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# Subduction history of the Paleo-Pacific slab beneath Eurasian continent: Mesozoic-Paleogene magmatic records in Northeast Asia

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**Abstract** This paper presents a review on the rock associations, geochemistry, and spatial distribution of Mesozoic-Paleogene igneous rocks in Northeast Asia. The record of magmatism is used to evaluate the spatial-temporal extent and influence of multiple tectonic regimes during the Mesozoic, as well as the onset and history of Paleo-Pacific slab subduction beneath Eurasian continent. Mesozoic-Paleogene magmatism at the continental margin of Northeast Asia can be subdivided into nine stages that took place in the Early-Middle Triassic, Late Triassic, Early Jurassic, Middle Jurassic, Late Jurassic, early Early Cretaceous, late Early Cretaceous, Late Cretaceous, and Paleogene, respectively. The Triassic magmatism is mainly composed of adakitic rocks, bimodal rocks, alkaline igneous rocks, and A-type granites and rhyolites that formed in syn-collisional to post-collisional extensional settings related to the final closure of the Paleo-Asian Ocean. However, Triassic calc-alkaline igneous rocks in the Erguna-Xing'an massifs were associated with the southward subduction of the Mongol-Okhotsk oceanic slab. A passive continental margin setting existed in Northeast Asia during the Triassic. Early Jurassic calc-alkaline igneous rocks have a geochemical affinity to arc-like magmatism, whereas coeval intracontinental magmatism is composed of bimodal igneous rocks and A-type granites. Spatial variations in the potassium contents of Early Jurassic igneous rocks from the continental margin to intracontinental region, together with the presence of an Early Jurassic accretionary complex, reveal that the onset of the Paleo-Pacific slab subduction beneath Eurasian continent occurred in the Early Jurassic. Middle Jurassic to early Early Cretaceous magmatism did not take place at the continental margin of Northeast Asia. This observation, combined with the occurrence of low-altitude biological assemblages and the age population of detrital zircons in an Early Cretaceous accretionary complex, indicates that a strike-slip tectonic regime existed between the continental margin and Paleo-Pacific slab during the Middle Jurassic to early Early Cretaceous. The widespread occurrence of late Early Cretaceous calc-alkaline igneous rocks, I-type granites, and adakitic rocks suggests low-angle subduction of the Paleo-Pacific slab beneath Eurasian continent at this time. The eastward narrowing of the distribution of igneous rocks from the Late Cretaceous to Paleogene, and the change from an intracontinental to continental margin setting, suggest the eastward movement of Eurasian continent and rollback of the Paleo-Pacific slab at this time.

**Keywords** Continental margin of Northeast Asia, Mesozoic-Paleogene, Igneous rocks, Paleo-Pacific slab, Subduction

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## 1. Introduction

The continental margin of Northeast Asia includes the Xing-Meng Orogenic Belt (XMOB), the eastern North China Craton (NCC), the Sikhote-Alin Orogenic Belt (SAOB), the islands of Japan, and the Korean Peninsula, all of which have experienced a complex tectonic history (Li et al., 1999b; Wu et al., 2011). Three tectonic regimes (the Paleo-Asian, Paleo-

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Pacific, and Mongol-Okhotsk oceans) existed in Northeast Asia during the Paleozoic and Mesozoic. The Mongol-Okhotsk Ocean is usually considered to have been a large bay of the Paleo-Pacific Ocean (Zorin, 1999; Parfenov et al., 2001) and was located between the Siberian Craton and the Sino-Korean Craton-Mongolian Plate during the late Paleozoic to early Mesozoic. This paper discusses the Paleo-Pacific and Mongol-Okhotsk tectonic regimes, respectively, owing to their independent evolutionary histories. In the Paleozoic, the tectonic evolution of the continental margin of Northeast Asia was characterized by the collision and amalgamation of microcontinental massifs and the final closure of the Paleo-Asian Ocean (Sengör and Natalin, 1996; Li, 2006), and crustal growth was characterized by horizontal accretion (Xiao et al., 2003; Li, 2006; Windley et al., 2007). In the Mesozoic, this region was influenced mainly by the circum-Pacific tectonic regime. However, the continental margin of Northeast Asia was also influenced by the Mongol-Okhotsk tectonic regime and closure of the Paleo-Asian Ocean in the early Mesozoic. Although some significant advances in our understanding of the Mesozoic volcanic rocks and accretionary complexes in Northeast Asia have been obtained in recent studies (Wu et al., 2007a; Xu et al., 2013a; Wang F et al., 2015, 2017), the onset and history of Paleo-Pacific slab subduction beneath Eurasian continent remain poorly constrained and are debated (Wu et al., 2011; Xu et al., 2013a; Sun et al., 2015; Wilde, 2015). To determine the Mesozoic subduction history of the circum-Pacific tectonic regime, it is necessary to determine the spatial-temporal extent and influence of different tectonic regimes on the eastern margin of Eurasian continent. Thus, this paper presents a review on the spatial-temporal distributions of Mesozoic-Paleogene igneous rock associations at the continental margin of Northeast Asia. In combination with studies of Mesozoic accretionary complexes and regional sedimentary formations, we have determined the tectonic setting of these Mesozoic igneous rocks and the spatial-temporal influence of different tectonic regimes on the continental margin of Northeast Asia. These observations provide an improved understanding of the Mesozoic-Paleogene subduction history of the Paleo-Pacific slab beneath Eurasian continent.

## 2. Geological setting of the Northeast Asia continental margin

The continental margin of Northeast Asia, which is the focus of this study, comprises northeast China, eastern north China, the Russian Far East, Japan, and South and North Korea, which correspond tectonically to the XMOB, eastern NCC, SAOB, islands of Japan, and Korean Peninsula. These tectonic regions are located on the western Pacific margin and constitute a trench-arc-basin system of the circum-Pacific tectonic regime.

The XMOB is the eastern segment of the Central Asian Orogenic Belt (CAOB), which is considered to be a collage of several microcontinents, including (from northwest to southeast) the Erguna, Xing'an, Songnen-Zhangguangcai Range, Jiamusi, and Khanka massifs (Li et al., 1999b; Wu et al., 2011). In the Paleozoic, the tectonic development of the XMOB was controlled by the evolution of the Paleo-Asian Ocean. Closure of this ocean resulted in micro-continent collision and amalgamation. Although the timing of amalgamation remains controversial, it is generally considered that it took place in the Paleozoic (Xu et al., 2012; Liu et al., 2016). The early Paleozoic granitoids and Toudaoqiao blueschists at the eastern margin of the Erguna Massif suggest that the collision between the Erguna and Xing'an massifs took place in the earliest Paleozoic (Ge et al., 2005; Zhao et al., 2014; Zhou et al., 2015). The collision between the Xing'an and Songnen-Zhangguangcai Range massifs has been variously assigned to the late early Carboniferous (Li et al., 2014), end-late Paleozoic to early Mesozoic (Miao et al., 2004), pre-Permian (Wu et al., 2002), and Cretaceous (Nozaka and Liu, 2002). There are also many different hypotheses regarding the timing of the collision between the Songnen-Zhangguangcai Range and Jiamusi massifs, including the Early Devonian (Meng et al., 2010), middle Silurian (Wang F et al., 2012), Middle Ordovician (Xie et al., 2008), Early-Middle Jurassic (Wu et al., 2007a; Zhou et al., 2010), end-early Paleozoic (Li et al., 1999b), and Precambrian (Cao et al., 1992). The collision between the Jiamusi and Khanka massifs took place either in the early Cambrian (Zhao, 2009), Early Devonian (Sun et al., 2001), or middle Permian (Meng et al., 2008).

The NCC is located to the south of the XMOB. Based on the presence of late Permian molasses (Li, 2006), late Permian to Early Triassic syn-collisional granites along the Solonker-Xra Moron-Changchun suture belt (Cao et al., 2013; Wang Z J et al., 2015), and metamorphism of the Hulan Group in central Jilin Province (~250 Ma; Wu et al., 2007a), it has been proposed that the final closure of the Paleo-Asian Ocean occurred in the late Permian to Middle Triassic (Xiao et al., 2009), resulting in the amalgamation of the NCC and XMOB (Zhang S H et al., 2010; Wu et al., 2011). The Triassic ultrahigh-pressure (UHP) metamorphism in the Dabie-Sulu orogenic belt, which has been subjected to zircon U-Pb (Ames et al., 1996) and mineral Sm-Nd dating (Zheng et al., 2002, 2003), indicates that collision between the NCC and Yangtze Block (YB) took place in the Triassic along the Qinling-Dabie-Sulu orogenic belt (Wu and Zheng, 2013).

