al. (2015) also proposed that the region had undergone granite cooling events and crustal uplift at 100–89 Ma and 89–87 Ma, respectively, in the Lesser Khingan and the Greater Khingan, corresponding to the first phase of tectonic inversion in the Songliao Basin.

(2)Eastern margin of East Asia

The eastward retreat of the Paleo-Pacific subduction zone didn't migrate to the eastern part of the ECS Shelf Basin until the Late Cretaceous. Coevally, the previous continental margin was transformed into a new intra-continent. The type of magmatic rocks was also transformed from Early Cretaceous subduction type (140–125 Ma), syn-orogenic type (125–110 Ma), post-orogenic type (110–99 Ma) to Late Cretaceous anorogenic type (94–81 Ma) (Chen Chenghong et al., 2000). In addition, the volumes of magmatic plutons decreased dramatically. Magmatic rocks of the anorogenic stage mainly include bimodal basalts-dacites, rhyolite, A-type miarolitic granites and mafic dyke swarms (Chen Chenghong et al., 2000). The Late Cretaceous granites in the Gyeongsang Basin and Korea Peninsula can be seen as a significant spatial-temporal migration that displays younger ages from west to east. The granites can be related to Au-Ag mineralization, its mineralization age is about 100–70 Ma (Choi et al., 2005), and younging to the east too. The rocks in the Gyeongsang Basin comprise a similar suite of basalts, trachyandesites, andesites, trachytes, dacites and rhyolites with high-potassium calc-alkali volcanic rocks (Chang Kihong, 1988), among which the zircon age of andesites and tuffs as island-arc magmatic rocks is about 91–65 Ma (Zhang Shuanghong et al., 2012, 2014). The Late Cretaceous granites (100–70 Ma) in Japan build a symbiotic relationship with the Late Cretaceous Shimanto melánge belt, Sanbagawa metamorphic belt and its fore-arc basin. There occurred ductile deformation among the granites at 100–87 Ma, and there is no deformation after that (Tamura et al., 2000, 2003). The metamorphic age of the Sanbagawa metamorphic belt is 90–70 Ma, while the ages of fore-arc rhyolites and granites are 86–84 Ma and 74–62 Ma (Mao Jianren et al., 2013; Sonehara and Harayama, 2007). Above all, the Late Cretaceous tectonic transition to the east of the Paleo-Pacific subduction zone made most of the intra-continental blocks of East Asia far away from the subduction zone in the Late Yanshanian Period, and the tectonism-magmatism-mineralization is not significantly associated with the Paleo-Pacific subduction. Then, the deformation and magmatic events that related to the subduction only developed in Japan, Korea Peninsula and other margins near the subduction zone.

Plenty of volcano-sedimentary basins developed in the eastern margin of East Asia in the Cretaceous. Sedimentary basins include the Ganhang faulted basins, the Jinqu Basin and the ECS Shelf Basin and others. The Ganhang faulted Basin started to form since the late Early Cretaceous, the half-graben basin with top-to-the south normal faults on the north side transformed into a depression basin in the middle-late Late Cretaceous (Yu Xinqi et al., 2005), and the sedimentary facies revealed that the Yongfeng-Chongren Basin, a part of the Ganhang Basin, developed an angular unconformity between Lower Cretaceous and Upper Cretaceous strata (Chen Liuqin et al., 2015). There is also an angular unconformity developed in the Jinqu Basin (Wang Minglei, 2006). The study on faults revealed that many faults dipped to the southeast, and thrusted toward the northwest (Shu Liangshu and Zhou Xinmin, 2002). It was interpreted as conjugate faults formed by the low-angle subduction of the Paleo-Pacific Plate. But this is in contradiction with the evidence of increasing subduction angles of the Paleo-Pacific Plate in this period. Thus, the top-to-the-NW thrust faults were more likely to be the inversion tectonics in the early Late Cretaceous. All the basins mentioned above changed from faulted depressions to thermal depressions under the compressional stress. Different from the transition from faulted depressions to thermal depressions in the southeast continental margin, the ECS Shelf Basin was still coevally controlled by extension. Three faulted depressions developed from west to east respectively, named the Oujiang-Lishui, the Minjiang-Xiapeng, the Keelung- Hsinchu, all of them have different stratigraphic successions of Upper Cretaceous age. Each faulted depression is characterized by a single fault or complex faulted depressions, which showed the half-graben with faults in the east and overlapping in the west (Hou Fanghui et al., 2015). The faulted depressions are located to east be in the back-arc extensional range of the Paleo-Pacific Subduction Zone (Fig. 5).

(3)Southern margin of East Asia

In Late Cretaceous, the magmatic arc developed in the southern Gangdese margin with continuously northward subduction of the Neo-Tethyan Ocean. The Cretaceous intermediate-acid intrusive rocks represent more than 65% of all the Gangdese-Nyainqentanglha Belt. The rock assemblages are dominated by granodiorites and monzogranites, intermediate to mafic in the south, and acidic in the north. The radioactive isotope ages of the igneous rocks have revealed that magmatism started in the Early Cretaceous and were continuous until the Eocene. However, the Neo-Tethyan subduction had a weak influence on the East Asian intra-continent at this time. The Qaidam Basin, north of the Tibet Plateau, was, as a whole, at the slow and smooth subsidence stage (Zhao Fan et al., 2013).

(4)Intra-continent of East Asia

In the Late Cretaceous, the East Asian intra-continent was far away from the subduction zone, and the magmatic activity had almost terminated. The Early Cretaceous faulted depressions had also undergone basin inversion or inversed to thermal depression. The Late Cretaceous basins east of the Tanlu Fault developed contraction structures. The Jiaolai Basin is characterized as an N–S-directed shortening depression which contributed to the contraction of the lacustrine basin. The crustal uplift occurred at 92 Ma to 89–87 Ma in the Jiaolai Basin and at 90–86 Ma in the Luxi Block, respectively (Dmitrienko et al., 2016; Song Ying et al., 2015). The North China Plain and the Taihang Mountains areas began to rise mainly in the Late Cretaceous, and developing a planation surface at the Beitai Stage (Wu Chen et al., 1999). The Greater Khingan-Taihang Mountain-Xuefeng Mountain areas underwent a further uplift (Fig. 5). The inversion of the faulted depressions within the East Asia Continent in the Late Cretaceous can be related to the rifting of the ECS Shelf Basin, which may be as a result of the eastward migration of the rifting center of basins following the eastward retreat of the subduction zone. In summary, the subduction of the Paleo-Pacific Plate still played a major role in the contraction of the intra-continental basins in the Late Cretaceous, but the dominant reason of the inversion was not the direct contraction but the back-arc extension.

A great number of studies of magmatic rocks show that some extensional rifting events in East Asia in the early Late Cretaceous were centered around the eastern North China Craton, accompanied by volcanic eruptions at a shallow structural level. However, the volcanic activities decreased sharply in the Late Cretaceous, and the early magmatic rocks inside and around the basins began to be exhumed and cooled.

3 Interaction between Two Major Dynamic Systems in East Asia and Cenozoic Evolution of the Earth Surface System

3.1 Paleogene dynamic system and evolution of the Earth surface system (65–23 Ma)

In Cenozoic, the Pacific Plate started to subduct beneath the East Asian continental margin after the Paleo-Pacific Plate had been exhausted. The East Asia region was under the combined effect of the southern Tethyan and the eastern Pacific tectonic domains, while the driving force from the Paleo-Asian Tectonic Domain to the north had basically disappeared. The tectonic and geomorphological evolution in East Asia was controlled by the interaction process between the two dynamic systems of the Tethyan and the Pacific tectonic domains (Li Sanzhong et al., 2011).

