Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas

Jianye Ren\textsuperscript{a,*}, Kensaku Tamaki\textsuperscript{b}, Sitian Li\textsuperscript{a}, Zhang Junxia\textsuperscript{a}

\textsuperscript{a}Institute of Sedimentary Basin and Mineral, Faculty of Earth Resources, China University of Geosciences, Wuhan 430074, PR China
\textsuperscript{b}Ocean Research Institute, University of Tokyo, 1-15-1 Minamidai, Nakano, Tokyo 164-6398, Japan

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Abstract

During the Late Mesozoic and Cenozoic, extension was widespread in Eastern China and adjacent areas. The first rifting stage spanned in the Late Jurassic–Early Cretaceous times and covered an area of more than 2 million km\textsuperscript{2} of NE Asia from the Lake Baikal to the Sikhot-Alin in EW direction and from the Mongol–Okhotsk fold belt to North China in NS direction. This rifting was characterized by intracontinental rifts, volcanic eruptions and transform extension along large-scale strike–slip faults. Based on the magmatic activity, filling sequence of basins, tectonic framework and subsidence analysis of basins, the evolution of this area can be divided into three main developmental phases. The first phase, calc-alkaline volcanics erupted intensely along NNE-trending faults, forming Daxing'anling volcanic belt, NE China. The second phase, Basin and Range type fault basin system bearing coal and oil developed in NE Asia. During the third phase, which was marked by the change from synrifting to thermal subsidence, very thick postrift deposits developed in the Songliao basin (the largest oil basin in NE China). Following uplift and denudation, caused by compressional tectonism in the near end of Cretaceous, a Paleogene rifting stage produced widespread continental rift systems and continental margin basins in Eastern China. These rifted basins were usually filled with several kilometers of alluvial and lacustrine deposits and contain a large amount of fossil fuel resources. Integrated research in most of these rifting basins has shown that the basins are characterized by rapid subsidence, relative high paleo-geothermal history and thinned crust. It is now accepted that the formation of most of these basins was related to a lithospheric extensional regime or dextral transtensional regime. During Neogene time, early Tertiary basins in Eastern China entered a postrifting phase, forming regional downwarping. Basin fills formed in a thermal subsidence period onlapped the fault basin margins and were deposited in a broad downwarped lacustrine depression. At the same time, within plate rifting of the Lake Baikal and Shanxi graben climaxed and spreading of the Japan Sea and South China Sea occurred. Quaternary rifting was marked by basalt eruption and accelerated subsidence in the area of Tertiary rifting. The Okinawa Trough is an active rift involving back-arc extension. Continental rifting and marginal sea opening were clearly developed in various kind of tectonic settings. Three rifting styles, intracontinental rifting within fold belt, intracontinental rifting within craton and continental marginal riftting and spreading, are distinguished on the basis of nature of the basin basement, tectonic location of rifting and relations to large strike–slip faults. Changes of convergence rates of India–Eurasia and Pacific–Eurasia may have caused NW–SE-trending extensional stress field dominating the rifting. Asthenospheric upwelling may have well assisted the rifting process. In this paper, a combination model of interactions between plates and deep process of lithosphere has been proposed to explain the rifting process in East China and adjacent areas. The research on the Late Mesozoic and Cenozoic extensional tectonics of East China and adjacent areas is important because of its utility as

\* Corresponding author.
E-mail address: jyren@dns.cug.edu.cn (J. Ren).

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an indicator of the dynamic setting and deformational mechanisms involved in stretching Lithosphere. The research also benefits the exploration and development of mineral and energy resources in this area. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Hundreds of extensional or transtensional basins developed over East China since Late Mesozoic time. Most of these basins contain a large amount of fossil fuel resources and form the economically important oil-, gas- and coal-producing bases in East China. Owing to the urgent demand for prospecting energy resources, rift systems in this area have been surveyed extensively by geological and geophysical methods during the past few decades. The fillings and structural geometry of extensional basins in this area have been described by many geologists (Ma and Wu, 1987; Tian et al., 1992; Gilder et al., 1991; Li, 1984; Li et al., 1987, 1995, 1997; Liu, 1986; Ru and Pigott, 1986). These research works have improved our understanding of the stratigraphic and structural framework and the evolution of the rift systems. However, the kinematic processes and geodynamic evolution of these basins are far from being understood. In order to better understand and predict sedimentary basin evolution and hydrocarbon distribution in this area, a detailed extension basin map and basin dynamic model based on plate tectonic is required.

The study area is located in Eastern China and adjacent areas, which lie between two of the most dynamic tectonic domains of the earth lithosphere, the subduction zones of the western Pacific and Himalayan tectonic belt. We integrate new information with existing geological and geophysical data from onshore and offshore Eastern China and adjacent areas, compile a new distribution map of Late Mesozoic and Cenozoic extensional basins, reconstruct the rifting evolution history through Late Mesozoic to Present in this area, and relate the plate tectonic evolution to the main phases of basin development from their genesis in the Late Mesozoic to the Present. Our alternative interpretation may be a key to understanding the intra-continental and continental margin tectonics and hydrocarbon distribution.

2. Spatial-temporal distribution of rifting

Rifting of different ages and tectonic setting has prevailed in Eastern Eurasia since the Late Jurassic, which has led to the formation of intracontinental extensional basins, marginal basins and other extensional tectonic features, and extensive rifting-related volcanism. Detailed geological and geophysical researches have revealed four rifting stages: Late Mesozoic rifting, Early Tertiary rifting, Neogene rifting and spreading, and quaternary rifting. Fig. 1 shows spatial-temporal distribution of extensional tectonics in study area since the Late Mesozoic and Fig. 2 indicates the formation range of typical basins in this area.
area. The division into stages was primarily based on age determinations from sediments within basins.

2.1. Late Mesozoic rifting and the Northeast Asia fault basin system

Late Mesozoic rifting mainly occurred in Northeast Asian area and was characterized by strong volcanic activity, formation of Basin and Range type fault basins and transtensional basins along large-scale strike-slip faults.

2.1.1. Widespread volcanic eruption

The volcanic activity developed along NNE or NE directions and mainly distributed along Daxing’anling tectonic–magmatic belt (Fig. 1). This belt was more than 1000 km away from Mesozoic subduction zone of the western Pacific (Faure and Natlin, 1992). Volcanism was active from Jurassic to Cretaceous with its peak in J3–K1. The rock types are dominated by high K calc-alkaline series, partly consisting of shoshonitic and calc-alkaline series. Some characteristics show that the volcanics are similar to those of island or continental marginal arcs (Wang, 1986; Zhao et al., 1994); however, there are many aspects that are not consistent with arc volcanics (Lu et al., 1997). From the research on the chemical analysis of the rocks, the volcanics in this area do not indicate obvious compositional polarity, and incompatible elements mass fraction are higher than those of the typical arc volcanics (Lu et al., 1997; Wang, 1986). Importantly, the volcanics are far from the Mesozoic subduction zone of the Pacific side. Therefore, it is difficult to explain the tectonic environment by a direct relation to subduction. Lu et al. (1997) and Zhu et al. (1997) concluded that it is related to intracontinental rifting, representing the first episode of Late Mesozoic rifting, and volcanism, and is one of the principal manifestations of Late Mesozoic rifting (Li et al., 1987). This intracontinental rifting was caused by both asthenospheric upwelling and the interactions between Eurasia–Pacific plate and Eurasia–India plate, and it will be covered in more detail later in the paper.