The Korean Peninsula can be divided into three massifs, which from north to south are the Rangnim, Gyeonggi, and Yeongnam massifs, separated by the Imjingang and Ogcheon belts, respectively (Zhai, 2016). The massifs all contain Precambrian metamorphosed basement rocks and Paleozoic sedimentary basins. The Rangnim Massif has similar basement and sedimentary cover rocks to the NCC (Zhao et al., 2006; Wu et al., 2007b), whereas the Gyeonggi Massif has similar basement and Ediacaran-Paleogene sedimentary cover rocks to the South China Block (SCB; Kim et al., 2013; Wu and Hou, 2016). Furthermore, the paleomagnetic pole for the lower Mesozoic Daedong Supergroup in the Gyeonggi Block is similar to that of the SCB (Uno and Chang, 2000). However, the sedimentary characteristics, detrital zircon ages of basement rocks, and paleomagnetic data suggest that the Yeongnam Massif has an affinity to the NCC (Uno, 2000; Kim et al., 2013). As such, two main models have been proposed to explain the tectonic evolution of the Korean Peninsula. First, it is a relatively complete Mesozoic orogenic belt from the Imjingang belt to the Ogcheon belt, which is the eastward extension of the Dabie-Sulu orogenic belt on the Korean Peninsula. The Rangnim and Yeongnam massifs correspond to the NCC and SCB, respectively. In this model, the similarity of the Yeongnam Massif with the NCC may be due to it being an exotic tectonic slice detached from the NCC during the late stage of orogeny. Uplift of the south China continental crust beneath the orogenic belt can then account for the Gyeonggi Massif being similar to the SCB (Wu and Hou, 2016). Second, Zhai et al. (2007) proposed a crustal detachment and thrust model, and suggested that the entire Korean Peninsula was a part of the NCC (Zhai, 2016), together termed the Sino-Korean Craton. However, the Hongseong Complex is likely an allochthon related to a Triassic collisional event. The collision belt between the YB and NCC is preserved along the western margin of the Korean Peninsula, but does not extend eastward into the Korean Peninsula (Hao et al., 2007).

The islands of Japan are the products of convergence of oceanic and continental plates, and contain a collage of terranes that amalgamated from equatorial or low-latitude regions since the Mesozoic. The islands have been suggested to be a continental fragment that rifted from the eastern Asian continental margin before the Japan Sea opened in the Miocene (ca. 15 Ma; Lee et al., 1999). Paleomagnetic data reveal a 'double door' opening mode of the Japan Sea (Otofuji et al., 1985, 1991) that involved clockwise rotation of southwest Japan and counterclockwise rotation of northeast Japan. Wu et al. (2017) considered that northeast Japan had separated from the Russian Far East prior to the opening of the Japan Sea, whereas the age spectra of detrital zircons from Jurassic clastic rocks and the Sr-Nd isotopic compositions of late Mesozoic to Cenozoic granitoids in southwest Japan suggest that it has an affinity to the Cathaysian margin of south China (Jahn, 2010). However, the Hida Belt on Noto Peninsula has different tectonic characteristics to southwest Japan. Various models have been proposed to explain the tectonic features of the Hida Belt, including: (1) the Hida Belt was once located in the eastern margin of the NCC (Takahashi et al., 2018), which is the eastward extension of the Sulu orogenic belt (Tsujimori et al., 2006; Ernst et al., 2007), given that inherited zircon cores in the Hida metamorphic rocks have similar ages (1860 and 2650 Ma, with rare Neoproterozoic ages) to those in the NCC; (2) the Hida Belt was part of the eastern margin of the CAOB (Oh, 2006; Zhao et al., 2013); and (3) the Hida Belt corresponds to the Ogcheon Belt on the Korean Peninsula, based on their similar deformation structures (Takahashi et al., 2010).

The SAOB lies to the east of the Bureya-Jiamusi-Khanka massif. Structural nappes, ophiolite mélanges, and chaotic olistostromes are widespread throughout the belt (Khanchuk et al., 1988; Zonenshain et al., 1990a, 1990b). Parfenov (1984) proposed that the SAOB is an accretionary orogen that represents a collage of different terranes closely related to Jurassic-Cretaceous subduction of the Paleo-Pacific slab beneath Eurasian continent. All the Mesozoic terranes are intruded by Late Cretaceous to Eocene granitic rocks or covered by large amounts of contemporaneous volcanic and volcanic-sedimentary rocks. A distinctive feature of the SAOB is that it is cut by a system of sinistral strike-slip faults, most notably the Central Sikhote-Alin Fault. This fault was most active in the Early Cretaceous and became inactive in the Late Cretaceous (Jahn et al., 2015).

## 3. Mesozoic-Paleogene magmatism at the continental margin of Northeast Asia

Compiled dating results for Mesozoic-Paleogene igneous rocks at the continental margin of Northeast Asia are presented in Appendix 1 (available at http://earth.scichina.com), and relative age probability plots are shown in Figure 1. The age peaks of these igneous rocks, along with their rock associations and regional unconformities, indicate that the magmatism can be subdivided into nine stages, Early-Middle Triassic (~245 Ma), Late Triassic (~226 Ma), Early Jurassic (~185 Ma), Middle Jurassic (~168 Ma), Late Jurassic (~151 Ma), early Early Cretaceous (145–135 Ma), late Early Cretaceous (~125 Ma), Late Cretaceous (~80 Ma), and Paleogene (~51 Ma). Our compilation of ages clearly reveals that: (1) Mesozoic magmatism was more widespread than Paleogene magmatism, with the latter only occurring at the eastern continental margin; (2) there was a magmatic hiatus from the Late Jurassic to early Early Cretaceous at the eastern continental margin of Northeast Asia (including the islands of Japan, Lesser Xing'an-Zhangguangcai Range (LXZR), and eastern Heilongjiang-Jilin provinces (EHJP); and (3) Mesozoic-Paleogene igneous rocks in northeast China and the Russian Far East show an eastward younging trend from the intracontinental region to the continental