(1)Dynamic system west of East Asia: the evolution of the Tethyan Tectonic Domain

In Cenozoic, the Neo-Tethyan Ocean subducted northward and gradually disappeared under the Eurasian Continent. With the opening of the Indian Ocean, the Indo-Australian Plate was separated from the Antarctic Plate and moved northward rapidly. The nearly S–N-trending transform fault adjusted the northward differential motions between the Indian Plate and the Australian Plate. And the Indian Plate which moved faster than the latter softly collided with the Eurasian Plate at about 55 Ma. The collision and the subsequent processes resulted in the formation of the Tibet Plateau which is one of the most significant Cenozoic tectonic events. The formation and uplift of the plateau had a profound impact on all aspects of the Earth system, having a great control on the tectonic evolution, basin formation, geomorphic change, ocean circulation system, climate system and ecosystem in East Asia and its adjacents. The tectonic movement in this period is called the Himalayan Movement with a wide range in space.

According to the influence for the adjacent areas, the evolutionary process of the Tibet Plateau can be divided into three stages including: (i) a soft collision, (ii) intracontinental consolidation of an early hard collision, and (iii) a relatively-unified deformation of late hard collision in the Qinghai-Tibet region (Liu Chiyang et al., 2009). There are two stages in the Paleogene: the period of soft collision is 60-44 Ma, and the affected range is mainly limited to the Yarlung Zangbo Suture and its two sides. While in the stage of intracontinental consolidation of early hard collision, 44–22±2 Ma, the affected range is mainly in the Tibet Plateau and its margins. However, the related deep-seated strike-slip faults have a significant influence on the broad areas adjacent to the plateau. Previous studies of volcanism also revealed that the evolutionary process of the plateau can be divided into three stages. And there were two stages in the Paleogene: in 65–45 Ma, the Indian Plate and the Eurasian Plate contacted and collided (soft collision), and the related sodic and potassic volcanic rocks were mainly distributed in the Lhasa Block, having a small amount of distribution in the Qiangtang Block. While at the second stage, the full collision (hard collision), started from 45–26 Ma, and the alkaline, peralkaline, and adakitic igneous rocks widely cropped out the Qiangtang Block within the Tibet Plateau (Xia Linqi et al., 2011). However, Wang Erqi (2017) proposed a classification scheme that slightly differs from the two above-mentioned schemes for the timing of the initial collision. This classification scheme reveals that during 65–45 Ma, the subduction-related calc-alkaline magmatic rocks developed in the Gangdese Terrane, and the Neo-Tethyan Ocean had not disappeared completely, but the initial collision between the Eurasian Plate and the Indian Plate didn't begin until about 45±5 Ma. Then the large-scale intracontinental convergence, namely the hard collision, occurred at 30±5 Ma, producing the present-day geological and geomorphological patterns of the Tibetan Plateau. The convergence rate curve of the Indian Plate and the Eurasian Plate shows that the convergence rates dropped continuously during 65–45 Ma, and fell suddenly at 45 Ma (Suo Yanhui et al., 2012), which could correspond to the beginning of the hard collision. Therefore, this paper uses the first classification scheme, that is, the time range of two stages in Paleogene are 65–45 Ma, 45–26 Ma or 22 Ma, respectively.

During the collision between the Indian Plate and the Eurasian Plate, the Tibetan Plateau was uplifting (Figs. 6–8) including a slow period of uplift in the Paleocene to the Oligocene (Xiao Xuchang and Wang Jun, 1998). Further studies revealed that the uplift occurred in 45–38 Ma (Pan Yusheng, 1999) and the Tibet Plateau rising center shifted from south to north. The apatite fission track and sedimentary records reveal that the Lhasa Block was uplifting in 64–51 Ma, while the Tanglha Range developed thrust-nappe structures in the northern Qiangtang Block and the Hohxil foreland basin developed along the thrust front (Wu Chihua, 2014). Further to the north, the Bayan Har Mountains and the East Kunlun Mountains did not have an obvious uplift (Fig. 6). With the continuous north-directed subduction of the Indian Plate, the Lhasa Block and the Qiangtang Block also uplifted intensively during the Late Eocene to the Oligocene (38–28 Ma) (Fig. 6). The highest uplift and denudation rates appeared north of the Tanggula Mountains in 38 Ma to 34 Ma. Farther north, the uplift of the Bayan Har Mountains and the East Kunlun Mountains had started, but didn't reach the peak of uplift (Wu Chihua, 2014).

(2)Dynamic system east of East Asia: the evolution of Pacific Tectonic Domain

The plate reconstruction shows that the present-day Pacific Plate developed from a triple junction of three mid-ocean ridges between the Izanagi, the Farallon and the Phoenix plates which were located in the present-day South Pacific Ocean at about 185 Ma (Engebretson et al., 1985) or 210 Ma (Seton et al., 2012). In this paper, the Izanagi Plate called the Paleo-Pacific Plate. With the NNW-directed or WNW-directed subduction of the Paleo-Pacific Plate beneath the East Asian continental margin, the Pacific Plate approached gradually the East Asian Continent, then the mid-ocean ridge reached the subduction zone and began its subducting beneath the East Asian continental margin at about 60 Ma (Müller et al., 2008). The Pacific Plate moved NNW-ward at the early stage, and turned to WNW-directed subduction at about 47 Ma, which was reflected by the turn of the Hawaii-Emperor Island Chains. And at that time the early S–N-trending and NE-trending transform faults may have become some initial subduction zones, resulting in a dextral transtensional stress field in East Asia in the case of a complete coupling between the continental and oceanic lithospheres (Xu Junyuan et al., 2014) as the subduction zone retreated eastward during this period. In the Paleocene, the Philippine Sea Plate was located near the equator and drifted northward in the Paleogene (Fig. 6).

Under the control of the dextral transtensional stress field, a series of basins developed on the eastern East Asian continental margins, such as the South Yellow Sea Basin, the ECS Shelf Basin, the Southwest Taiwan Basin, the Pearl River Mouth Basin, the Qiongdongnan Basin and the Yinggehai Basin (Li Sanzhong et al., 2012a, b; Hui Gege et al., 2016a, b; Wang Pengcheng et al., 2017; Zhao Shuju et al., 2017) (Figs. 6 and 7). The South Yellow Sea