Continental Marginal volcanic belt in the eastern-most part of the eastern Asia continent developed from Okhotsk–Chukotka belt, through Sikhote Alin, Korea to southeastern China coast (Fig. 1). This belt contains intrusive and volcanic rocks ranging in age from J3 to K2 with an eruptive peak at 130–120 Ma. Most of these intrusive and volcanic rocks were related to active continental margin magmatism caused by westward subduction of an oceanic plate. The intrusive and volcanic rocks related to rifting occurred in Late Early Cretaceous and Late Cretaceous. The chemistry, trace element constitution, rare earth element constitutions and accessory mineral assemblage indicate that these intrusive and volcanic rocks are characterized by a bimodal magmatic association and A-type granites, suggesting continental crustal stretching (Cong, 1977; Tao, 1992).

2.1.2. Northeastern Asian fault basin system

The second episode of Late Mesozoic rifting is represented by the development of the Basin and Range type fault basin system (Li et al., 1987, 1995; Ren et al., 1997), which is characterized by evenly spaced parallel mountain ranges and intervening basins. This fault basin system covers an area of more than 2 million km² in Northeastern Asia, and consists of about 300 NE–NNE-trending half grabens or grabens. These basins commonly are 50–150-km long and 10–50-km wide, and have abundant coal, petroleum and gas resources. This fault basin system extends westward to Lake Baikal and eastward to near the Sikhot-Alin belt. The distribution of this fault basin system lies mainly in the Mongol–Okhotsk fold belt, and it also extends southward into North China craton (Figs. 1 and 3). Most of Late Mesozoic fault basins in North China craton is covered by Cenozoic basins.

Bounded by Daxing’anling tectonic–magmatic belt, the fault basins west of the Daxing’anling are characterized by simple graben, half graben and compound fault basins with very thin postrift sediments. In contrast, the Songliao basin (SLb in Fig. 1), with very thick postrift deposits and the largest basin bearing oil and gas in China, is located in east of the Daxing’anling. Postrift subsidence in Songliao Basin lasted till the end of the Cretaceous when the basin was partially inverted.

According to the model of Buck (1991), this fault basin system shows the features of widely distributed rifting and has a style similar to the Basin and Range province of the western America. Estimation of lithospheric stretching amount on basis of the cross-section of rifted area indicates more than 100 km of horizontal amounts of lithospheric extension within China (Ren
et al., 1997; Lin et al., 1997), suggesting strong stretching and rifting of lithosphere in this area during Late Mesozoic time.

2.1.3. Transtension along large-scale strike–slip fault

One of the general features of Mesozoic deformation in eastern Asia is the formation of a series of NNE-trending faults parallel to the continental margin, and the most famous one is the Tancheng–Lujiang strike–slip fault (Fig. 1). Some geologists think these faults were sinistral faults during Jurassic–Cretaceous (Xu, 1982; Xu and Zhu, 1994), which suggests a sinistral transpression stress regime in eastern Asia. From the basin research, however, the tectonic stress regime above sinistral transpression had been changed to dextral transtension regime by the end of Late Jurassic. Fig. 3 illustrates distribution of Late Mesozoic fault basins in the both sides of the Tancheng–Lujiang strike–slip fault. From this figure, it can be seen that east of the Tancheng–Lujiang strike–slip fault, fault basins near the Tancheng–Lujiang strike–slip fault trend NNE direction, while eastward away from this strike–lip fault, fault basins trending direction changes to NEE. West of the Tancheng–Lujiang strike–slip fault, fault basins trend near W–E next to the Tancheng–Lujiang strike–slip fault, while westward away from the strike–lip fault, fault basin trend changes to NE. In addition, the Tancheng–Lujiang strike–slip fault got into rift evolution stage during Late Mesozoic time (Xu et al., 1982), and was filled by sedimentation composing of fine grained lacustrine clastic rocks (J₃–K₁)-volcanic rocks (K₁)-red alluvial plain clastic rocks (K₂). These characteristics show that dextral transtension regime dominated the deformation in both sides of the Tancheng–Lujiang fault basins in Late Mesozoic, which was in accordance with the tectonic stress regime of Northeast Asia Fault Basin system above.

2.2. Early tertiary rifting

A strong orogenic event, called “Late Yanshan Movement” in China, occurred in the latest Cretaceous–Eocene. This tectonic event was characterized by sinistral transpression regime and mainly affected the NE China block and the North China block. Strong tectonic inversion occurred in the Songliao basin of the NE China block (Fig. 2), forming NNE- or NE-trending anticlines and thrusts during 77–65 Ma, as well as regional unconformity T03 (Fig. 4). This tectonic event caused that the Tancheng–Lujiang fault switched sense to sinistral in the Latest Cretaceous, which ended Late Mesozoic rifting in both sides of the Tancheng–Lujiang strike–slip fault, and led to formation of regional unconformity TR in the Bohaiwan basin (Figs. 5 and 6).

Following uplift and denudation, caused by the latest Cretaceous compressional tectonic event stated above, the Tertiary rifting stage produced widespread rift systems in both the continent and continental margin of Eastern Asia. These rifted basins were usually filled with several kilometers of alluvial and lacustrine deposits, and contain a large amount of hydrocarbons. The beginning of the Early Tertiary rifting was characterized by alkaline basalts which formed fissure eruptions (Tian et al., 1987; Ye et al., 1997). These rift basins can be grouped into two systems, a continental rift basin belt and a continental marginal basin belt. The major part of continental rift basin belt lies in the Bohaiwan basin (BHb in Fig. 1), the second largest hydrocarbon-bearing rift basin in China, which has an area of nearly 200,000 km². Towards the south, the southern North China basin (SNCb in Fig. 1) and Jianghan basin (JHb in Fig. 1) are both the components of same rift system.

It should be noted that during the Late Cretaceous–Eocene, southeastern margin of the South China was in an extension regime. This area lies close to the subduction zone of the Kula-Pacific plates, and back-arc rifting led to another major fault basin system, Southwest China Basin group (SECb in Fig. 1), formed in Southeast China whose development climaxed with deposition of the Late Cretaceous–Paleocene continental red beds (Fig. 1). However, the extent of deposition started to shrink from the Paleocene onwards, and basins ceased to subside by Eocene time.
The Tancheng–Lujiang fault belt with its two NE extensions in Northeast China, Yilan–Yitong fault belt and Fushun–Mishan fault belt, is the biggest strike–slip fault belt in East China. This fault system has undergone a complicated geological evolution, which includes the transformation between sinistral strike–slip and dextral strike–slip, and between trans-tension and transpression, clearly indicating that the

Fig. 3. Late Mesozoic basin tectonic map in both sides of the Tancheng–Lujiang strike–slip fault (location see as Fig. 1).
Mesozoic and Cenozoic stress field in East China were reversed at least twice. In the two NE extended branches of the fault zone, there are the Yilan–Yitong Graben (YYg in Fig. 1) and the Fushun–Meihekou Graben (FMg in Fig. 1), which all show a combined process of extension and strike–slip during the basin evolution (Tian and Du, 1987; Ren et al., 1999).

The Offshore Tertiary basins are distributed inland and within the marginal seas. The inland sea basins occurred on continental crust, such as the South Yellow Sea basin (SYSb in Fig. 1) and the Beibuwan basin (BBWb in Fig. 1). They have similar characteristics with the intracontinental rift basins. Continental marginal basins occurred on continental and transitional crust. They generally are located in the back-arc area of Western Pacific suprasubduction zone. The NE-trending East China Sea basin (ECSb in Fig. 1) is the biggest of these basins. Towards the southwest, there are the NE- or NEE-trending Southwest Taiwan (SWTb in Fig. 1), Pearl River Mouth and the Qiongdongnan basins (PRMb and QDNb in Fig. 1). In contrast, the Yinggerhai basin (YGHb in Fig. 1) trends NW. This basin is located along the Red River strike–slip fault zone, and is interpreted as a transform-extensional basin (Li et al., 1999).