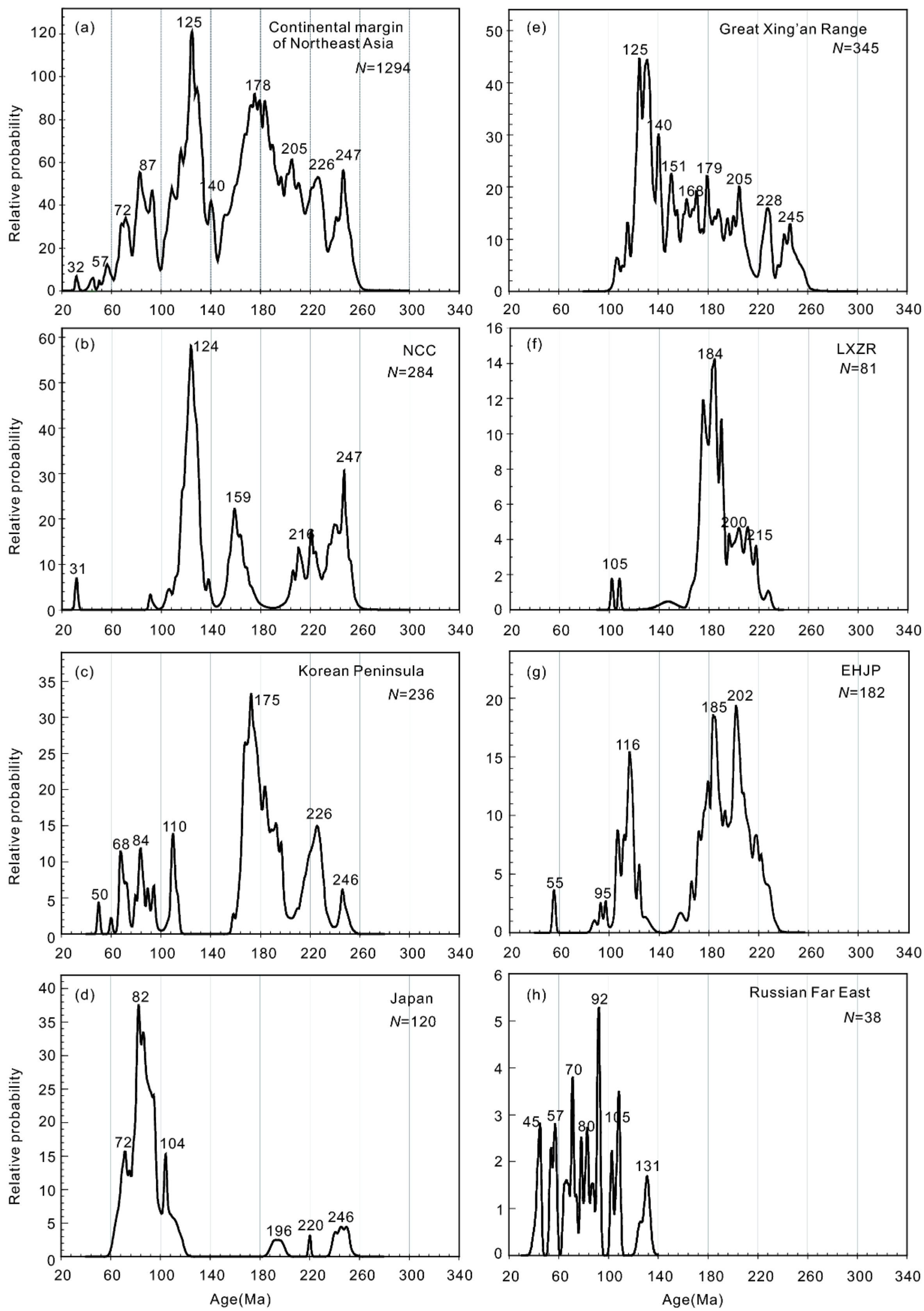


**Figure 1** Relative age probability plots (RPP) for Mesozoic-Paleogene igneous rocks at the continental margin of Northeast Asia. Data are listed in Appendix 1; *N* is the number of ages. (a) Continental margin of Northeast Asia, (b) the NCC, (c) Korean Peninsula, (d) Japan, (e) Great Xing'an Range, (f) the LXZR, (g) the EHJP, and (h) the SAOB.

margin (i.e., from the Great Xing'an Range to LXZR, EHJP, and SAOB).

## 4. Spatial-temporal patterns of Mesozoic-Paleogene igneous rock associations: Constraints on tectonic settings

### 4.1 Early-Middle Triassic magmatism

Early-Middle Triassic igneous rocks at the continental margin of Northeast Asia are found mainly in the Erguna-Xing'an massifs along a NE-SW trend and in the NCC along an E-W trend (Figure 2). In addition, small amounts of Early-Middle Triassic igneous rocks are found on the Korean Peninsula and in the Hida Belt of Japan.

#### *4.1.1 Erguna-Xing'an massifs*

Early-Middle Triassic igneous rocks in the Erguna-Xing'an massifs are dominated by granitoids, along with minor amounts of coeval gabbrodiorites, diorites, and basaltic andesites (Tang et al., 2014; Li et al., 2017; Appendix 2). The basaltic andesites are from the Tamulangou Formation in the Heihe area of the Xing'an Massif. These rocks have low $SiO_2$ (50.66–53.98 wt.%) and relatively high Cr (13.7–62.9 ppm), Co (29–40 ppm), and Ni (32.4–34.6 ppm) contents. The basaltic andesites are also enriched in light rare earth elements (LREEs) and large-ion lithophile elements (LILEs), and depleted in heavy rare earth elements (HREEs) and high-field-strength elements (HFSEs). Their zircon $\varepsilon_{Hf}(t)$ values range from 8.5 to 12.7, indicating that the primary magma was derived by partial melting of a mantle wedge that had been metasomatized by subduction-related fluids (Li et al., 2017).

Here, we analyze the diorites, granodiorites, and granites from the Enhe-Jiuka-Moerdaoga area in the Erguna Massif to reveal the tectonic setting of the Early-Middle Triassic igneous rocks (Tang et al., 2014). These granitoids have $SiO_2$=47.63–56.06 wt.%, $Mg^{\#}$ = 19–52, $Al_2O_3$=14.27–17.23 wt.%, and $Na_2O+K_2O$=6.77–9.28 wt.%. They belong to the high-K calc-alkaline series and are metaluminous to weakly peraluminous I-type granites (Figure 3a and b). Their zircon $\varepsilon_{Hf}(t)$ values of –2.0 to 6.6 indicate that the primary magma was derived from partial melting of depleted lower crust. Furthermore, strong linear correlations between $SiO_2$ and other major elements suggest that the chemical variations of this suite of rocks can be attributed to fractional crystallization (Tang et al., 2014). Geochemically, the granitoids are characterized by enrichments in LREEs and LILEs, depletions in HREEs and HFSEs, and no Eu anomalies (Figure 3c and d). These igneous rock associations are similar to those

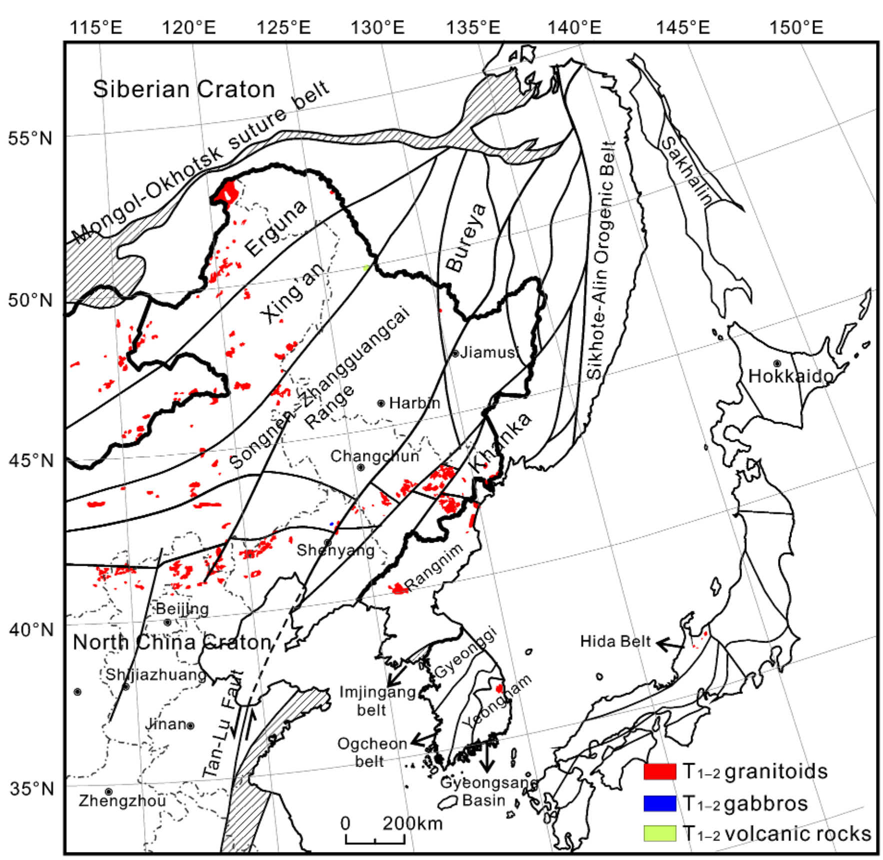


**Figure 2** (Color online) Distribution of Early-Middle Triassic igneous rocks at the continental margin of Northeast Asia.