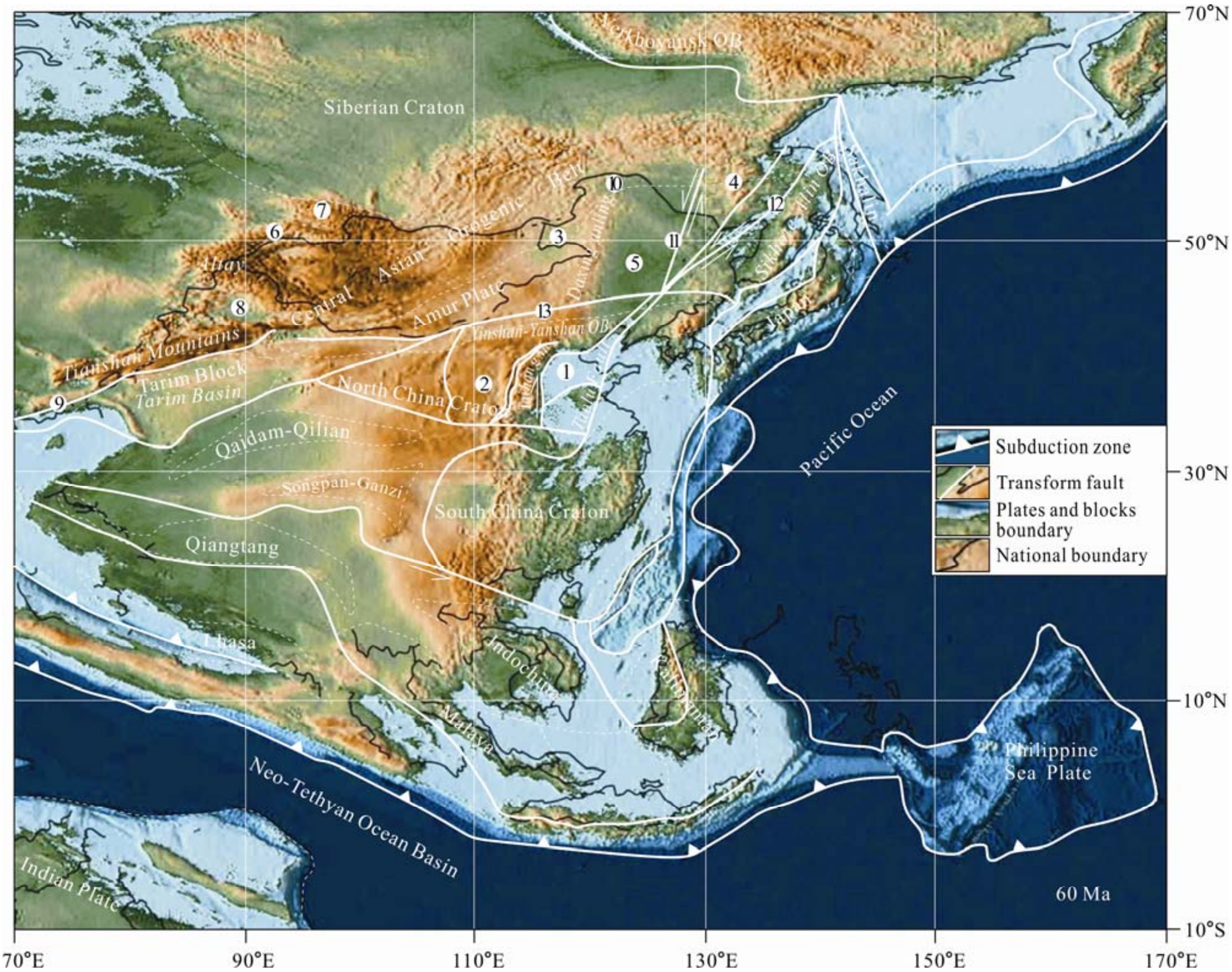

Fig. 6. Tectonic and geomorphological reconstruction of Paleogene East Asia at ca 60 Ma.
Abbreviations: M-Mountains; OB-Orogenic Belt. 1, Bohai Bay Basin; 2, Ordos Basin; 3, Hailar-Tamsag Basin; 4, Mongolian-Okhotsk Orogenic Belt; 5, Songliao Basin; 6, Western Sayan Mountains; 7, Eastern Sayan Mountains; 8, Junggar Basin; 9, Cherchen Fault Zone; 10, Mohe Basin; 11, Ilan-Yitong Fault; 12, Dunhua-Mishan Fault; 13 -Solon-Xar Moron-Changchun Fault

Basin is a Cenozoic basin characterized by horsts, grabens and tilted faulted blocks, and this basin which is controlled by the NE- to NNE-trending dextral strike-slip faults was divided into three parts including the western, central and eastern parts. At the beginning of the Cenozoic, the depression occurred in the western and central parts of the basin, and shifted to the central part of the basin in the Paleocene, while the activities were concentrated in the eastern part in the Early Eocene, but migrated to the eastern end of the basin in the Late Eocene (Liu Dongying, 2010). Overall, the ages of the sedimentation and faulting in the basin are characterized by eastward youngering. And the basin-controlling faulting and sedimentation also had a tendency to weaken eastward (Chen Ling and Zhong Guangjian, 2008). The ECS Shelf Basin began to broaden and rift at the end of the Late Cretaceous. In the Paleocene, the basin entered into a pull-apart and rifting stage controlled by the dextral and right-stepping strike-slip faults. Meanwhile, the sedimentary thickness, fault activity intensity and basin structures reveal that the main faulted depression was located in the west of the basins in the Paleocene (Suo Yanhui et al., 2012, 2013, 2014, 2015). However, the main faulting and the depocenter of the basins were located in the eastern depression in the Eocene-Oligocene. Generally, the ages of the fault system and the basin sedimentation tended to be younger eastward. At the beginning of the Oligocene, the Yuquan Movement happened in the ECS Shelf Basin, which is mainly manifested by folds in the central part of the basin, but by thicker deposition in the eastern basin and the Okinawa Trough. In the Cenozoic, the northern basins of the South China Sea were controlled by the dextral pull-apart processes of the NE- to NNE-trending faults. Moreover, in the Middle and Late Eocene, the rapid deposition (the sedimentation rates are about 250–170 m/Ma) occurred mainly in the Pearl River Mouth Basin and