Another major Early Tertiary marginal sea basin area is located in the southern South China Sea. Compared with the northern margin of the South China Sea, much less is known about the geology of this area. The Zengmu basin (ZMb in Fig. 1) is the largest basin in this area, which has an area of 235,000 km² and a sedimentary thickness of more than 10 km. It was filled with Tertiary sediments and has been controlled by NW-trending faults, leading to gradual stepped-block subsidence to the northeast (Jiang et al., 1994). Towards northeast, a series of NE-trending abundant

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Fig. 4. Filling sequences and tectonic evolution of the Songliao basin. Subsidence rate is in reference to Lin et al., 1997.
Fig. 5. A seismic profile across the southeastern Bohai basin. Profile location is shown in an insert figure.
banks and small basins, such as Yunqing basin YQb in Fig. 1), Andu basin (ADb in Fig. 1) and Liyue basin (Lyb in Fig. 1) developed. These banks and basins are suspected to be the result of the extension of continental crust. Seismic profiles show that the extension in this area is relatively weak and localized in both time and space in contrast to the widespread early Tertiary extension structure in the northern margin of the South China Sea (Zhou et al., 1995).

Strong volcanism accompanied the late Cretaceous and early Tertiary rifting (Fig. 1). Paleocene to Oligocene basin-filling tholeiitic to transitional basalts occurred in the Bohaiwan basin of east China (Fan and Hooper, 1991; Ye et al., 1997). Eocene to Oligocene basalt flows were encountered in wells within the Pearl River Mouth basin and the southwest Taiwan basin (Yu, 1990).

2.3. Neogene intracontinental rifting and the spreading of the marginal sea

During this stage, the Bohaiwan, East China Sea, and South China Sea basins, etc., were involved in postrift regional subsidence (Fig. 2), forming the broad
depression, while the rifting was constrained in lake Baikal, western North China and the Gulf of Thailand. The Baikal rift zone was formed exactly along the southeastern margin of the Siberia Craton and has been active from late Oligocene to Present (Tapponnier and Molnar, 1979; Zonenshain and Savostin, 1981). Its total length is more than 2000 km. Numerous extensional faults and grabens are developed in the rift zone (Zonenshain and Savostin, 1981; Kimura and Tamaki, 1986; Hutchinson et al., 1992). The trends of faults and grabens are variable along its extent: ENE to the northeast of Lake Baikal which is situated along the central part of Baikal rift zone, NNE to NE along Lake Baikal, EW to the southwest of Lake Baikal. Two stages of the activity of the Baikal rift zone are well documented. The earlier rifting resulted as a pull apart by sinistral transforming during Oligo-Miocene time, and the later rifting was caused by EW extension since Pliocene time (Tapponnier and Molnar, 1979; Kimura and Tamaki, 1986).

Two Late Tertiary rift systems, the Hetao–Yinchuan rift system and Shanxi graben system, were developed in western North China (Fig. 1). The Hetao–Yinchuan graben system consists of two individual grabens: the NNE-trending Yinchuan Graben and the E–W-trending Hetao Graben. The Shanxi graben system consists of a series of en echelon grabens. Each graben trends NE, whereas the entire graben system is oriented NNE. Although rifting started to develop in the Hetao–Yinchuan graben system and the southern part of the Shanxi graben system in the early Oligocene or late Eocene, the major extension and rapid subsidence occurred later in the Neogene and Quaternary (Ye et al., 1987; Wang, 1987). Rifting in Shanxi rift system propagated from the southwest to the northeast during the Oligocene to Pliocene period.

The Gulf of Thailand basin (GTb in Fig. 1) is located south of the Wanchao–Three Pagodas strike-slip faults and consists of a series of small basins. These basins are oriented N–S and controlled by N–S-trending normal faults. Polanchan et al. (1991) interpreted these N–S-trending depocenters as pull-apart basins along right-lateral NW–SE fault zones.

The spreading of the marginal seas was the second principal tectonic event that occurred in the study area during this period. Western Pacific marginal basins, such as Japan Sea, Shikoku-Parece Vela Basin and South China Sea, opened during the late Oligocene to the middle Miocene (Fig. 2). Based on the magnetic anomaly lineations, the spreading of South China Sea took place from 32 to 16 Ma (Taylor and Hayes, 1983; Briais et al., 1993). The topography and the distribution of magnetic anomaly lineations suggest that the zone of oceanic crust widened to the east. The Manila trench bounds the eastern margin of the zone of oceanic crust. Detailed magnetic anomaly data show a westward propagation of a past spreading system.

The Japan Sea can be divided into three major deep sea basins: Japan, Yamato, and Tsushima basins. The Japan basin is identical to normal oceanic crust overlying by 2000 to 3000 m of sediments and shows a rather simple morphology of a wide, deep-sea basin. Magnetic anomaly lineations imply that the eastern part of the Japan Basin was formed by a seafloor spreading system that propagated southwestward (Tamaki et al., 1995). Identification of magnetic anomalies and results of ODP Leg 127 and Leg 128 in the Japan Sea indicate that the seafloor spreading initiated at ca. 28 Ma and lasted till 18 Ma (Tamaki et al., 1992; Tamaki, 1995). A slow convergence began recently along the eastern margin of the Japan Sea (Tamaki and Honza, 1985) and the Japan Sea is about to disappear by subduction. The Yamato and Tsushima basins are characterized by complicated seafloor topography with many ridges, rises, banks and seamounts. Extended continental crust, which resulted from the rifting of Proto-Japanese island arcs, is widely distributed in this area.

The most widespread phase of volcanism occurred in East Eurasia from Miocene to recent (Fig. 1). In Mongolia and Northeast China Miocene to recent tholeiitic and alkaline basalts were erupted in proximity to major fault systems (Whitford-Stark, 1987; Zhou, et al., 1988). Volcanism commenced in the Indochina in mid to late Miocene time with the eruption of tholeiitic followed by alkaline basalts.

2.4. Quaternary rifting

The rifting during Quaternary time is indicated by the high level of seismicity and high heat flow (average ~ 1.6 HFU). The rapid faulting and subsidence on the present site of the Bohaiwan sea during the Pleistocene gave rise to the development of an inland sea and to the marine transgressions preserved as numerous marine horizons in the Quaternary sediments of the North China. Fault plane solutions and
other seismic data suggest that the faulting is primarily right strike-slip with a large amount of subsidence in pull-apart regions between steps of the NNE-trending strike-slip faults in nature (Chen and Nabeluk, 1988; Ye et al., 1987). Farther east, the Okinawa Trough is the only active rift related to back-arc extension (Park et al., 1998; Kimura, 1985). On the Hainan Island of China, volcanism began in Quaternary time, though displaying an eruption sequence similar to volcanism in the Indochina.

3. Subsidence history and tectonic evolution of basins

Most of the mentioned above rifts located in East China and adjacent areas are associated with major sedimentary basins. New data from wells and seismic profiles during oil and gas exploration in these basins have allowed, in some cases, reinterpretation of existing data leading to better constraints on models for basin structure and evolution. By applying backstripping techniques, subsidence history of the basins has been examined and gives quantitative results for major changes in their extensional history.

The backstripping method removes the effect of sediment loading from the basement subsidence, thus allowing quantification of the tectonic basement subsidence (Steckler and Watts, 1978). The amount of compaction is calculated using empirical porosity/depth relations for the specific lithology of each layer. Local isostatic behavior of lithosphere is assumed during the backstripping procedure. Below, we focus on the subsidence analysis of several selected basins, including the Late Mesozoic Songliao basin, the Cenozoic Bohaiwan basin and the Yinggerhai, Qiondongnan and Pearl River Mouth basins in southeast China. These basins comprise the principal oil and gas prospecting and producing areas in China.