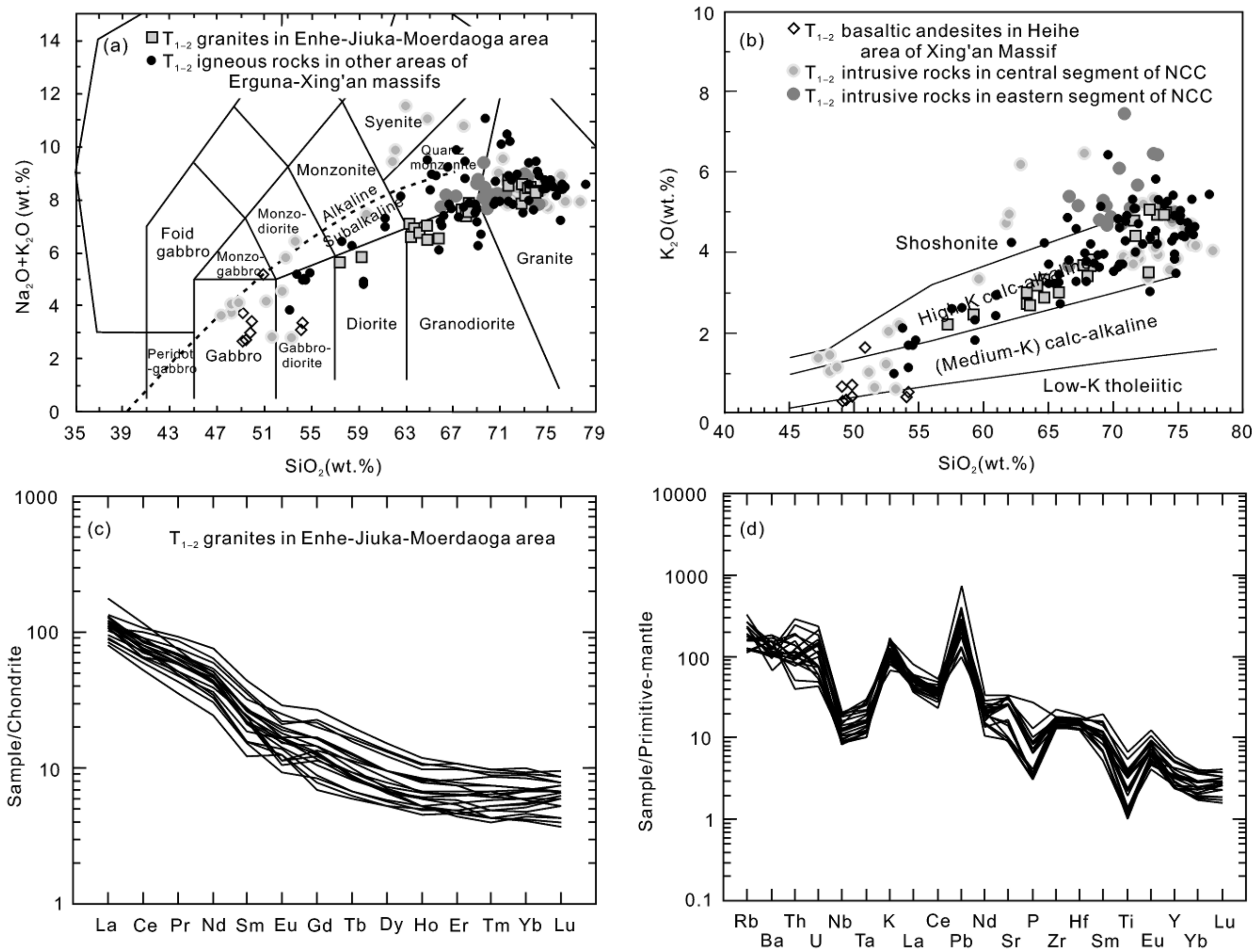


**Figure 3** (a) $SiO_2$ versus ($Na_2O+K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for Early-Middle Triassic igneous rocks in the Erguna-Xing'an massifs and northern margin of the NCC. The field boundaries in (a) and (b) are from Le Maitre (1989) and Peccerillo and Taylor (1976), respectively. (c) Chondrite-normalized REE patterns and (d) primitive-mantle-normalized trace element spidergrams for the Early-Middle Triassic igneous rocks in the Enhe-Jiuka-Moerdaoga area. Chondrite and primitive mantle values are from Boynton (1984) and Sun and McDonough (1989), respectively.

developed in eastern Pacific Andean-type active continental margin settings (Pitcher, 1983, 1997). In addition, the Babayi porphyry copper-molybdenum (Cu-Mo) deposit (237 Ma) in the Erguna Massif and the Tumurtin Ovoo skarn zinc (Zn) deposit in the central Mongolian Massif (241 Ma; Jiang et al., 2010) formed contemporaneously. Given these lines of evidence, we conclude that the Early-Middle Triassic igneous rocks in the Erguna-Xing'an massifs formed in an active continental margin setting.

The Early-Middle Triassic igneous rocks in the Erguna-Xing'an massifs are found along the southeastern side of the Mongol-Okhotsk suture belt along a NE-SW trend. These rocks and their geochemical characteristics are different from the alkaline and adakitic rocks at the northern margin of the NCC (see Section 4.1.2). In summary, we conclude that the Early-Middle Triassic magmatism in the Erguna-Xing'an massifs formed in an active continental margin setting related to the southward subduction of the Mongol-Okhotsk oceanic slab beneath the Erguna Massif, and that there is no relationship between these rocks and the Paleo-Asian tectonic regime.

*4.1.2 Northern margin of the North China Craton*

The Early-Middle Triassic igneous rocks at the northern margin of the NCC crop out in its central segment (i.e., northern Hebei to western Liaoning provinces and Inner Mongolia within the NCC) and eastern segment (i.e., central-eastern Jilin Province in the Paleozoic continental margin accretionary belt). The Early-Middle Triassic igneous rocks in the central and eastern segments of the NCC have different rock associations and geochemical characteristics.

The rocks in the central segment of the NCC consist of alkaline granites, alkali feldspar granites, and syenites, belonging to the alkaline series (Figure 3a and b). In addition, some granitoids belong to the high-K calc-alkaline series, and together with coeval gabbros form a bimodal igneous rock association. The alkaline and bimodal igneous rocks are likely to have formed in an extensional setting, which raises the question as to which tectonic regime this extensional setting was related to? Three lines of evidence shed insights into this question. Firstly, late Permian strata that are sporadically exposed in the Solonker-Linxi area overlie early Permian strata across an angular unconformity (IMBGMR, 1991). This indicates that a period of orogenic compression took place in the central segment of the NCC from the end of the early Permian to late Permian. Secondly, abundant middle Permian igneous rocks related to a collisional orogeny are found in Inner Mongolia, such as garnet-bearing monzogranites in the Kangbao area (281–266 Ma; Wang X L et al., 2007), the Halaheshao Pluton in the Daqingshan area (261 Ma; Zhao et al., 2007), and the Damiao Pluton in the Sizhiwangqi Banner of Inner Mongolia (265 Ma; Zhang Y M et al., 2009). Thirdly, in the early Permian, mixed cold- and warm-water fauna were present at the northern margin of the NCC along the Solonker-Xra Moron-Changchun-Yanji suture belt, suggesting that the Paleo-Asian Ocean was narrow at this time. The continent-continent collision took place at the end of the early Permian (Cao, 2013). In summary, we suggest that the late early Permian to middle Permian igneous rocks in the central segment of the NCC formed in a compressional tectonic setting related to closure of the Paleo-Asian Ocean (Cao, 2013), whereas the Early-Middle Triassic igneous rocks formed in a post-collisional extensional setting.

The Early-Middle Triassic igneous rocks in the Paleozoic continental accretionary belt (central-eastern Jilin Province) of the eastern segment of the NCC are geochemically different from those in the central segment. Most of the Early-Middle Triassic granitoids in the eastern segment are depleted in HREEs, and have high Sr and low Y contents, exhibiting an affinity to adakitic rocks (Figure 4; Sun et al., 2004; Zhang et al., 2004; Cao, 2013; Wang Z J et al., 2015). These rocks include the Jianping granites in the Liaoyuan area (249 Ma), the Yishan monzogranites (247 Ma), the Dayushan granites in the Panshi-Huadian area (248 Ma), garnet- and muscovite-bearing monzogranites in the Yitong area (244 Ma), the Liushugou monzogranites in the Yanbian area (245 Ma), and the Bailiping monzogranites (249–245 Ma). These rocks have $Na_2O/K_2O$ ratios and $Mg^{\#}$ values of less than 2 and 0.5, respectively, and low Cr, Co, and Ni contents, indicating that their primary magma was derived by partial melting of thickened lower continental crust. In addition, these Early-Middle Triassic granitoids in the eastern segment are slightly younger than the peak metamorphic age of the Hulan Group (late Permian), which further indicates that they are syn-collisional granites. We conclude that the final collision between the NCC and the northern amalgamated block (i.e., XMOB) occurred in the Early-Middle Triassic, representing the final closure of the Paleo-Asian Ocean (Wu et al., 2007a; Wang Z J et al., 2015).

In summary, the initial closure of the Paleo-Asian Ocean occurred in the central segment of the NCC during the late early Permian to middle Permian, and final closure occurred in the eastern segment during the Early-Middle Triassic. The Early-Middle Triassic igneous rocks in the central and eastern segments of the NCC formed in a post-collisional extensional and continent-continent collisional setting, respectively, indicating a scissor-like closure of the Paleo-Asian Ocean from west to east.

#### *4.1.3 Korean Peninsula and Hida Belt of Japan*

Minor Early-Middle Triassic igneous rocks crop out on the Korean Peninsula and in the Hida Belt of Japan, including the Kwanmo granites (248–240 Ma; Zhang Y B et al., 2016) and Unsan syenites (234 Ma; Wu et al., 2007b) at the northern margin of the Rangnim Massif, the Yeongdeok granites in the Gyeongsang Basin of the Yeongnam Massif (250–245 Ma; Yi et al., 2012), and gneissic granites in the Hida Belt (250–240 Ma; Takahashi et al., 2010; Mao, 2013). The Kwanmo and Yeongdeok granites on the Korean Peninsula, as well as the gneissic granites in the Hida Belt, are depleted in HREEs and have high Sr and low Y contents, exhibiting an affinity to adakitic rocks (Figure 4; Yi et al., 2012). It is important to determine whether these rocks formed in the same tectonic setting.