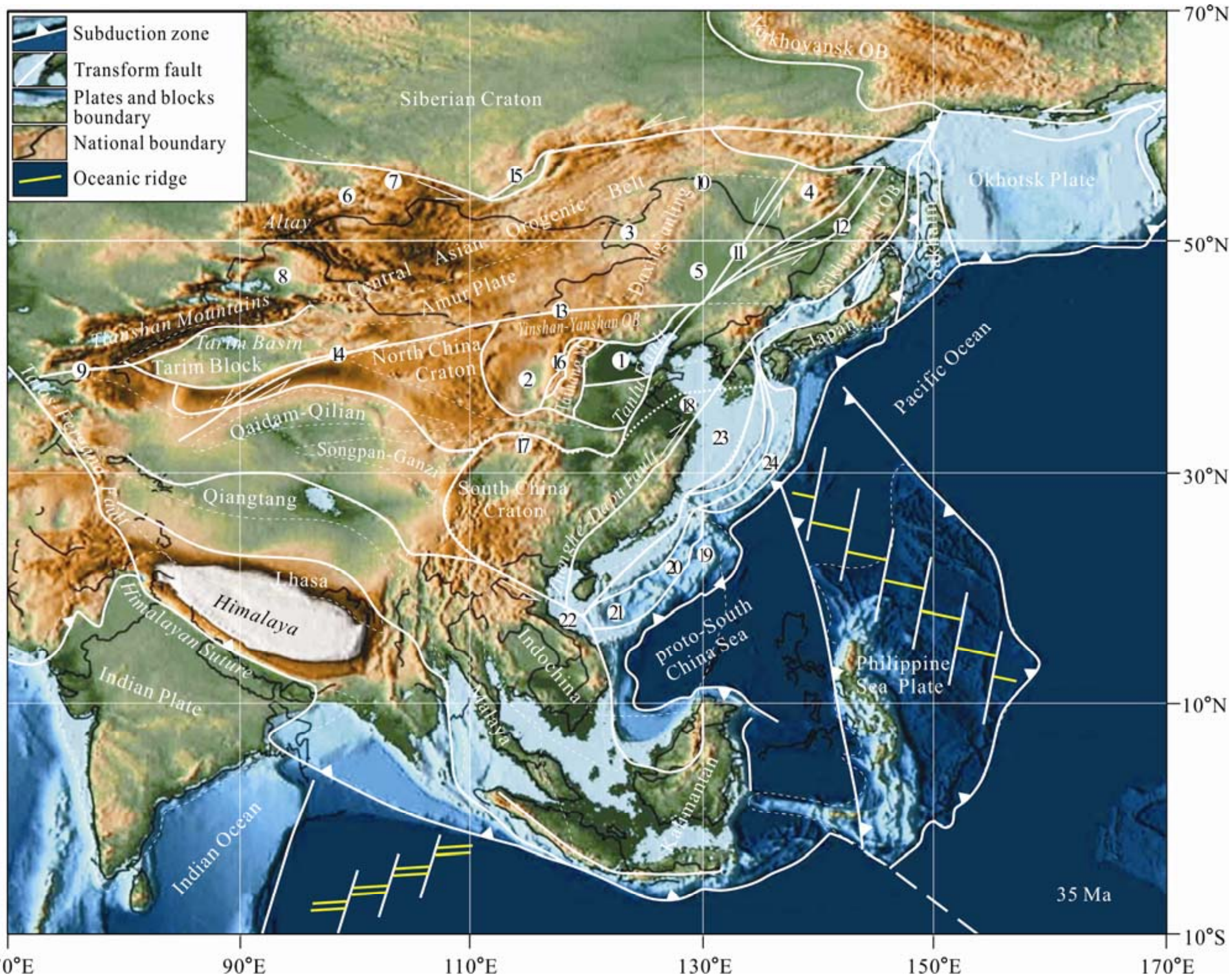

Fig. 7. Tectonic and geomorphological reconstruction of Neogene East Asia at ca 35 Ma.
Abbreviations: M-Mountains; OB-Orogenic Belt. 1, Bohai Bay Basin; 2, Ordos Basin; 3, Hailar-Tamsag Basin; 4, Mongolian-Okhotsk Orogenic Belt; 5, Songliao Basin; 6, Western Sayan Mountains; 7, Eastern Sayan Mountains; 8, Junggar Basin; 9, Cherchen Fault Zone; 10, Mohe Basin; 11, Ilan-Yitong Fault; 12, Dunhua-Mishan Fault; 13 -Solon-Xar Moron-Changchun Fault; 14, Altyn-Tagh Fault ; 15, Baikal Rift; 16, Shanxi Graben; 17, Qinling-Dabie Orogenic Belt; 18, South Yellow Sea Basin; 19, Southwest Taiwan Basin; 20, Pearl River Mouth Basin; 21, Qiongdongnan Basin; 22, Yinggehai Basin; 23, East China Sea Shelf Basin; 24, Okinawa Trough

the western Qiongdongnan Basin (Ren Jianye et al., 2002). In the Late Eocene to Early Oligocene, the depocenter was in the eastern part of the Pearl River Mouth Basin and the Southwest Taiwan Basin (Wang Pengcheng et al., 2017). The deposition of the northern South China Sea Basin started since the Paleocene. In the Paleogene, the depositional thickness was greater in the western part than in the eastern part. At the same time, the northern South China Sea Basin and the ECS Shelf Basin were linked into a unified basin (Fig. 7), and the stratigraphic type, sedimentary system and facies between the two basins could be compared with each other, respectively (Zang Yibo et al., 2016). At the end of Oligocene, the activities of strike-slip faults ceased, and its end time was earlier in the west than in the eastern parts of the northern South China Sea Basin, while the basin structure changed from faulted depression to thermal depression (Wang Pengcheng et al., 2017). At the end of Eocene, the South China Sea Ocean Basin began to open, and the early mid-ocean ridge was located in the northwestern sub-basin and the eastern sub-basin. While the mid-ocean ridge propagated to the southwestern sub-basin in the Neogene.

(3)The connection zone of dynamic systems of the east and west sides of East Asia: intracontinental evolution in East Asia

In the Cenozoic, the two major dynamic systems had the combined effects on East Asia, which inherited from the Mesozoic tectonics. The North China Craton showed extensive extensional deformation, while the South China Craton was relatively stable, with extensional deformation mainly concentrated in the ECS Shelf Basin (Li Sanzhong et al., 2011).

During the Paleogene, the interior of the North China

Craton was under the control of a sinistral stress field (Dmitrienko et al., 2016). The extensional deformation of the Western Block of the North China Craton is around the Ordos Basin (Zhang Yueqiao et al., 2006). The Shanxi Graben System overlapped on the Paleoproterozoic Trans-North China Orogen had not yet developed and was in a slowly uplifted tectonic setting in the Paleogene (Zhao Junfeng et al., 2009). The Taihang Mountains in the eastern boundary of the Shanxi Graben System experienced rapid erosion in the Early Cenozoic, and the denudation rates are about 0.07–0.1 km/Ma, while the geothermal gradient is 30℃/km (Dumitru et al., 2001), which are consistent with the results of previous apatite fission track analysis (Cao Xianzhi et al., 2015). The Bohai Bay Basin in the eastern North China Craton had a strong extension and was the center for lithospheric rifting and destruction in the Paleogene. The Bohai Bay Basin was cut by the NE- to NNE-trending lithospheric faults, such as the Piedmont Fault Zone of the Taihang Mountain, the Cangdong Fault, the Lanliao (Lankao-Liaocheng) Fault and the Tanlu Fault, which belong to the dextral right-stepping pull-apart and rifted basin (Li Sanzhong et al., 2012). The absence of Early Paleocene sedimentary members may represent the uplift processes of the basement in the Bohai Bay Basin. After that, the rifting began to develop and be more significant in the Eocene. And a series of graben and half-graben systems along the NE-, NNE-, or WNW-trending faults developed under the control of basement-involved faults (Suo Yanhui et al., 2013). The evolution of the Bohai Bay Basin could be divided into a few obvious phases: the initial rifting began in the Paleocene and was intensified in the Early Eocene; the basin entered the broadening and fast rifting stage after the Eocene Kongdian Movement, while the fault stretched in a S-N direction, corresponding to the Oujiang Movement in the ECS Shelf Basin, then the whole basin began to unify. After the Early Oligocene Jiyang Movement, the basin entered the main active period called the pull-apart- rifting stage, corresponding to the Yuquan Movement in the ECS Shelf Basin, and it is a graben-type basin controlled by a NE- to NNE-trending dextral right-stepping strike-slip faults. During the Late Oligocene, the Dongying Movement caused the basin to enter the half graben stage, and the main controlling fault of the deposition in the basin was a nearly E-W-trending listric-shaped normal fault. After the deposition of the Dongying Formation at the end of Oligocene, the basin gradually switched into a depression controlled by thermal subsidence, and the differential uplifting-subsidence movement of the faulted blocks basically stopped in the basin (Xu Jie et al., 2001). On the whole, the Bohai Bay Basin changed from a rifted basin to a pull-apart basin and then into a half-graben faulted basin, and finally into a thermal depression basin in the Paleogene. At the same time, the basin structures changed from graben type to dustpan-shape half-graben and then to saucer-shape depression (Li Sanzhong et al., 2011). Spatially, the Paleogene tectonic migration in the basin was very obvious. The fault activity, depocenter and subsidence center of the basins gradually evolved from west to East (Suo Yanhui et al., 2013; Wang Tonghe, 1988).