3.1. The Songliao Basin in Northeast China

The Songliao basin, with an area about 260,000 km², was formed during Late Jurassic to Cretaceous time (Fig. 2). In contrast to the basins west of the Daxing‘anling (Ren et al., 1997, 1998), the Songliao basin is characterized by a typical “two-layer” structural pattern. The lower layer consists of late Jurassic–Early Cretaceous fault basins alternating with uplifts. These fault basins were filled by volcanics and alluvial-lacustrine deposits. The upper layer consists of a broad depression, in which lacustrine and delta systems developed during Late Cretaceous time and alluvial fan and fluvial strata were deposited during Eocene and Neogene time. Based on the filling sequence and structures of the basin, the tectonic evolution of the basin can be divided into three phases (Fig. 4). A first rifting phase characterized by intense volcanic eruptions represented by Late Jurassic Xing‘anling Group and regional uplift of the crust in the basin area. The second and the third phase that are characterized by formation of fault-bounded basins and a broad downwarped depression, respectively, and tens of middle to small-scale fault basins that have been revealed during exploration of oil. A breakup unconformity, \( T_3 \), between the Quantou and Dengluoku formations separates the synrift deposits from the postrift sequence (Fig. 4). The synrift sequence consists of the Shahezhi, Yincheng, Denglouku, and Quantou formations. These strata are confined within NNE-trending isolated grabens and half grabens (Fig. 1). The greatest depth of the subbasins reaches 10 km. During the postrift period, basin fills onlapped the basin margin and were deposited in a broad downwarped lacustrine depression. The inversion of the basin took place from during deposition of Sifangtai and Minshui formations, by movement on a number of NNE-trending inversion faults, broad anticlinal arches or domes and inversion of the \( T_{03} \) unconformity. These structures formed the major oil traps in the basins.

The basin subsidence rate from backstripping (Fig. 4) indicates a rapid synrift subsidence period with a relatively slow postrift thermal subsidence phase. The total subsidence rate and tectonic subsidence rates were about 160–240 and 80–100 m/Ma, respectively, during the synrift stage. Subsidence rate decreased abruptly after deposition of the Quantou Formation. This transition is delineated by the breakup unconformity (\( T_3 \)) and also corresponds to a major change in sediment lithology and of the depositional environment to a broad lake basin.

3.2. The Bohaiwan basin in East China

The Bohaiwan basin is underlain by the Precambrian stable Sino-Korean craton and has a roughly
rhombic shape elongated north–northeast and with a maximum width of about 450 km (Fig. 1). The crustal extension in this area commenced during the Late Jurassic and persisted into the early Cretaceous. Compressional or transpressional stress caused the uplift of basin during the Latest Cretaceous (Tian et al., 1992), forming the regional unconformity $T_R$ (Figs. 5 and 6). Rifting within this area resumed during Paleocene and took place along a series of major NNE- or NEE-trending normal fault zones that caused deep and rapid subsidence of the basins. Up to 6 km of continental and lacustrine clastics accumulated in these fault basins. Most of the fault basins display the geometry of half grabens. Sedimentation along the steeper, fault controlled flanks of these basins was generally dominated by deep water lacustrine shales and mudstones, containing turbiditic sands and massflow deposits. On the gentler flanks of these basins, sedimentation was dominated by fluvial and deltaic sand fans and by bioclastic carbonate banks. These basins are separated by elevated blocks that were eroded during the early Tertiary or were locally covered with very thin Paleogene sediments. Rifting process terminated at the end of the early Tertiary and was followed by a regional doming at which time the whole area was subjected to a short period of erosion. Following erosion, an overall widespread thermal subsidence began to develop and resulted in the present saucer-shaped basin in which the Paleocene fault basins and intervening uplift blocks are both covered by Neogene and Quaternary sediments. Its sedimentary fill is dominated by fluvial sandstones and mudstones.

Within the filling sequence of the basin, three prominent unconformities are present and can be traced throughout the basin on seismic profiles (Fig. 5). The $T_R$ boundary marks the bottom of Cenozoic fill sequence and is an obvious regional unconformity caused by regional compression or transpression stress field during latest Cretaceous time (Tian et al., 1992). This boundary is characterized by a marked truncation of the underlying Late Mesozoic basin strata or basin basement. $T_1$ unconformity is at the top of the early Tertiary sequence and is the prominent breakup unconformity separating Paleogene synrift basin fill from Neogene postrift basin fill. Within the synrift sequence, a clear unconformity ($T_{str}$) can be traced on the seismic profiles (Fig. 5). This unconformity is characterized by truncation of the underlying synrift sequence at the margin of the basin, becoming a conformable boundary in center of the basin.

Fig. 7 shows isopach map for basin fill of the Dongying subbasin, a typical fault basin in the Bohaiwan basin, in which there were two isolated depocentres, respectively, along the nearly W–E-striking Chengnan fault and the NWW-striking Shichun fault during deposition of Kongdian Fm. and the fourth member of Shahejie Fm. (Fig. 7A,B), indicating the basin fill of Kongdian Fm. and the fourth member of Shahejie Fm. (during the first rifting episode shown as Fig. 6) was controlled by nearly W–E or NWW-trending syndepositional normal faults.

Isopach maps for the third member of Shahejie Fm.–Dongying Fm. strata (during the second rifting episode shown as Fig. 6b) also show the two depocentres. One, major depocentre distributes along the Binnan fault, the Lijing fault and the Shengbei fault, and another minor depocentre along the Gaoqing fault. The long axis of both depocentres all extends in NE–SW direction.

Therefore, the synrifting phase of the basin can be divided into two rifting episodes. The first episode occurred from Paleocene to Middle Eocene time, forming a series of NEE- or near E–W-trending basins. The second episode occurred from Late Eocene to Oligocene time, when a number of NE- or NNE-trending basins formed.

Based on the earthquake, quaternary sediments and variable values of heat flow, Chen and Nabelek (1988) explained the Bohaiwan basin as a pull-apart basin, and extrapolated this process back to the Tertiary from the overall shape of the basin (a “lazy Z”). However, pull-apart model cannot explain the following geological facts: (1) The Tancheng–Lujiang strike–slip fault passes through the eastern boundary of the Bohaiwan basin and continues southwards to the eastern side of the Qingling–Dabie orogenic belt (Fig. 1). (2) The western boundary of the Bohaiwan basin is actually a series of normal faults dipping eastward (Fig. 1). (3) As stated above, starting from the Late Eocene, the controlling boundary normal fault trending of the Bohaiwan basin was changed greatly from nearly EW direction to NE or NNE direction. We consider the Bohaiwan basin is a superimposed basin constituted by four prototype basins separated by unconformities $T_R$, $T_{str}$ and $T_1$ stated above, and its evolution can be not explained by a simple pull-apart basin model.
Subsidence rate of the basin during the synrift period was high (Figs. 6 and 8). The maximum tectonic rate and total rate of subsidence was about 140 and 400 m/Ma, respectively. Both rates, however, decreased abruptly to less than 20 and 40 m/Ma, respectively, during postrift period, which corresponds to a major change from lacustrine to alluvial and flood plain sedimentary environments.