The Rangnim Massif has similar basement and sedimentary cover rocks to the NCC, and is generally considered part of the NCC (Zhao et al., 2006; Wu et al., 2007b). The Kwanmo granites are geochemically similar to coeval granites in the eastern segment of the NCC (central-eastern Jilin Province; Figure 4; Zhang Y B et al., 2016), indicating that they formed in a similar tectonic setting. Therefore, the Kwanmo granites in the Rangnim Massif may have formed in a syn-collisional setting related to final closure of the Paleo-Asian Ocean, whereas the presence of the Unsan syenites indicates a post-collisional extensional setting in the eastern segment of the NCC and northern Korean Peninsula since the end-Middle Triassic (Wu et al., 2007b).

It is unclear whether the tectonic setting of the Yeongnam Massif and Gyeongsang Basin was part of the SCB (Wu and Hou, 2016) or NCC (Zhai, 2016). The Yeongdeok granites are adakitic rocks, similar to coeval granites in the eastern segment of the NCC and northern Korean Peninsula (Figure 4), and quite different from those in the SCB (Wang Y L et al., 2005, 2007; Zhou et al., 2006). Moreover, dextral ductile shear occurred in the Cheongsan Shear Zone at the northwestern margin of the Yeongnam Massif during the Middle-Late Triassic (Ree et al., 2001; Takahashi et al., 2010, 2018). Therefore, we conclude that the Yeongnam Massif had separated from the northeastern margin of the NCC on account of Middle-Late Triassic shearing, and given that the Early-Middle Triassic Yeongdeok granites, together with coeval granites in the eastern segment of the NCC and northern Korean Peninsula, formed in a syn-collisional setting related

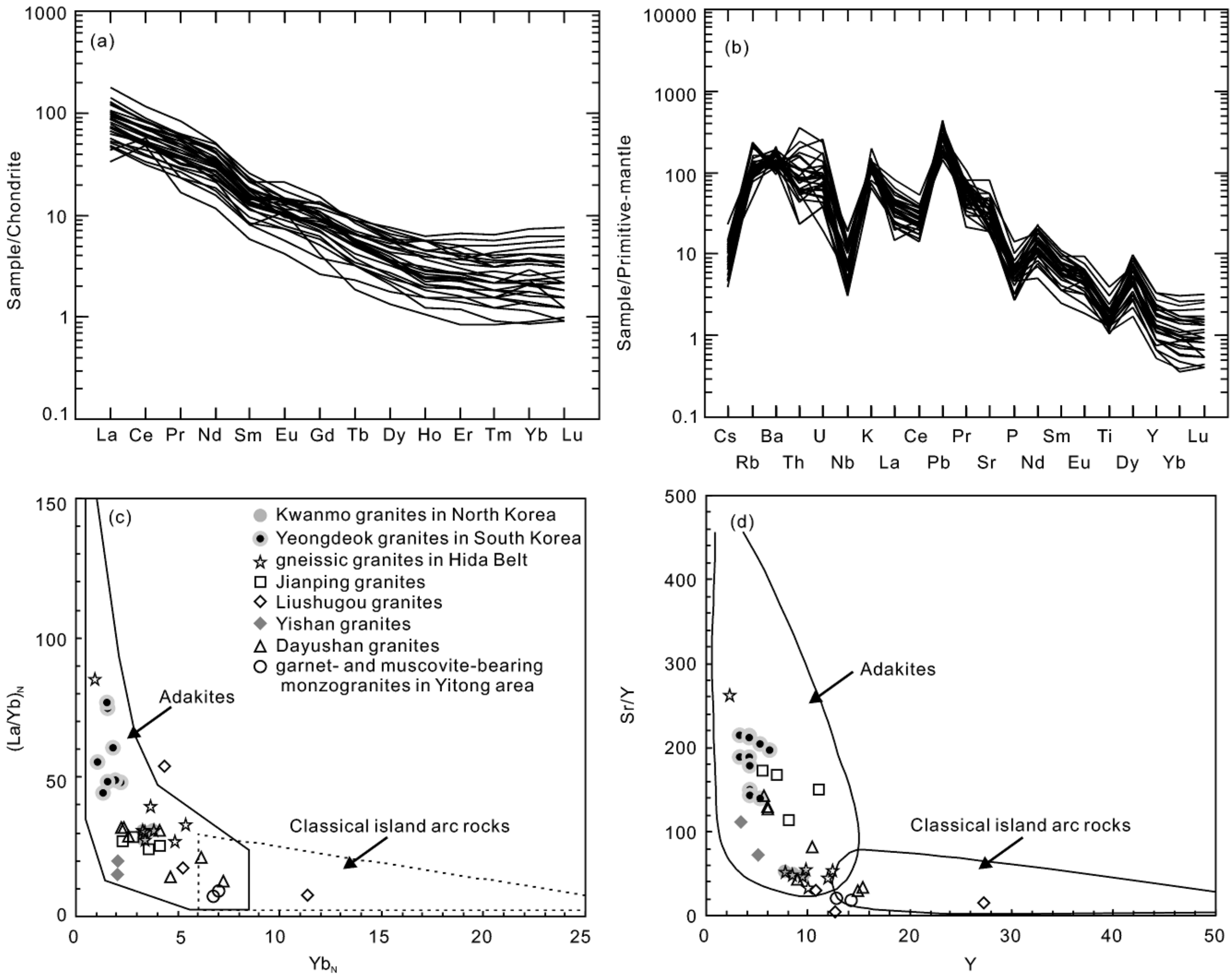


**Figure 4** (a) Chondrite-normalized REE patterns, (b) primitive-mantle-normalized trace element spidergrams, (c) $(Yb)_N$ versus $(La/Yb)_N$, and (d) Y versus Sr/Y diagrams (Defant and Drummond, 1990) for Early-Middle Triassic adakitic rocks in the NCC, Korean Peninsula, and Hida Belt of Japan.

to the final closure of the Paleo-Asian Ocean.

It is necessary to assess the tectonic nature of the Hida Belt to determine the tectonic setting of the Early Triassic gneissic granites. However, the Hida Belt has been variously correlated with the NCC, Sulu orogenic belt, and Ogcheon belt. The metamorphic ages (240–225 Ma) of UHP metamorphic rocks in the Sulu orogenic belt are younger than the gneissic granites (250–240 Ma) in the Hida Belt, based on U-Pb dating results for coesite-bearing zircon in mantle rocks (Liu and Xu, 2004). This precludes correlation of the Hida Belt with the Sulu orogenic belt. The absence of Early-Middle Triassic igneous rocks in the Ogcheon Belt also rules out its correlation to the Hida Belt. Given this observation, and the similar geochemical features of the Hida Belt and Early-Middle Triassic igneous rocks at the northern margin of the NCC, we conclude that the Hida Belt was separated from the northeastern margin of the NCC due to Late Triassic clockwise shearing upon the Funatsu Shear Zone (Takahashi et al., 2010, 2018). As such, the Early Triassic gneissic granites in the Hida Belt also formed in a syn-collisional setting related to the final closure of the Paleo-Asian Ocean.

*4.1.4 Tectonic setting of the Early-Middle Triassic igneous rocks*

The Early-Middle Triassic igneous rocks are found mainly in the Erguna-Xing'an massifs and at the northern margin of the NCC, along with lesser amounts on the Korean Peninsula and in the Hida Belt. The Early-Middle Triassic intermediate-silicic igneous rocks in the Erguna-Xing'an massifs belong to the high-K calc-alkaline series (Appendix 2), and are found along the southeastern side of the Mongol-Okhotsk suture belt. These rocks formed at an active continental margin related to the southward subduction of the Mongol-Okhotsk oceanic slab beneath the Erguna Massif. The Early-Middle Triassic alkaline and bimodal igneous rocks in the central segment of the NCC formed in a post-collisional extensional setting. Most coeval igneous rocks in the eastern segment of the NCC, Korean Peninsula, and Hida Belt are adakitic rocks that formed in a syn-collisional setting related to the final closure of the Paleo-Asian Ocean. In addition, the difference in the tectonic setting of the central and eastern segments of the NCC reveals a scissor-like closure of the Paleo-Asian Ocean from west to east.

### 4.2 Late Triassic magmatism

Late Triassic igneous rocks at the continental margin of Northeast Asia are found mainly in the Erguna-Xing'an massifs, LXZR-EHJP, northern margin of the NCC, and on the Jiaodong-Liaodong-Korean peninsulas (Figure 5).