3.2 Evolution of dynamics and Earth surface system since Neogene (25–0 Ma)

(1) Western dynamic system: evolution of Tethyan Tectonic Domain

The collision of the Indian to the Eurasian plates entered into an intracontinental evolution stage in the Neogene. There were different levels of shortening between the blocks in the Tibetan Plateau, which entered a unified deformation stage (Liu Chiyang et al., 2009). The Miocene tectonic activity was strong and the intracontinental convergence was intensified which produced large-scale thrusts, nappe structures and décollement systems. The Main Central Thrust and the Main Marginal Thrust are active in succession (Li Tingdong, 1995) to result in the start of fast uplift of the plateau and the present-day topography (Fig. 8). After the Neogene, the uplift of the Tibet Plateau was characterized by multi-stage, heterogeneous, and different velocity (Pan Yusheng, 1999). The initial uplift of the plateau occurred in the Early-Middle Miocene (23–11.7 Ma) (Ge Xiaohong et al., 2006) which can be divided into three stages: 25–17, 13–18 and 3–0 Ma (Pan Yusheng, 1999). Other scholars proposed that the uplift of the Tibet Plateau can be divided into two stages: the Miocene to Pliocene stage with medium uplift rate, and the Pleistocene to Holocene stage with rapid uplift rate (Xiao Xuchang and Wang Jun, 1998). But there are many arguments about the main uplifting period until now. For example, Harrison et al. (1995) and Quade et al. (2011) thought the main uplifting period is 8 Ma, in which the Himalaya rapidly uplifted and suffered from denudation. The altitude of the Himalaya was about 1000 m, the Himalaya's peak may have reached 2000-3000 m. Meanwhile, there was a planation surface and a series of basins formed in the southern margin of the Himalaya, which accumulated a large amount of detrital material and began to form an alluvial fan in the Bay of Bengal (Li Tingdong, 1995). Li Jijun et al. (2001) revealed that the main uplifting period is 3.6 Ma, it resulted in the main planation surface which represented the beginning of the Qingzang Movement. The Qingzang Movement can be subdivided into three episodes: A, B and C at about 3.6 Ma, 2.6 Ma and 1.7 Ma, respectively.

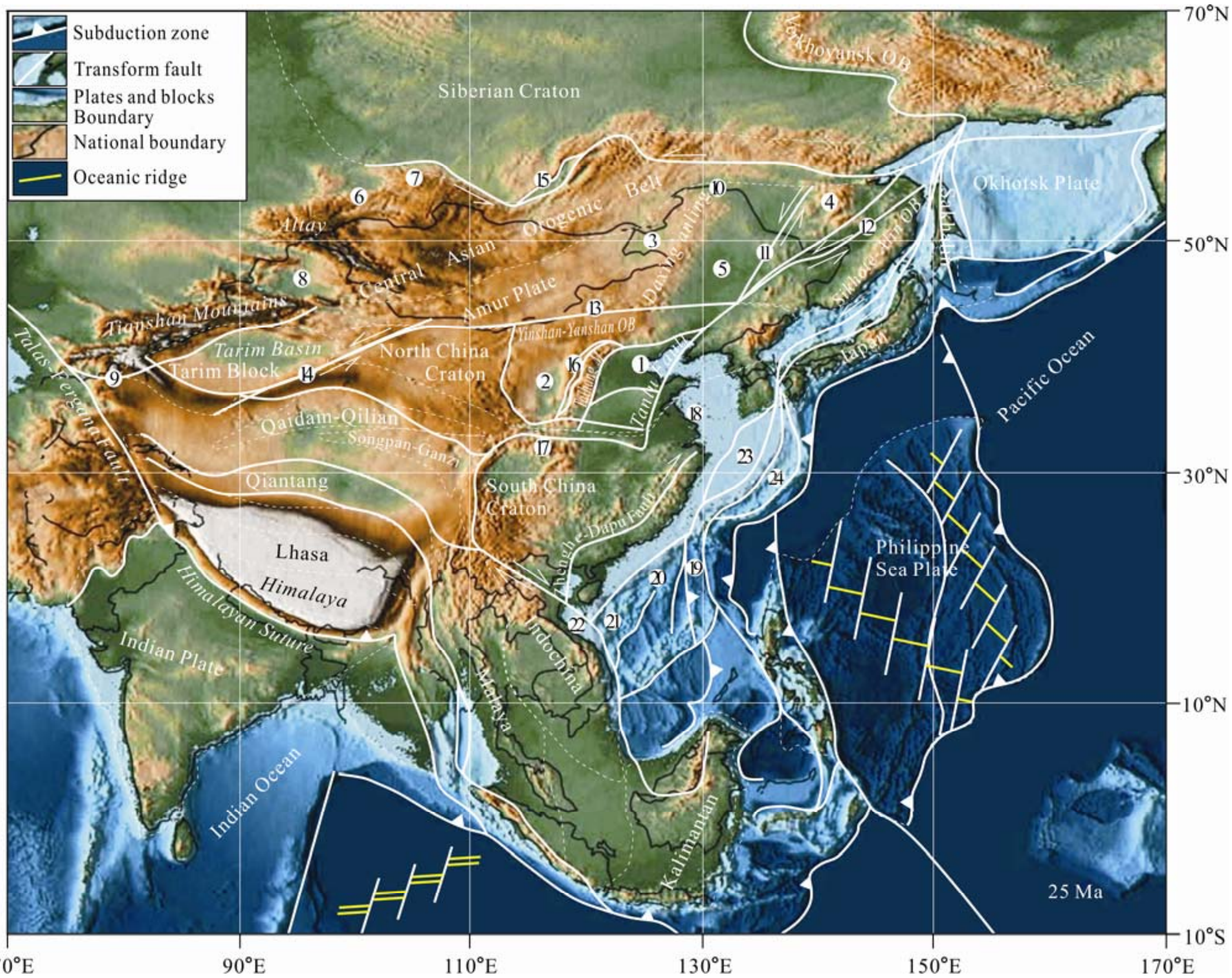

Fig. 8. Tectonic and geomorphological reconstruction of Neogene East Asia at ca 25 Ma.
Abbreviations: M-Mountains; OB-Orogenic Belt. 1, Bohai Bay Basin; 2, Ordos Basin; 3, Hailar-Tamsag Basin; 4, Mongolian-Okhotsk Orogenic Belt; 5, Songliao Basin; 6, Western Sayan Mountains; 7, Eastern Sayan Mountains; 8, Junggar Basin; 9, Cherchen Fault Zone; 10, Mohe Basin; 11, Ilan-Yitong Fault; 12, Dunhua-Mishan Fault; 13 -Solon-Xar Moron-Changchun Fault; 14, Altyn-Tagh Fault ; 15, Baikal Rift; 16, Shanxi Graben; 17, Qinling-Dabie Orogenic Belt; 18, South Yellow Sea Basin; 19, Southwest Taiwan Basin; 20, Pearl River Mouth Basin; 21, Qiongdongnan Basin; 22, Yinggehai Basin; 23, East China Sea Shelf Basin; 24, Okinawa Trough

Zheng Du (2006) further confirmed that the uplift of the Tibet Plateau during the 3.6 Ma Movement had a strong integrity and periodicity while the amplitude of uplift was significantly different and decreased from west to east.

During the Neogene, the deformation of the Tibetan Plateau extended toward the surrounding blocks, and a series of thrusts, folds and sinistral strike-slip faults developed in the northeastern margin of the plateau at 8 Ma. Meanwhile, the Altyn, Minshan, Longmenshan Mountains and the Sichuan-Yunnan Plateau showed an acceleration of the tectonic activity and tectonic uplifting (Zhang Peizhen et al., 2006). Geochronological data of ^{39}Ar-^{40}Ar revealed that the southeastern margin of the Tibet Plateau had episodic uplifting since the Late Cenozoic, at ages of about 10.1 Ma, 5.7–4.4 Ma, and 3.6 Ma, respectively (Chen Wen et al., 2006), which can compare with the deformation stages in the interior of the Tibet Plateau. The maximum altitude of the Tibet Plateau is in the Himalaya, which was attributed to the indentation of the Indian Continent on the south side of the Tibet Plateau and the dynamic topography may account for a significant portion. However, tectonic escape and mantle flow by lateral creeping may occur on both side of the Himalaya. Therefore, there is no mantle force to support the large-scale mountains.