It is worth noting that both the rapid subsidence of the synrift period and the slow subsidence of the postrift period feature episodic evolution (Fig. 6). The subsidence rates are relatively low during deposition of the Kundian formation, and rift initiation and sedimentation kept pace with subsidence. The climax of rifting took place during deposition of the Fourth Member of the Shahejie Formation to the third Member of the Shahejie formation, when the subsidence rate increased markedly and sedimentation did not keep pace with subsidence. The subsidence rate during deposition of the Second Member of the Shahejie formation to the Dongyin formation, decreased again. From rift initiation to rift climax and to rift contraction, the depositional environment changed from an early
fluvial, to shallow lake to a deep lake, and again to fluvial and shallow lake (Fig. 6). Another principal feature of subsidence curve is acceleration subsidence since deposition of the Minhuazheng Formation (about 5 Ma), which corresponds to the present rifting stage in East China.

Fig. 9. Filling and tectonic evolution of basins on northern South China Sea. BUF: breakup unconformity.
3.3. Basins on the northern margin of South China Sea

These basins, with great potential of large oil/gas reserves, include the Qiongdongnan, Yinggerhai, Pearl River Mouth and Beibuwan basins (Fig. 1) in which the Qiongdongnan and the Pearl River Mouth basins are characterized as divergent margin basins and were formed by extension. The NNW-trending Yinggerhai basin is situated along the Red River fault belt and has been recently suggested to be of transtensional origin (Li et al., 1995, 1999). In resemblance to other Atlantic-type passive margin basins, these basins show a typical double-layer configuration, that is, grabens, half grabens and horsts in their lower parts overlain by broad basin subsidence in their upper parts resulting from thermal cooling of lithosphere in a postrift phase. Detailed seismic interpretation and fossil zones near breakup unconformity have shown that the cessation of rifting and the commencement of the thermal subsidence did not occur synchronously along the margin. The rifting phase of the Pearl River Mouth basin ended early and the breakup unconformity, T7, is located within Oligocene strata (Fig. 9), whereas the transitional boundary (T6) from synrift phase to postrift phase in the Qiongdongnan and Yinggerhai basins is located between Oligocene and Miocene strata (Figs. 9 and 10). A conspicuous effort has been devoted to understanding the evolutionary history of these basins (Ru and Pigott, 1986; Zhou et al., 1995; Lin et al., 1997; Gong et al., 1997). In contrast to many other passive margins, episodic rifting characterizes the northern margin of South China Sea. Based on seismic and drilling data and research on the structures, filling sequences and subsidence history of these basins, three rifting episodes have been identified (Fig. 9).

The first rift episode commenced in nearly end of Cretaceous and ended in early Eocene time, forming a
small group of fault basins, filled with continental red beds and Paleocene–Lower Eocene alluvial coarse-grained clastics. These fault basins are similar to the small fault basins distributed widely on Southeastern China (Fig. 1) and trend NNE–NE.

The second rift episode occurred in Middle Eocene (about 50 Ma) to Early Oligocene time (about 29 Ma). This rift episode can be subdivided into two secondary episodes. The first, during the Middle and Late Eocene was a period of rapid subsidence, resulting in a new generation of NE–NEE-trending fault basins filled with a mainly lacustrine strata, dominated by dark shales with sandstone interbeds. These strata are the principal source for hydrocarbon in the area. The second, during the Late Eocene to Early Oligocene was a relative stable period of subsidence. Pre-existing fault basins continued to subside and were filled by continental, coarse-grained clastics with coal beds. Basin backstripping indicates that the tectonic subsidence rate during the second rifting episode changed from 250 to 40 m/Ma in the Yinggerhai basin, from 180 to 50 m/Ma in the Qiongdongnan basin and from 170 to 50 m/Ma in the Pearl River Mouth basin (Fig. 10).

The third rift episode occurred in Late Oligocene time, in which the Yinggerhai and Qiongdongnan basins continued to subside with associated faulting, but the Pearl River Mouth basin entered a postrifting thermal subsidence phase. The fault basins of this period were filled with shallow marine or bay deposits. Fan delta and fluvial delta deposits developed along fault margin of the basins.

In the postrift phase, discrete fault basins were involved in a widespread thermal subsidence, forming united broad depressions. Oligocene and Miocene strata in the Pearl River Mouth basin and Miocene strata in the Qiondongnan basin and Yinggerhai basin onlap over margins of early fault basins, displaying a typical bull-head structure. Sea-level rise during this phase caused regional transgression and the marine deposits covered the basin area. The Beibuwan basin is mainly filled by inland sea deposits. The Pearl River Mouth, Qiondongnan and Yinggerhai basins are covered with continental margin facies, which graded seawards from shoreline/delta to shelf and slope deposits.

As shown by Fig. 10, the subsidence rate of postrift phase was still very high and was characterized by episodic evolution, which is clearly distinguished from those of typical passive margin. Two rapid episodes of subsidence can be identified during the postrift period from Fig. 10. the first rapid subsidence took place during Early and Middle Miocene for the Yinggerhai and Qiondongnan basins, and during Late Oligocene for the Pearl River Mouth basin. Many SEE-trending growth faults formed during this tectonic event. The second rapid subsidence started in Pliocene and persists to the present, which is coeval with basalt eruption over the shelf area of the northern margin of South China Sea and large-scale geofluid activation in this area (Li et al., 1999).

4. Discussion

The rifting mechanism is a complex process that must be studied within its regional and plate tectonic framework. In the next section, based on our research, together with other published works, we discuss the plate tectonic framework of rifting and the deep processes within the lithosphere to attempt to explain the triggering factors, mechanisms and evolution of Late Mesozoic and Cenozoic rifting.

4.1. Tectonic framework of rifting through Late Mesozoic to Present

4.1.1. Three types of rifting

Continental rifting and the opening of marginal sea basins appear to have developed in various kinds of tectonic settings. The basement of the basin, pre-existing intracontinental strike–slip faults and the basin location in the plate tectonic framework affect strongly the style of rifting and opening. The following rifting styles can be distinguished in this area.

4.1.1.1. Intracontinental rifting within an orogenic belt. This setting is characterized by pervasive extension or so-called wide rifting (Buck, 1991). Two typical examples are the Late Mesozoic Northeastern Asian fault basin system and the fault basin group within South China fold belt (Fig. 1). Distribution of the former is largely within the Paleozoic Mongol–Okhotsk orogenic belt located between the Sino–Korean craton and the Siberia craton. A number of pre-existing NE-trending fractures and sutures developed within this orogenic belt, which apparently controlled formation of small to middle sized fault basins.
4.1.1.2. Intracontinental rifting within craton. This setting is generally controlled by large pre-existing dextral strike–slip faults in craton. The Bohaiwan basin, Yilan–Yitong graben, Yinggerhai basin, Shanxi graben and Baikal graben may be taken as typical examples. The Bohaiwan basin and Yilan–Yitong graben are located on the west side of Tancheng–Lujiang strike–slip fault and the western branch of Tancheng–Lujiang fault in Northeast China, respectively (Fig. 1). Initiation of these basins was induced by right lateral slip along the Tancheng–Lujiang fault (see next section for explanation). The Yinggerhai basin is situated on the Red River fault. Generation of this basin is related to a pull-apart at a releasing bend of the strike–slip fault.

4.1.1.3. Continental marginal rifting. This setting is related to collision–extrusion, pull-apart along transcurrent fault or to frontal subduction. As described above, three basin evolutionary episodes occurred in basins on the northern margin of South China Sea. The first episode was within a back-arc extensional domain, from Late Cretaceous to Paleocene, and was caused by the steepening dip of a subducted oceanic slab (Ru and Pigott, 1986; Pigott and Ru, 1994). The second and the third basin episodes were initiated by the collision of the Indian and the Eurasian plates. The continued northward penetration of India led to the tectonic escape and subsequent clockwise rotation of the Indochina Block, creating regional transtension and strike slip motion along the Red River Fault (Tapponnier et al., 1986; Pigott and Ru, 1994). The South China Sea and the Japan Sea are the largest marginal sea basins in the western Pacific and are characterized by asymmetric back-arc spreading (Tamaki, 1995; Jolivet et al., 1989, 1994). The Okinawa trough is an active rift basin where stretching is the result of purely subduction processes related to the Philippine sea plate passing under the Eurasian plate (Kimura, 1985).