#### *4.2.1 Erguna-Xing'an massifs*

Late Triassic igneous rocks in the Erguna-Xing'an massifs are mainly granitoids and minor intermediate-mafic rocks (Appendix 2). A small amount of Late Triassic volcanic rocks occurs in the Handaqi-Zhalantun-Moguqi area of the Xing'an Massif (Li et al., 2017). These rocks in the Erguna-Xing'an massifs have similar features to the Early-Middle Triassic igneous rocks within the massifs. Firstly, these Late Triassic rock associations are similar to those developed in eastern Pacific Andean-type active continental margin settings. Secondly, these rocks chemically belong to the high-K calc-alkaline series (Figure 6a and b). Thirdly, the A/CNK values of most Late Triassic granitoids are less than 1.1, showing an affinity to I-type granites. Fourthly, the primary magmas of the Late Triassic mafic igneous rocks were derived by partial melting of a mantle wedge metasomatized by subduction-related fluids. Fifthly, contemporaneous porphyry Cu-Mo deposits are found in the Erguna-Xing'an massifs and adjacent regions, including the Taipingchuan (202 Ma; Chen et al., 2010) and Badaguan (228–218 Ma; Tang et al., 2016a) porphyry Cu-Mo deposits in the Erguna Massif, and the Aryn Nuur porphyry Mo deposit (~229 Ma; Liu et al., 2010) in the Central Mongolian Massif. Finally, the Late Triassic igneous rocks are found along the southeastern side of the Mongol-Okhotsk suture belt in a NE-SW orientation (Figure 5). Given these observations, we conclude that the Late Triassic igneous rocks in the Erguna-Xing'an massifs formed at an active continental margin, related to the southward subduction of the Mongol-Okhotsk oceanic slab during the Triassic.

#### *4.2.2 Lesser Xing'an-Zhangguangcai Range and eastern Heilongjiang-Jilin provinces*

Late Triassic igneous rocks in the LXZR are composed of intrusive and volcanic rocks (Appendix 2). A distinct $SiO_2$ compositional gap is observed in the Late Triassic igneous rocks in the LXZR (Figure 6a and b), displaying a marked bimodality. Combined with the presence of coeval A-type granites (Wu et al., 2002), it has been suggested that the Late Triassic igneous rocks in the LXZR formed in an extensional environment (Xu et al., 2013a; Wang F et al., 2015; Guo et

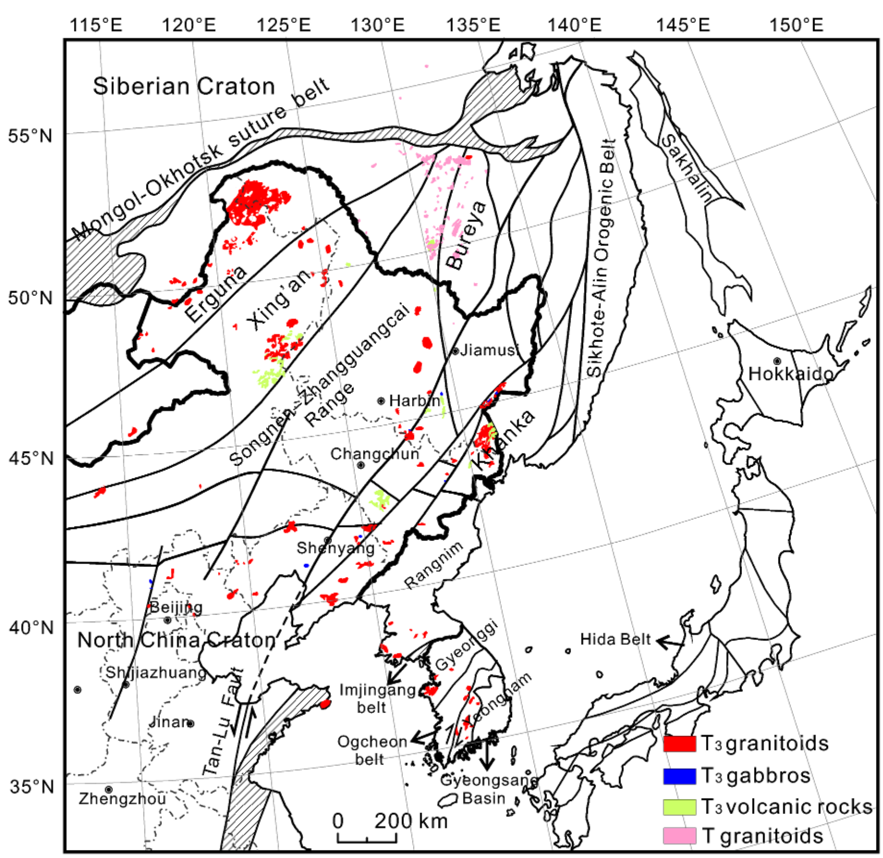


**Figure 5** (Color online) Distribution of Late Triassic igneous rocks at the continental margin of Northeast Asia.

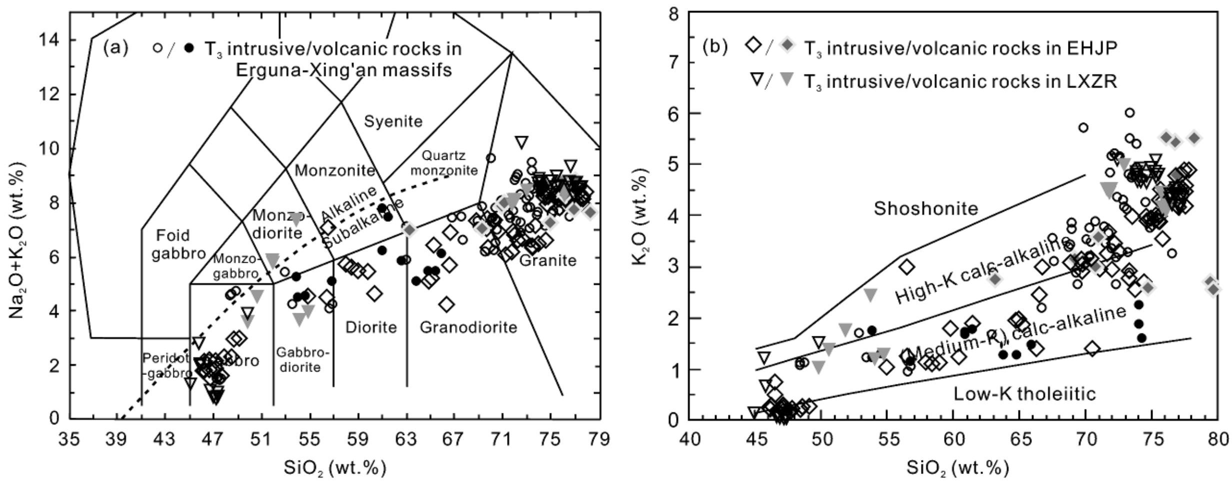


**Figure 6** (a) $SiO_2$ versus ($Na_2O+K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for Late Triassic igneous rocks in the Erguna-Xing'an massifs and LXZR-EHJP.

al., 2016).

Late Triassic igneous rocks in the EHJP (Dongning-Wangqing-Hunchun area) are found mainly on the south-eastern side of the Dunhua-Mishan Fault, and tectonically belong to the western margin of the Khanka Massif (Figure 5). These Late Triassic igneous rocks are dominated by granitoids and rhyolites, as well as subordinate syenites and gabbros (Appendix 2). The granitoids and rhyolites display an affinity to A-type granites, and the mafic-ultramafic rocks are related to Cu and Ni ore deposits (Wu et al., 2004; Xu et al., 2009, 2013a), implying that the Late Triassic igneous rocks in the EHJP formed in an extensional environment (Wang F et al., 2015; Yang H et al., 2015).

Based on geochronological data and the spatial distribution of Paleozoic-Mesozoic igneous rocks within the Songnen-Zhangguangcai Range and Jiamusi and Khanka massifs, Wang F et al. (2016) inferred that the offset along the Dunhua-Mishan Fault has been ~300 km since the Late Triassic. A paleogeographic reconstruction indicates that the eastern EHJP may be connected to the southern part of the Zhangguangcai Range. Therefore, the Late Triassic igneous rocks in the LXZR and EHJP possibly formed in the same tectonic setting. Some studies have considered that Late Triassic magmatism in the LXZR-EHJP was closely related to the subduction of the Paleo-Pacific slab beneath Eurasian continent (Wu et al., 2011; Zhou and Wilde, 2013; Yang H et al., 2015). However, the absence of Late Triassic calc-alkaline igneous rocks and accretionary complexes at the eastern margin of Northeast Asia, and the presence of Late Triassic marine-terrestrial sediments at the eastern margin of the Jiamusi Massif and the Russian Far East indicates that the eastern margin of Northeast Asia was a passive continental margin during the Late Triassic (Zhang et al., 2015). This excludes the possibility that the Late Triassic igneous rocks in the LXZR-EHJP were related to the subduction of the Paleo-Pacific slab. We propose two possible tectonic regimes for this Late Triassic extensional environment. First, the paleogeographic extension direction of the LXZR-EHJP in the Late Triassic was sub-parallel to the Mongol-Okhotsk suture belt. Late Triassic calc-alkaline igneous rocks in the Erguna-Xing'an massifs, and coeval bimodal igneous rocks and A-type granites and rhyolites in the LXZR-EHJP, exhibit systematic chemical changes from the continental margin to intracontinental regions. This result indicates that these rocks formed in an active continental margin setting and in an extensional environment, possibly a back-arc basin related to the southward subduction of the Mongol-Okhotsk oceanic slab. Second, lithospheric extension after the closure of the Paleo-Asian Ocean may have continued until the Late Triassic (see Section 4.2.3). The Late Triassic igneous rocks in the LXZR-EHJP might have formed in this extensional environment related to the closure of the Paleo-Asian Ocean.