(2) Eastern dynamic system: evolution of the Pacific Tectonic Domain

After 23 Ma, the Pacific Subduction System retreated eastward continuously which resulted in the thermal subsidence of the South Yellow Sea Basin, the northern basins in the South China Sea, and the ECS Shelf Basin to undergo a transition from faulted depression to thermal depression. The secondary depressions in each basin connected to each other to form a unified basin which is controlled by thermal subsidence and the feeble intensity of magmatic activity. In the middle Miocene, the ECS Shelf Basin suffered from an intense erosion. The eastern depression of the ECS Shelf Basin developed inversion tectonics and the Miocene strata were involved in folding (Wang Feng et al., 2005; Li Sanzhong et al., 2013), corresponding to the regional Longjing Movement. Meanwhile, the Okinawa Trough and the Shikoku-Parece Vela Basin began to develop. The average sedimentary thickness of the Okinawa Trough increases from 3–4 km in the southern segment to 7–8 km in the northern segment (Dmitrienko et al., 2016; Liu Bo et al., 2016), and the average crustal thickness increases from 14–16 km in the southern segment to 19–23 km in the northern segment. The maximum basement thickness in the northern Okinawa Trough does not exceed 17 km, while that in the central part is 13–14 km. The crustal nature of the Okinawa Trough might have changed from initial oceanic crust to hypoextensional and thinned continental crust from south to north (Liu Bo et al., 2016). The initial opening time of the Okinawa Trough is 17 Ma and the activity can be divided into normal back-arc rifting stage, passive transtension stage and initial oceanic spreading stage at ages of about 17–15 Ma, 15–6 Ma and 6–2 Ma, respectively. From Early to Middle Miocene, the mid-ocean ridge of the South China Sea propagated from the Eastern Sub-Basin to the Southwestern Sub-Basin. At the same time, the Kalimantan Block and the Dangerous Ground Block collided and started an intracontinental evolution (Wang Pengcheng et al., 2016) (Fig. 8).

From Late Oligocene to Middle Miocene, the Japan Sea opened during 28-18 Ma, and its spreading rate is about 20–40 cm/yr (Jolivet et al., 1994). Meanwhile, the Dahel Basin and the Tsushima Basin developed in the Early-Middle Miocene. In the Middle-Late Miocene, the Tsushima Strait began to form, and the Karafuto and Japan Island started to drift away southward (Dmitrienko et al., 2016), gradually away from the East Asian Continent to form the unified subsidence belt including the Okhotsk Sea, the Japan Sea, the East China Sea and the South China Sea (Fig. 8). With the continuous retreat of the Pacific Subduction Zone, the East Asian continental margin gradually transited to the present-day Japan-type trench-arc-basin system. From west to east, there developed the Japan Island Arc (23–0 Ma), the Izu-Bonin volcanic arc (20–0 Ma) and the Mariana volcanic arc (Nokleberg, 2010). The Philippine Sea Plate migrated northward and began to affect the structures in East Asia (Honza and Fujioka, 2004; Jolivet et al., 2010) in the Neogene. A large amount of magmatic rocks developed in the northern Okinawa Trough due to the oblique subduction under the NNW-directed extension at the rate of 6 cm/yr along the East Asian continental margin at about 17 Ma (Liu Bo et al., 2016). The Philippine Sea Plate subducted along the Nankai Trough to the Japan Island Arc before 5 Ma (Shiono, 1992).

(3) Transition zone of eastern and western dynamic systems: evolution in East Asia

The main active region of East Asia in Neogene is in the Shanxi Graben System. The Shanxi Graben System is located on the west side of the gravity gradient zone extending along the Greater Khingan Mountains, the Taihang Mountains and the Xuefeng Mountains, and on the east side of the North–South-Trending Tectonic Zone consisting of the Helan Mountains, the Liupan Mountains and the Longmen Mountains. The graben system is NNE-trending, including the Datong, Xinding, Taiyuan, Linfen, Changzhi and Yuncheng basins from north to south (Fig. 8). The northern boundary of the graben system is the WNW-trending Zhangjiakou-Penglai Strike-slip Fault (Guo Lingli et al., 2015), its southern boundary is a series of WNW-trending faults in the southern part of the North China Craton (Xu Liqing et al., 2013), its western boundary is the Lishi Fault and its eastern boundary is the Changzhi Fault (Wu Qi et al., 2013). The extension and the rapid subsidence of the Shanxi Graben System occurred in the Neogene-Quaternary (Ren Jianye et al., 2002). The Datong, Taiyuan and Yuncheng basins in the graben system are NE-trending, while the Linfen and Xinding basins are NNE-trending. The NE-trending Yuncheng Basin in the south and the Datong Basin in the north developed first. It is similar to the Shikoku-Parece Vela Basin, which indicated that the back-arc spreading of the Pacific Plate in the Mariana Subduction Zone may have had an influence on it. However, the Shanxi Graben System developed in the west of the Taihang Mountains, indicating that the dynamics of the Indian-Eurasian collision is weakening, and this has also been tested by the numerical simulation of Liu Mian et al. (2004). Meanwhile, the two faulted basins are perpendicular to the collision-related dynamic systems of the Tibetan Plateau and the Central Asian collision and extrusion system, which may be related to the N-S-directed compression. The Shanxi Graben System developed since the Miocene, and the boundary faults are NE–NNE-trending dextral transtensional faults with the main effect of strike slipping. The maximum thickness of the sedimentary strata in the basin is 3000–5000 m. However, the NNE-trending basins developed since the Pliocene, and the main boundary faults are normal faults. The down-faulted range are less than the NE-trending basins, such as the sedimentary thickness of the Linfen and Xinding basins is about 2000 m. The boundary faults of the Shanxi Graben System are subdivided into four groups: NNE-, NE-, WNW- and E–

W- trending faults. Previous studies revealed that the NNE –NE- trending faults are dominated by normal faults (Zhang Shimin, 2000), but field investigation shows that the NNE-trending faults are strike-slip ones. The sedimentation of the Shanxi Graben System increased in the Quaternary Period and the activity of the NE- and NNE-trending faults had been strengthened. Moreover, the extensional directions changed from NW-SE to NNE-SSE and the strikes of the developed faults also changed from NE-trending to E–W-trending (Wu Qi et al., 2013).

4 Tectonic Transition and Topographic Inversion in the Meso-Cenozoic East Asian Superconvergence

East Asia has been long-term surrounded by the Tethyan, Paleo-Asian and (Paleo-) Pacific tectonic domains. The Meso-Cenozoic tectonic evolution is basically a result of the co-influence of the three domains. The tectonic regimes changed from convergence and collision in Late Triassic–early Early Cretaceous to extension and delamination in late Early Cretaceous–Cenozoic. The simultaneous convergence of different blocks and the following extension are a foreshadow of the assembly of the Supercontinent Amasia, providing a real instance for understanding the complex processes of a supercontinent cycle.