4.1.2. History of Pacific and Tethys convergence and its relation to the rifting

The Late Mesozoic and Cenozoic rift systems in this area lie between two of the most dynamic tectonic domains of the earth’s lithosphere, the subduction zones of the western Pacific and Tethys-Himalayan tectonic belt. The direction and rate of subduction from the Pacific side and subduction/collision along the Tethys domain have changed several times since Mesozoic, which caused the variation of stress field in eastern Eurasia in space and time. Here, we ascribe the cause of rifting in eastern Eurasia to the interactions between plates in terms of the analysis on the convergence rate and convergence direction of India–Eurasia and Pacific–Eurasia.

Fig. 2D shows the changes of convergence rates of Pacific–Eurasia and India–Eurasia since Late Cretaceous. It can be seen from this figure that Late Cretaceous convergence rate of the Pacific–Eurasia plates was 120–140 mm/year (Engebretson et al., 1985; Northrup et al., 1995), when the stress field of eastern China was characterized by sinistral transtension (Tian and Du, 1987), which caused inversion of Late Mesozoic basins, for example, the Songliao basin, and the uplift and erosion of most of the east China (forming the TR unconformity in Fig. 5). The convergence rate declined substantially during early Tertiary and reached a minimum in Eocene of 30–40 mm/year. In contrast, the late Cretaceous convergence rate of the India–Eurasia plates was about 100–110 mm/year and increased during early Tertiary and reached a maximum in Paleocene of 170–180 mm/year at 65 Ma (Lee and Lawver, 1995), then decreased, but remained higher than that of the Pacific–Eurasia plates during same period until about 40 Ma, which corresponds to early Tertiary rapid synrifting period of Eastern China (Fig. 2B). The rapid India–Eurasia convergence would cause two tectonic consequences within eastern Eurasia. The first is extrusion eastward and southeastward of microcontinental blocks and the second is the dextral transtension along pre-existing NE–NNE-trending strike–slip faults. Thus, we postulate that rapid northward movement of the India plate relative to Eurasia may have resulted in the dextral transtension stress field, triggering the Cenozoic rifting of east Eurasia. From Miocene to the Present, the Pacific–Eurasia convergence rate increased to an average of 100–110 mm/year. At the same time, the India–Eurasia convergence rate decreased to 50 mm/year and the basins in east Eurasia entered the thermal subsidence stage (Fig. 2A).

It is more difficult to explain the cause of the Late Mesozoic rifting. Indian–Eurasian collision, which began about Late Eocene and has continued to the Present, is a typical example of continental collision. This example shows deformation does not cease at the time
of contact between continental blocks, but continues for a long time following initial contact. Collision of the Indochina Block–Eurasian Continent is an important tectonic event during Triassic times. The Indochina Block is now located south of the South China, but it located more to the northwest before the opening of the South China Sea (Tapponnier et al., 1982; Kimura et al., 1990). It maybe possible that the Late Mesozoic rifting resulted from continued intracontinental deformation after the Late Triassic contact between the Indochina Block and Eurasian continent, which induced the NW–SEward extension dominating Late Mesozoic rifting in northeastern Asia (Fig. 11A).

Based on the discussion above and published works on reconstruction of plate tectonics, a plate tectonic framework and kinematic evolution of rifting in Eastern Eurasian continent since Late Mesozoic are shown in Fig. 11.

Fig. 11A shows the Late Mesozoic tectonic setting. Rifting was concentrated in the Mongol–Okhotsk fold belt, forming a series of small to middle sized fault basins that were widely distributed in NE Asian area. In the Bohaiwan area of east China, some small NEE-trending fault basins related to dextral shear motion along the Tancheng–Lujiang fault formed.

During the Cenozoic, rapid northward movement of the Indian plate relative to Pacific plate triggered the Cenozoic rifting in the east Eurasian continent. From Paleocene to Middle Eocene time (Fig. 11B), the Pacific plate moved NW and the Indian plate moved NNE. Lithospheric deformation in the Sino–Korean craton probably occurred first along the Tancheng–Lujiang fault domain, the weakest domain in the craton. The movement direction of the Indian plate was roughly parallel to the strike of middle and southern segment of the Tancheng–Lujiang fault, and oblique to its northern segment. Therefore, the western block of the Tancheng–Lujinag fault moved northward, causing a pull apart between two blocks of the fault at the releasing bends in the Northeast China and forming transtensional basins, such as the Yilan–Yitong Graben and the Fushun–Meihoukou basin. In the North China block, the dextral shear motion along the Tancheng–Lujiang fault led to formation of early near E–W-trending basins of the first basin episode of the Bohaiwan basin, and these small basins lie in the tension domain at the west side of the Tancheng–Lujiang dextral strike–slip fault. Another basin area formed during this period was along the South China margin, where a series of NE-trending fault basins formed from Late Cretaceous to Paleocene time and were caused by back-arc rifting.

Starting in the Late Eocene time (Fig. 11C), a global reorganization of plate was triggered by the termination of oceanic subduction beneath the India–Eurasia collision zone (Patriat and Archache, 1984). The Australia and India started to become a single plate and move together northwards. The Pacific and Philippine plates are interpreted to have comprised a single continuous plate prior to 43.5 Ma moving in a NNW direction (Hilde et al., 1977). Following the major plate reorganization, changed to NWW and major transform fault is thought to have developed into a subduction zone dividing the plate into the westerly Philippine plate and the easterly Pacific plate. This plate reorganization is evident in the Pacific plate by the change in orientation of the Emperor–Seamount chain, as described by Patriot and Archache (1984).

The effect of this event on the eastern Asian continent was profound. The extensional regimes in the eastern Eurasian continent resulting from the collision of India–Eurasia are proposed as the driving force for basin formation, initiating a most extensive rifting episode in this region during Cenozoic time. In North China, the transtension along the northern segment of the Tancheng–Lujiang Fault was changed into extension in NW–SE direction (Ren et al., 1999). The NNE-trending basins of the second basin episode of the Bohaiwan basin were formed. In South China, the extrusion and clockwise rotation of Indochina Block related to the collision of India–Eurasia caused the formation of a series of NE-trending basins on the northern margin of South China Sea. From the researches on basin structures, migration of basin depocentres (Fig. 12), it can be seen that the dextral regime, not sinistral regime as described by Tapponnier et al. (1982, 1986) and Peltzer and Tapponnier (1988) controlled the formation and development of basins related to strike–slip faults in Southeast Asia.

The density seismic lines show that the fault at the western margin of the Yinggerhai basin orientated in the SN direction, one of the subsidiary faults of the NW Red River fault that changed in the direction from the major fault after entering the bay (Fig. 12). The depocenters during Oligocene and Miocene was in the SN direction and migrated eastwards. This shows that the
Fig. 11. Plate tectonic framework and evolution of rifting in east Eurasia. The length of arrow indicates relative convergence rate between plates. Small arrow pairs indicate local extensional direction. Section x–x′ is shown in Fig. 13. SC: Siberia Craton; MOFB: Mongol–Okhotsk Fold Belt; SKC: Sino–Korean Craton; YC: Yangtze Craton; T.L. fault: Tancheng–Lujia fault; B. basin: Bohaiwan basin.
rapid subsidence zones controlled by SN basement faults in the northwestern part of the basin shifted eastward. Thus, the extension of the basin in the Oligocene and Miocene was accompanied by the dextral strike-slip movement of the major NW basement faults. A similar case has been reported for the Sumatra basin, Sunda basin in Southeast Asia (Packham, 1993).