### *4.2.3 Northern margin of the North China Craton*

Late Triassic igneous rocks in the central segment of the northern margin of the NCC consist of alkaline complexes and mafic-ultramafic rocks (Appendix 2) that are characterized by alkali minerals, such as aegirine-augite, nepheline, and alkali amphibole (Zhang S H et al., 2010). Late Triassic granites in the eastern segment of the northern margin of the NCC are A-type granites, along with coeval mafic-ultramafic rocks, constituting a bimodal rock suite (Appendix 2; Figure 7a and b; Wu et al., 2002, 2011; Cao, 2013). In addition, the absence of 240–225 Ma sedimentation and the presence of Late Triassic molasse deposits in the eastern segment of the NCC and its adjacent suture zone reveal a change from orogenic uplift to post-orogenic extension. Given the presence of alkaline and bimodal igneous rocks and molasse deposits, we propose that the northern margin of the NCC was in a post-orogenic extensional environment during the Late Triassic. Furthermore, Late Triassic igneous rocks at the northern margin of the NCC are found along the Solonker-Xra Moron-Changchun-Yanji suture belt, trending E-W (Figure 5) and indicating that they formed in a post-orogenic extensional environment related to the final closure of the Paleo-Asian Ocean.

*4.2.4 Jiaodong-Liaodong-Korean peninsulas*

Small amounts of Late Triassic igneous rocks are found on the Jiaodong-Liaodong-Korean peninsulas (Figure 5). The Late Triassic igneous rocks on the Jiaodong Peninsula comprise the Jiazishan quartz syenites (215 Ma), pyroxene syenites (215 Ma), and mafic dikes (201 Ma), as well as the Chashan biotite-alkali feldspar granites (205 Ma; Appendix 1). The Late Triassic igneous rocks on the Liaodong Peninsula consist of a suite of mafic-intermediate-silicic intrusive rocks with ages of 226–210 Ma (Appendixs 1 and 2). One representative example of such rocks is the Xiuyan granites (host rocks) and its mafic enclaves. Nepheline is found in Late Triassic syenites on the Liaodong Peninsula. The Late Triassic igneous rocks on the Korean Peninsula also consist of a suite of mafic-intermediate-silicic intrusive rocks (Appendix 2) that formed mainly at 234–210 Ma (Appendix 1). In summary, the Late Triassic igneous rocks of the Jiaodong-Liaodong-Korean peninsulas belong to the alkaline and shoshonite series (Figure 7a and b), and most of the granites display A-type affinities (Yang et al., 2005; Mao, 2013), suggesting that they formed in an extensional environment. This extensional setting may have been related to the subduction of the Paleo-Pacific slab, closure of the Paleo-Asian Ocean, or the collision between the NCC and YB.

Late Triassic igneous rocks at the continental margin of Northeast Asia are composed of alkaline rocks, A-type granites, and rhyolites, as well as bimodal igneous rocks that formed in an anorogenic extensional environment, and are different from the rock associations found in typical active continental margin settings. Thus, subduction of the Paleo-Pacific slab beneath Eurasian continent could not have occurred during the Late Triassic. The final closure of the Paleo-Asian Ocean resulted in the collision between the NCC and XMOB, and the formation of granites, quartz monzonites, and ultramafic rocks (but no intermediate-mafic rocks) along the Solonker-Xra Moron-Changchun-Yanji suture belt in an E-W orientation. However, the Late Triassic igneous rocks of the Jiaodong-Liaodong-Korean peninsulas are mainly alkaline, mafic-intermediate-silicic rocks with a NE-SW orientation parallel to the Sulu orogenic belt, and are clearly different from those at the northern margin of the NCC related to the closure of the Paleo-Asian Ocean. In addition, their formation ages (231–205 Ma; most are <225 Ma) are younger than the UHP metamorphic ages of the Sulu orogenic belt (240–225 Ma; Liu et al., 2004; Wan et al., 2005; Yang and Wu, 2009). As such, we conclude that the Late Triassic igneous rocks of the Jiaodong-Liaodong-Korean peninsulas formed in an extensional environment related to lithospheric delamination after collision between the NCC and YB.

*4.2.5 Tectonic setting of the Late Triassic igneous rocks*

Late Triassic igneous rocks at the continental margin of Northeast Asia are found mainly in the Erguna-Xing'an massifs, LXZR-EHJP, northern margin of the NCC, and Jiaodong-Liaodong-Korean peninsulas. The Late Triassic igneous rocks in the Erguna-Xing'an massifs are a suite of calc-alkaline mafic-intermediate-silicic rocks (Appendix 2) with a NE-SW orientation along the southeastern side of the Mongol-Okhotsk suture belt, indicating their formation in an active continental margin setting related to southward subduction of the Mongol-Okhotsk oceanic slab. Late Triassic igneous rocks at the northern margin of the NCC comprise alkaline complexes and cogenetic mafic-ultramafic rocks, A-type granites, and bimodal igneous suites. These rocks are oriented E-W along the Solonker-Xra Moron-Changchun-Yanji suture belt, indicating formation in a post-orogenic extensional environment related to the final closure of the Paleo-Asian Ocean. The Late Triassic bimodal igneous rocks and A-type granites and rhyolites in the LXZR-EHJP formed in an extensional environment that was related to either the southward subduction of the Mongol-Okhotsk oceanic slab or closure of the Paleo-Asian Ocean. Late Triassic igneous rocks of the Jiaodong-Liaodong-Korean peninsulas belong to the alkaline and shoshonite series, and most of the granites have A-type affinities. The formation ages of these rocks are younger than UHP metamorphic ages of the Sulu orogenic belt, suggesting their formation in an extensional environment related to lithospheric delamination after collision between the NCC and YB.

### 4.3 Early Jurassic magmatism

Early Jurassic igneous rocks at the continental margin of Northeast Asia are located mainly in the Erguna-Xing'an massifs, LXZR, EHJP, and the Yeongnam and Rangnim massifs of the Korean Peninsula. Small amounts of Early Jurassic igneous rocks are found in the NCC on Liaodong Peninsula (Figure 8).

*4.3.1 Eastern Heilongjiang-Jilin provinces-Korean Peninsula-Hida Belt*

Early Jurassic igneous rocks in the EHJP consist of a suite of mafic-intermediate-silicic intrusive and volcanic rocks (Figure 9a and b; Appendixs 1 and 2; Xu et al., 2013a), including calc-alkaline volcanic rocks at the eastern margin of the Jiamusi Massif (Wang et al., 2017).

Early Jurassic igneous rocks of the Korean Peninsula are found mainly in the northeastern part of the Rangnim and Yeongnam massifs. The intrusions in the northeastern part of the Rangnim Massif include the Daedokri (193 Ma), Won-

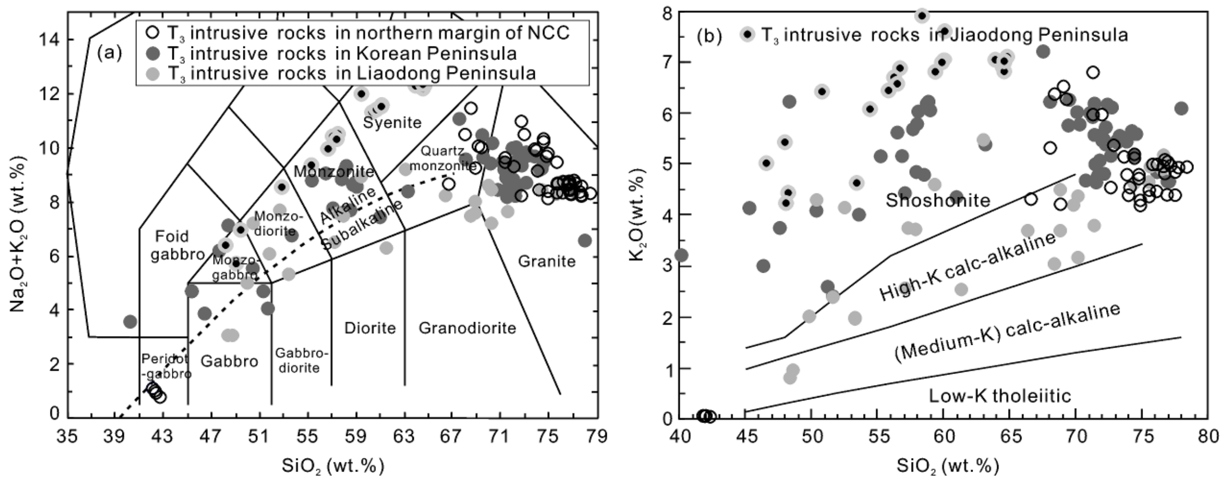


**Figure 7** (a) $SiO_2$ versus ($Na_2O+K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for Late Triassic igneous rocks of the Jiaodong-Liaodong-Korean peninsulas.