4.1 Transition from E–W-trending to NE-trending tectonic regimes

Since the Late Triassic, East Asia has been under a tectonic setting of subduction and convergence. However, East Asia was still not a complete rigid block, the northwestern margin experienced an intra-continental deformation after the closure of the Paleo-Asian Ocean. The pre-existing mountains such as the Altay Mountains and the Tianshan Mountains underwent a rapid exhumation. The thrusting in the South Tianshan and North Tianshan Mountains resulted in the uplift and erosion of the in-between Junggar Basin. In northern East Asia, the scissor-like closure (early in the west and late in the east) of the Mongol-Okhotsk Ocean resulted in the formation of E–W- trending structural belts. In Central China, as the subduction of the Sulu segment of the Shangdan Ocean beneath the northeastern Greater South China Block, the North China Block indented into the Greater South China Block to develop an orocline around the eastern margin of the North China Block in the Early–Middle Jurassic (Guo Runhua et al., 2017; Li Sanzhong et al., 2017a). At the same time, the Indosinian subduction of the South China Block beneath the North China Block along the western segment of the Shangdan Suture and the Mianlue Suture produced the so-called “Crocodile-Mouth Structure” at depth in the Qinling Orogen and an E–W-trending structural lineation on the surface along the Dabie Orogen (Dong Shuwen et al., 2005, 2007; Li Sanzhong et al., 2010; Zhang Guowei et al., 2013). In eastern East Asia, an ocean-continent connection zone formed since the Indosinian period from Sakhalin in the north to Kalimantan Island in the south, the initiation of the Paleo-Pacific subduction symbolized a transition from passive to active continental margins and the beginning of the Paleo-Pacific Tectonic Domain. A tectonic regime is co-influenced by three dynamic systems in the north, south and east formed.

In the Late Triassic–Middle Jurassic period, the compression caused by a westward progressive subduction of the Paleo-Pacific Plate resulted in the uplift of the East Asia continental margin similar to the formation of the Andes Mountains in South America. Some accretionary complexes developed in the Nadanhada area. The emplacement of I-type granites in the eastern Greater Khingan Mountains at 210–155 Ma and in the Jincheng, Fujian Province (southeast coastal range) at 187 Ma have a similar geochemical property to those granites in volcanic arc (Liu Qian et al., 2011; Wu Fuyuan et al., 2011a), which should be related to the subduction of the Paleo-Pacific Plate. While the compression related to subduction between Late Triassic-Middle Jurassic are mostly yielded in areas near the subduction zone. The intra -continent was still influenced by the early E–W- trending tectonic regime. Wang Bin et al. (2006) proposed that the E–W-trending Tethyan tectonic regime transited to the NE -trending Paleo-Pacific tectonic regime, being characterized by compressional deformation and rapid piedmont deposition in the Middle Jurassic.

During the late Middle Jurassic, the subduction already had an influence on the magmatism and deformation in the interior East Asia. The 170 Ma adakites in the Dexing area should be related to the subduction (Wang Guoguang et al., 2012; Zhou Qing et al., 2012). In addition, the Hanfang Granite in the Gan County, Jiangxi Province, emplaced at 169.8 Ma (Li Jiankang et al., 2012), and other igneous rocks are between 170~150 Ma (Zhao Xilin et al., 2012), the extensive mineralization in the Nanling area occurred between 165-150 Ma (Mao Jingwen et al., 2007). The transition from depletion to enrichment of Hf isotopes at 160 Ma implies the extension was replaced by contraction at depth (Liu Lei, 2015). The structural analysis for this area also shows the influence of subduction on the interior of East Asia. Wang Pengcheng et al. (2015) revealed the NE-trending early Yanshanian thrusting in the Middle-Lower Yangtze River area. Zhang Yueqiao et al. (2009) proposed the NE-trending early

Yanshanian deformation superimposed on the pre-existing E–W- trending structures, and the transition from the Tethyan Tectonic Domain to the Paleo-Pacific Tectonic Domain occurred at 170±5 Ma. The lithospheric deformation at depth and at shallow levels might be decoupled, which might be evidence of the destruction of a craton starting from the deep. Song Chuanzhong et al. (2010) also suggested that the transition happened in early Yanshanian period based on studies in the Middle-Lower Yangtze River area. The tectonic regime of the interior East Asia transited from E–W-trending to NE-NNE-trending in the Late Triassic-Middle Jurassic. The extensive magmatism and deformation occurred at about 170–160 Ma indicate that the transition is related to the progressive subduction of the Paleo-Pacific Plate. Therefore, we propose that the transition occurred at about 170–160 Ma, while the inversion from contraction to extension occurred later, which belongs to another tectonic event.

4.2 Transpression and development of the Andean-type continental margin and the eastern North China Plateau

In the Late Jurassic-early Early Cretaceous times, the final closure of the Okhotsk Ocean resulted in the collision of the Siberia Craton and the Amur Plate, and then the formation of the Okhotsk structural belt accompanied by N–S-directed shortening and eastward or westward extrusion and escape tectonics. The collision influenced the deposition in the adjacent basins, including the Tarim, Junggar and Turpan basins (Hendrix et al., 1992; Wu Lei et al., 2011b). The compression in the Altay and Tianshan Mountains resulted in extrusion and uplift of 153–143 Ma, and the thrusting and shortening of the Junggar Basin in between. The collision-related force transmitted thousands of kilometers to control the second episode of the Yanshanian Movement in the Yinshan-Yanshan Mountains (Zhao Yue et al., 2004), north of the North China Block. The southern East Asia was also in a tectonic setting of subduction and collision. The closure of the Bangong Co-Nujiang Ocean and the subsequent collision between the Qiangtang Block and the Lhasa Block resulted in an uplift and intense erosion. Plate reconstruction of the eastern East Asia revealed the westward progressive subduction and compressional stress field in both the margin and interior of the continent. The subduction influenced an intra-continental area wider than 1000 km far away from the trench. The Middle Jurassic strata (175–161 Ma) are almost absent in Southeast China. The northern Fujian Province experienced intense thrusting, tested by a discovery of coal-bearing strata beneath the Caledonian intrusions (Mao Jianren et al., 2013) and the development of a series of NE-trending metamorphic belts. All the geological records indicate the East Asian continental margin was an Andean-type margin, topographically with a narrow mountain range along the margin. Due to the NNW-directed oblique subduction of the Paleo-Pacific Plate, a series of NNE–NE - trending transpressional left-lateral strike-slip faults formed at about 160–130 Ma shown by the dating results (Zhu Guang et al., 2005; Zhang Yueqiao et al., 2007; Gu Chengchuan et al., 2016).

Due to the simultaneous subduction or collision of the three tectonic domains to the north, south and east, East Asia was under a transpressional stress field. Then a series of NNE–NE- trending strike-slip faults cut the East China region into several triangular blocks, controlling the development of different types of basins, superimposing and reforming the previous Indonisian–early Yanshanian structures. The shortening and thickening of the crust in North China led to the rise of the eastern North China Plateau, which is also indicated by the occurrence of adakites. The plateau grew from northeast to southwest, centered on the present-day Bohai Bay Basin. The plateau mainly developed during Late Jurassic-Early Cretaceous times.