From Late Oligocene to Neogene (Fig. 11D), the Pacific–Eurasia convergence rate increased (Northrup et al., 1995), stopping extension above in eastern Asia and many rift systems in East China gradually evolved into thermal subsidence stage. The rifting in this stage was localized in large strike-slip faults. The spreading of oceanic crust occurred in Japan Sea and South China Sea. From Fig. 12, the extension of the Yinggehai basin in this stage was still accompanied by the dextral strike-slip movement of the major NW basement faults. In Gulf of Thailand and Malay area, a dextral along Three Pagodas Fault systems and Malay Fault system is required to form the N–S trending a series of small basins (Polanchan et al., 1991).

As suggested by previous workers (Tapponnier et al., 1982, 1986; Kimura and Tamaki, 1986), the
Baikal rift and its associated sinistral shear zone and the Shaanxi–Shanxi Graben, Hetao–Yinchuan graben in North China may be interpreted as by-products of the India–Eurasia collision in Eocene. With the aid of layered lithosphere model, Davy and Cobbold (1988) and Jolivet et al. (1990) further recognized the importance of numerous large N–S-trending dextral strike–slip fault system like Sakhalin–Hokkaido shear zone that were not accounted for in the earlier plasticine models (Tapponnier et al., 1982, 1986), they showed how the dextral system, which acted as conjugate shear sets with sinistral system in a regional system, controlled the formation and evolution of Japan Sea.

Thus, the sedimentary basins during late Oligocene and Miocene are the result of two regional conjugate shear systems resulted from collision of India–Eurasia. Far from the indenter, the most obvious deformation features related to collision are localized strike–slip shear zones and the basins generally lie in releasing bend or other local extending location along these strike–slip faults. Further away from it, marginal basins have opened during the collision process. The intracontinental strike–slip faults and back-arc spreading cooperate to shape the basins in the eastern Asian continent during late Oligocene and Miocene.

The opening in marginal sea basins stopped sometime in the Late Neogene, and a new compressional stress system was established and ultimately led to the formation of subduction along the eastern side of the basins (Fig. 11D). The subduction in the Ryukyu trench facilitates the back-arc extension in the Okinawa basin.

4.2. Rifting and dynamics of asthenosphere

4.2.1. Deep structure of eastern Eurasia

The thermal anomaly in the lower lithosphere in Eastern China and adjacent areas related to rifting is commonly shown by the following evidences:

1. All areas within Eastern China and adjacent areas where lithospheric thickness is reduced coincide with areas of the Late Mesozoic and Cenozoic rifting. Geophysical data now show that the shallowest point of asthenosphere in the Sonliao basin is at about 60 km in depth, and a thin lithosphere (60–120 km) is present below the Bohaiwan gulf of the Sino–Korean craton (Ma and Wu, 1987; Lu and Xia, 1993; Tian et al., 1987; Gong et al., 1997). The top of asthenosphere trends generally to NNE, but deepens towards the flanks of the area. Analysis from the Paleozoic Kimberlites indicates east Sino–Korean craton was underlain by ca. 200 km of lithospheric before Late Mesozoic rifting (Griffin et al., 1998), implying that lithosphere of 80–140 km under the Bohaiwan basin has been removed during rifting period.

2. The elevated geotherm is shown in the rifted areas. In Bohaiwan Basin, the paleogeotherm at the Moho in Paleozoic time was ca. 400 °C determined by the garnet geotherm from xenolith in basalt (Griffin et al., 1998), and it has been elevated to 700–800 °C determined from present heat flow data (Liu, 1987). In the Songliao basin, the ordinary geothermal gradient is 3.11–4.8 °C/100 m with a maximum of 6.2 °C/100 m. The average heat flow of this basin is 2.24 HFU (Tian et al., 1992). In the Bohaiwan basin, the average heat flow is more than 1.6 HFU and the Bohai gulf and the coast areas have the highest heat flow values ranging from 1.77 to 2.53 HFU (Liu, 1987). The average geothermal gradient in the northern South China Sea is 3.21 °C/100 m. From the Pearl River Mouth basin westward to the Yinggerhai basin, the geothermal gradient increases gradually. The average heat flow of the Pearl River Mouth basin is 71.9 mW/m² with a range of 47–100.9 mW/m². The Zengmu basin in southern South China Sea has a prominent high thermal anomaly with an average heat flow of 97.6 mW/m². Eastward, the heat flow decreases sharply to 65.3 mW/m² (Gong et al., 1997).

3. Rifting is often associated with lithospheric uplift and intense volcanism. There is a coincidence between the location and extent of many rift systems such as the Late Mesozoic fault basin system in northeastern Asia, the Bohaiwan basin and strongly active areas of volcanic eruption (Fig. 1), which indicates deep lithospheric processes or upwelling of asthenosphere closely related to development of basins.

4. The anomalously hot asthenosphere beneath rifted areas have been observed from seismic tomography. The South China Sea, the East China Sea, the Bohaiwan basin, and the Japan Sea all show low-velocity upper mantle anomalies in the upper 350, 300 and 150 km, respectively (reference to the plate 1 of Fukao et al., 1992). These low velocity anomalies are generally accepted to be related to hot, partial melted and active regions. Beneath these depths, fast velocity
anomalies, which are considered to correspond to subducted slabs (Fukao et al., 1992) are imaged.

Several models have been proposed to explain the generation of asthenosphere upwelling in east Eurasia. For example, the hotspot and plume model (Castillo, 1988; Duncan and Richards, 1991), the hotcell model or hot region model (Miyashiro, 1986) proposed that hot spots or deep mantle plumes control the rifting and volcanism. The mantle extrusion model (Flower et al., 1998) invoked collision-related extrusion mantle lobes as a possible cause of trench rollback. Below, we speculate more complicated situations for the deep thermal anomaly related to intraplate rifting.

4.2.2. Dynamics of asthenosphere in east Eurasia

East Eurasia is a composite continent formed by the amalgamation of several continental and micro-continental blocks (Faure and Natlin, 1992). Several fold belts that separate these continental blocks are considered to be of Paleozoic and early Mesozoic ages (Maruyama et al., 1989). Big continental blocks include the Siberia craton, Sino–Korean craton and Yangtze craton (Fig. 1). The lithosphere of Asia in Fig. 10 has been simplified into four crustal blocks, the Siberian craton, Sino–Korean craton and Yangtze craton (Fig. 1). The lithosphere of Asia in Fig. 10 has been simplified into four crustal blocks, the Siberian craton, Mongol–Okhotsk fold belt, Sino–Korean craton and South China Block. From craton to fold belts lithospheric thickness changes, forming steps in the lithospheric structure. The large-scale faults in craton, boundaries between craton and fold belt, paleo-sutures and faults in a fold belt are structural lines of weakness in lithosphere, and localize strain during intraplate deformation. Based on simulating calculation, King and Anderson (1995) showed that step topographic features and transtension and extension of lithosphere along lines of weakness will induce secondary convection cells, which may lead to thermal anomalies in the deep lithosphere. The rifting in eastern Eurasia was strongly controlled by the structural lines of a weakness in an orogenic belt or craton. A considerable proportion of the volcanism related to rifting lies along the large faults or the boundary between craton and fold belt, for example, the northern boundary of the Sino–Korean craton (Smith, 1998), where a significant change in lithospheric thickness is expected. Therefore, we postulate that large-scale interactions between the Pacific, Eurasian and Indian plates, the topographic structure of lithosphere in eastern Eurasia and the motion along large-scale faults were important controls on formation of the deep thermal anomaly beneath rifted areas. Fig. 13 shows the development of thermal anomaly during rifting periods.