In the late Early Cretaceous, the eastern margin and interior of East Asia began to be controlled by transtension as the subduction zone of the Paleo-Pacific began to retreat to the east and the angle of the subducted plate became steeper (Hou Fanghui, 2014). The NE-NNE-trending fault system transited into a sinistral transtensional system after 135 Ma (Zheng Changqing et al., 2015; Li Gang, 2013). At the same time, a series of rifted basins formed, such as the Bohai Bay Basin and the Jiaolai Basin (Ren Jianye et al., 2002). During the strike-slip faulting and the formation of the basin, a large number of metamorphic core complexes developed in East Asia. The ages mainly range from 135 to 125 Ma, with a small part of it continuing to the end of the Early Cretaceous. In the late Early Cretaceous, East Asia stretched intensively to form a large number of volcanic-intrusive rocks, with the main acidic-to-acidic high-K calc-alkaline combination. The early rocks (135–125 Ma) distribute across the Lishui-Haifeng Fault to the west, showing patchy distribution. However, the rocks of later ages (less than 125 Ma) are mainly confined to the coasts of Zhejiang and Fujian provinces. The ages of the rocks tend to be younger from west to east. The typical Andean-type continental margin formed during the Late Jurassic- late Early Cretaceous (160–135 Ma) was gradually destroyed and the mountain gradually disappeared (Fig. 4). At the same time, the plateau in North China collapsed and some adakite rocks developed within or around the plateau. It reveals that the deformation since 132 Ma started to significantly shrink from the outer to the inner part of the eastern North China Plateau, and the plateau completely disappeared at 127–125 Ma (Yang Jinhui et al., 2006; Zhang Qi et al., 2009). Thus, the transition from contraction to extensional tectonics keeps at the same time.

4.3 Cenozoic geomorphological inversion

In the Mesozoic-Cenozoic tectonomorphological inversion in East Asia occurred three times: The first inversion took place during the Late Triassic. The Paleo-Pacific subduction initiated, with the transition of the passive to the active continental margins on the eastern East Asia. The topography changes from low to high. The second inversion took place in the late Cretaceous, the Andean-type active continental margin was damaged and the eastern North China Craton collapsed. The topographic changes from high to low (Figs. 4 and 5). The third inversion took place in the Cenozoic. The Andean-type active continental margin completely disappeared and changed to the trench- arc- basin system. The topography in eastern East Asia changes from high to low, while the Tibetan Plateau uplifted and became the world's ‘the third pole’ (Figs. 6–8). Therefore, the Cenozoic geomorphological inversion is mainly controlled by the joint control of the Neo-Tethyan Tectonic System and the Pacific Tectonic System, forming a step-shaped terrain and landform from west to east in East Asia.

During the Paleogene Neo-Tethyan subduction, the Indian Plate collided with the Eurasian Plate to produce the Tibet Plateau. The collisional influence in the Paleogene mainly occurred in the interior and margins of the Tibetan Plateau, and the strike slip faults have a significant effect on the local production in the vast ranges around the plateau. Furthermore, the uplifting of the plateau results in the first-order step-like terrain. The Pacific Plate began to roll back and subduct towards the East Asian continental margin at about 60 Ma. The early motion sense of the Pacific Plate was NNW-directed. At 47 Ma the subduction direction was WNW-directed, developing a dextral transtensional stress field in the East Asian continental margin. Under the control of the dextral transtensional stress field, the North China Craton had a strong extensional development within the interior of the Bohai Bay Basin. The basin rifted in the Early Paleogene. In the Oligocene, it became a pull-apart basin and later followed a graben-like faulted depression. Under the intense extension, a second-order step-like terrain developed along the Greater Khingan-Taihang-Xuefeng Mountains gravity gradient zone. A number of the basins, for example, the South Yellow Sea Basin, the ECS Shelf Basin and the peripheral margins of the South China Sea, developed on the eastern East Asian connection zone (Fig. 7) (Zhao Shujuan et al., 2017; Li Sanzhong et al., 2012a, b; Wang Pengcheng et al., 2017; Hui Gege et al., 2016a, b). The basin is controlled by a series of NE-NNE-trending strike slip faults. The early-stage basins are a graben-type pull-apart basin, and the late-stage ones are a half-graben faulted basin. Its stratigraphic thickness, intensity of fault activity, basin pattern and basin structure show that the basins were gradually active from west to east, forming the third-order step-like terrain along the eastern East Asian basins.

The Neogene evolution of the Tibet Plateau propagated northward under the intra-continental stage, and the plateau became a unified plateau (Liu Chiyang et al., 2009). The intense Miocene tectonic activity and the intensification of intracontinental convergence have led to the formation of large-scale thrusts, nappe structures and extrusion tectonics (Li Tingdong, 1995). The plateau began to strongly uplift into the present-day geomorphological state (Fig. 8). The main uplifting phases are in the Miocene–Pliocene and Pleistocene–Holocene, respectively. After 23 Ma, the western Pacific subduction zone continued to retreat eastward. The main extensional zone migrated to the east of the ECS Shelf Basin. The basins in the eastern East Asian continental margin formed in the Paleogene changed from faulted depression to thermal depression. The formation of a unified basin by the second depression zone and interaction within each basin is controlled by thermal subsidence and inversion tectonics. And the inversion tectonics developed in some basins. The Okinawa Trough and the Shikoku- Parece Vela Basin began to open. As the Japan Sea opened and the Sakhalin and the Japan Islands began to drift southward (Dmitrienko, 2016), gradually moving away from the East Asian continent. Furthermore, the present-day trench-arc-basin system gradually formed. The main Neogene intra-continental activities in East Asia are in the areas of the Shanxi Graben and the Baikal Rift. The extension of the Quaternary grabens and rifts enhanced and the deposition rate increased. Zhao Dapeng et al. (2017) revealed that the stagnant slab of the subducted Pacific Plate in the mantle transition zone was confined to the east of the Taihang Mountains and did not affect the Shanxi Graben in the central North China Craton. Numerical simulations reveal that the deep mantle flow during the uplift of the Tibet Plateau can reach the location of the Shanxi Graben System (Liu Mian et al., 2004). Therefore, the formation of the Shanxi Graben System may also be related to the evolution of the southern Tethyan Tectonic System.

5 Conclusions

In summary, we systematically discuss the processes of massive micro-continental blocks or terranes converging toward northern Laurasia during the Gondwana assembly and may represent a microcosm of the supercontinent assembly. To understand this process there are two aspects of core scientific significance: (1) Does it reveal what will happen in the process of supercontinental assembly? What are the associated resources, environment and geohazards? (2) During the supercontinent assembly, how do the Earth surface system processes such as weathering, erosion, denudation, sedimentation, deformation, metamorphism, hydrocarbon accumulation and mineralization respond to deep geodynamic processes in the context of superconvergence among three or more plates? Based on these issues, we have few new understandings for the formation processes of macroscopic geomorphology and geology in East Asia.

1) During the subduction of the Paleo-Pacific Plate to the East Asian Continent, East Asia is gradually controlled by the 160–170 Ma transition of the E–W-trending Tethyan Tectonic Domain and the Paleo-Asian Tectonic Domain to the NE-striking Paleo-Pacific Tectonic Domain in Late Triassic to Middle Jurassic times.

2) From Late Jurassic to late Early Cretaceous, the East Asian Continent was under a convergent environment. Under the westward subduction of the Paleo-Pacific Plate, the eastern margin of East Asia was controlled by the regional stress field of transpression and the Andean-type active continental margin eventually formed. The plateau of eastern North China formed to result in the East Asian overall landform of high in the east and low in the west.

3) In late Early Cretaceous, the stress fields in East Asia changed from transpression to pull-apart or transtension during the retreating subduction of the Paleo-Pacific Plate. The change of tectonic regimes occurred between 135 Ma and 125 Ma. Then the Andean-type continental margin began to enhance a destruction of the North China Craton and the collapse of the eastern North China Plateau.

4) Cenozoic East Asia experienced a huge terrain reversal or morphotectonic inversion. As the Tibet Plateau uplifted, the East Asian intra-continental basins and marginal basins began to develop. The tectono-basin-magmatic belt is characterized by an eastward migration. The macro-topography and geomorphology is replaced by the eastern high terrain in the Mesozoic to the western high step-style terrain in the Cenozoic.

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