During the Late Mesozoic time (Figs. 11a and 13a), based on the research on the kimberlites, Griffin et al. (1998) showed that the Sino–Korean craton was underlain by a ca. 200-km-thick lithosphere. Thus, the structure of northeastern Asian region suggested two obvious steps in lithospheric thickness from ca. 150 to 200 km under the Siberian craton and the Sino–Korean craton to less than 100 km under the Mongol–Okhotsk fold belt (Smith, 1998). Mantle flow around these topographic features would set up secondary convection cells based on the model of King and Anderson, (1995). Therefore, the long-lived asthenospheric upwelling inferred under this fold belt by Zonenshain and Savostin (1981) becomes a consequence of this variation in lithospheric thickness. Asthenospheric upwelling would heat and weaken the lithosphere, which would facilitate the Late Mesozoic rifting. Extension and transtension along paleo-fractures in the Mongal–Okhotsk fold belt triggered the deep processes of the lithosphere and decompression melting of lithosphere, forming intense volcanism represented by the Daxing’anling volcanic belt (Lu et al., 1997). The upwelling of asthenosphere further drove the Late Mesozoic rifting. We suggest that the most likely location of the thermal anomaly center lies beneath the Songliao basin. Supporting evidence comes from the very thick thermal subsidence sequence in this basin and its greater calculated stretching factor. From subsidence history, Lin et al. (1997) concluded the stretching factor reaches 1.6 in this area, implying greater uplift of asthenosphere during rifting. Whereas the stretching factor in rifted area, west of the Daxing’anling is only 1.1–1.3 calculated from balance section estimations (Ren et al., 1998).

During Paleocene to middle Eocene time (Figs. 11b and 13b), transtension along the Tancheng–Lujiang fault induced secondary convection in asthenosphere. When lithosphere thinned, decompression of the upwelling asthenospheric mantle produced melt which rapidly moved upward into the overlying crust, causing volcanism. Upwelling of asthenosphere would serve to erode an already thinned continental mantle during Mesozoic rifting and Archean lithosphere would be replaced by denser but hotter material. The
Fig. 13. Deep lithospheric setting for the Late Mesozoic and Cenozoic rifting. (A) J3–K1. (B) Paleocene–Middle Eocene. (C) Late Eocene–Oligocene. (D) Miocene–Pliocene. (E) Pleistocene–Present. SC: Siberia Craton; MOFB: Mongol–Okhotsk Fold Belt; SKC: Sino–Korean Craton; YC: Yangtze Craton; T.L. fault: Tancheng–Lujia fault; CL: crustal lithosphere; ML: mantle lithosphere; A: asthenosphere. The section position is shown in Fig. 11. Lithospheric framework is after Smith (1998).
thermal effects on density would initially outweigh the greater intrinsic density of the new lithosphere and lead to uplift. The uplift of lithosphere produced tensional stress on surface, which may have well assisted the lithospheric rifting in the Bohaiwan basin, forming NNE-trending basins (Figs. 11c and 13c). Stretching continued until Oligocene. During Miocene–Pliocene (Figs. 11d and 13d), eastward asthenospheric flow may have made the subducting slab steepen and rollback, cause injection of asthenosphere and spreading in the marginal sea (Tatsumi et al., 1990). In the Bohaiwan area, the cooling of denser upwelling asthenosphere would lead to subsidence of the surface below the original isostatic level and induce the development of a broad basin. Following the collision of India into Asia, pull-aparts along fractures, such as Lake Baikal, and lithosphere–asthenosphere boundary topography may have induced the secondary convection under Mongol–Okhotsk fold belt and the boundary area between craton and fold belt. Volcanism occurred mainly along the craton boundary (Smith, 1998). By Pleistocene–Present time (Figs. 11d and 13d), volcanism occurred throughout the Mongol–Okhotsk fold belt underlain by an extensive thermal anomaly of lithosphere. Present topography of lithosphere under Asia reached its present state.

Thus, a combination of the deep process of lithosphere and large-scale interaction between plates would suggest the most comprehensive explanation for the rifting in eastern Eurasia. The fast movement northward of the Indian plate relative to Pacific plate would have caused the NW–SE-trending extensional stress field and intense intraplate deformation. It would also have led to mantle flow eastward or southeastward. The mantle flow around basal lithospheric topography and the motion along large-scale faults would induce the asthenospheric upwelling, which caused the thermal anomaly under the rifted areas and also further assisted and enhanced the rifting process in this area.

5. Conclusions

We have compiled a new tectonic map of rifting in Eastern China and adjacent areas since the Late Mesozoic (Fig. 1), summarized the evolutionary history of rifting in eastern Eurasia (Fig. 2) from Late Mesozoic to Present, and discussed the dynamic setting of the deep lithosphere and the plate tectonic regimes, mainly based on data from exploration of oil, gas and coal in this area and published works. The main conclusions are as follows:

1) Extension has occurred widely and repeatedly in the eastern China and its adjacent areas continent since the Late Mesozoic to Present, resulting in development of a large number of continental rift systems and marginal sea basins. Four rifting stages, Late Mesozoic, early Tertiary, Neogene and Present, have been recognized based on the research on basin fill, structures and subsidence history of sedimentary basins, marginal sea basins and rifting-related volcanism.

2) Continental rifting and marginal sea opening developed several different tectonic settings. Three rifting styles, intracontinental rifting within fold belt, intracontinental rifting within craton and continental marginal rifting and spreading, are distinguished. Intracontinental rifting within fold belts is characterized by pervasive extensional or transtensional deformation. A great number of middle to small fault basins are distributed along pre-existing faults and palaeo-sutures in orogenic belts. Owing to the stability of cratons, intracontinental rifting within cratons occurred mainly along large-scale strike–slip faults. The tectonic setting of continental margin rifting and spreading is very complex.

3) The cause of the rifting in the eastern Eurasia is the large-scale interaction between the Pacific, Eurasian, and the Indian plates. The rapid convergence of India–Eurasia relative Pacific–Eurasia led to the NW–SE-trending extensional stress field dominating rifting in this area. Consequent intraplate deformation reactivated the pre-existing faults and palaeo-sutures. The rotation and extrusion of microcontinental blocks along E–W- or SE-trending palaeo-fractures and dextral transtension along NE- or NNE-trending large-scale strike–slip faults controlled the various styles of rifting in eastern Eurasia.

4) Due to the surrounding of slabs along the eastern and southeastern margins of east Eurasia, convergence of India–Eurasia would generate mantle flow to the east and southeast. Mantle flow around topographic features at the lithosphere–asthenosphere boundary would set up secondary convection, which may also be caused by transtension along large faults. Considering the deep lithospheric structure before the Late Mesozoic rifting (Fig. 13A), long-lived asthen-
spheric upwelling induced by topographic features would heat and weaken the lithosphere under the Mogol–Okhotsk fold belt. It may be one of the principal reasons that the Late Mesozoic rifting was concentrated in this fold belt. Transtension or extension along pre-existing faults would further elevate the asthenosphere upwelling or trigger asthenospheric upwelling, which may have led to the volcanism related to rifting and further enhanced the rifting process. Thus, a combination of the deep lithospheric processes of and large-scale interaction between plates would offer the most comprehensive explanation for the rifting in eastern Eurasia.

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