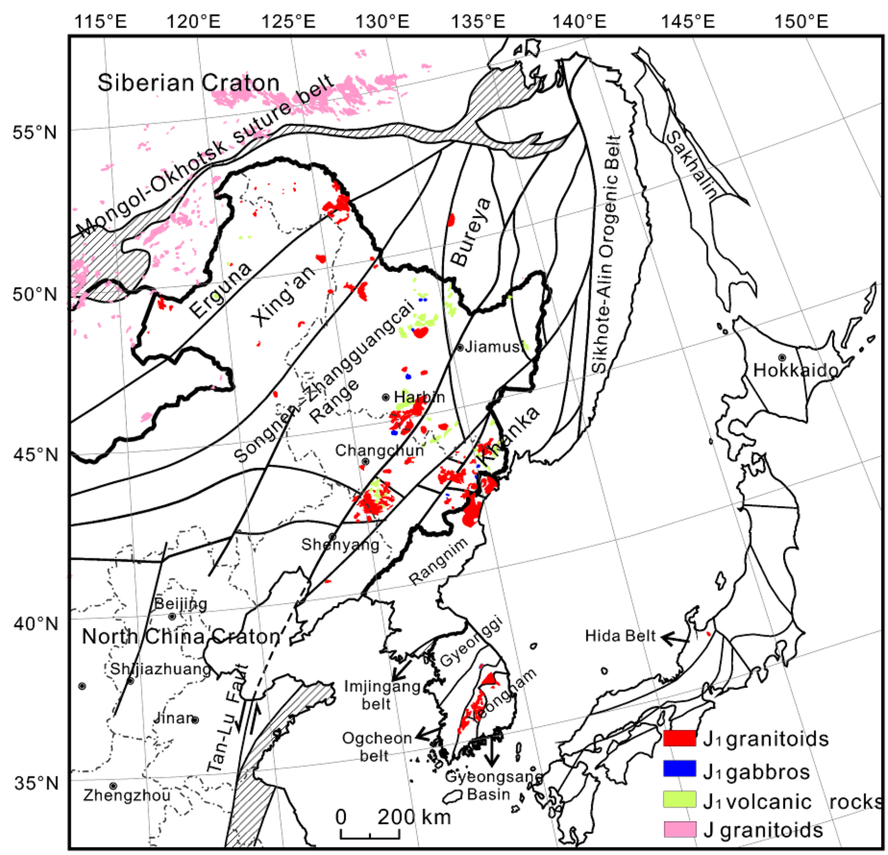


**Figure 8** (Color online) Distribution of Early Jurassic igneous rocks at the continental margin of Northeast Asia.

sanki (198–191 Ma), Gongsim (185 Ma), Sungam (199 Ma), and Musanri granitoids (184 Ma; Wu et al., 2007b; Zhang Y B et al., 2016). Representative intrusions in the Yeongnam Massif are the Beonam (196–190 Ma), Deochang (198 Ma), Sunchang (189–177 Ma), and Hapcheon (194 Ma) granitoids (Appendixs 1 and 2; Kee et al., 2010; Mao, 2013), as well as the Yeonghae (196–195 Ma) and Satkabong (192 Ma) diorites (Yi et al., 2012).

Minor Early Jurassic granites are present in the Hida Belt of Japan, such as the Okumayama granodiorites (191 Ma; Takahashi et al., 2010) and biotite granites (197 Ma; Zhao et al., 2013). In addition, the Okumayama Pluton hosts coeval mafic micro-granular enclaves (193 Ma; Takahashi et al., 2010).

Early Jurassic igneous rocks in the EHJP-Korean Peninsula-Hida Belt belong to the medium- to high-K calc-

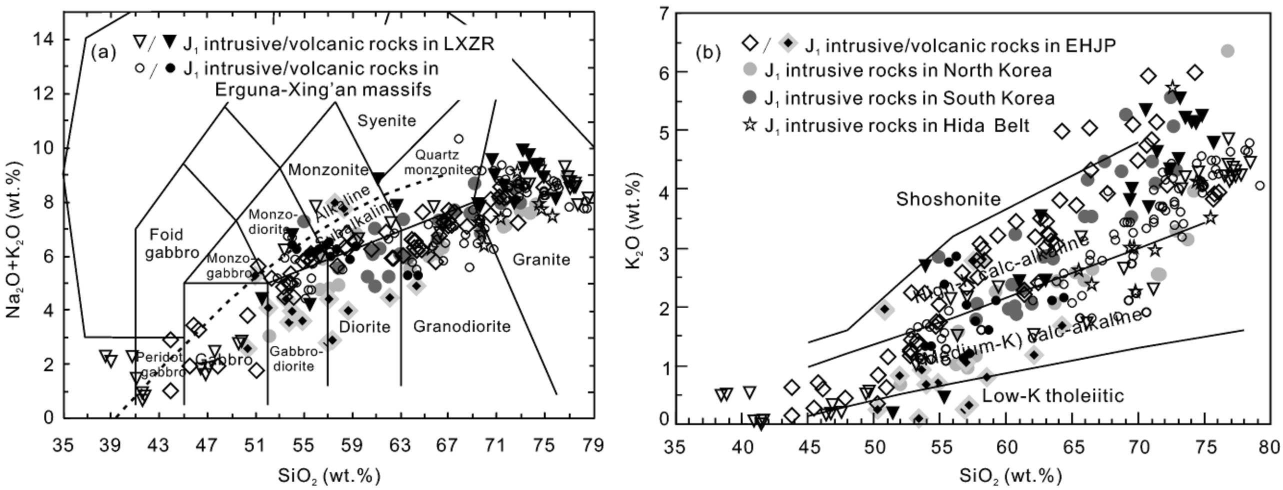


**Figure 9** (a) $SiO_2$ versus ($Na_2O+K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for Early Jurassic igneous rocks at the continental margin of Northeast Asia.

alkaline series (Figure 9a and b) and are characterized by enrichments in LILEs and depletions in HFSEs (Figure 10), typical of arc-like rocks. The Early Jurassic mafic rocks in the EHJP were generated by partial melting of lithospheric mantle that had been metasomatized by subduction-related fluids (Guo et al., 2015; Wang et al., 2017). Moreover, Early Jurassic accretionary complexes associated with slab subduction have been identified at the eastern margin of Eurasian continent and the Japan islands, including the Heilongjiang complex in China, which yields a deformation age of 186–176 Ma (Li et al., 1999b; Wu et al., 2007a), the Khabarovsk complex in the Russian Far East (Fukuyama et al., 2013; Safonova and Santosh, 2014), and the Mino-Tamba complex in southwest Japan (Isozaki, 1997). These features, combined with the NE-SW distribution of these rocks parallel to the continental margin of Northeast Asia, indicate that these Early Jurassic igneous rocks formed in an active continental margin setting. As such, we conclude that the Early Jurassic magmatism in the EHJP-Korean Peninsula-Hida Belt was related to the initial subduction of the Paleo-Pacific slab beneath Eurasian continent.

### 4.3.2 *Lesser Xing'an-Zhangguangcai Range*

Early Jurassic igneous rocks in the LXZR are dominated by mafic and silicic igneous rocks that belong to the calc-alkaline series, although some subordinate rocks are part of the alkaline series (Figure 9a and b). The Early Jurassic intermediate volcanic rocks are considered to be the mixing products of basaltic and rhyolitic magmas (Tang et al., 2011). Therefore, the Early Jurassic igneous rocks constitute a bimodal rock suite that was produced in an extensional environment (Yu et al., 2012; Wang et al., 2017). Furthermore, the Early Jurassic igneous rocks in the LXZR form a NE-SW trending belt similar to those in the EHJP (Figure 8). The calc-alkaline igneous rocks in the EHJP and bimodal igneous rocks in the LXZR exhibit systematic chemical variations from the continental margin to intracontinental region, corresponding to active continental margin and back-arc extensional settings related to subduction of the Paleo-Pacific slab, respectively. As such, we conclude that subduction of the Paleo-Pacific slab beneath Eurasian continent began in the Early Jurassic.

### 4.3.3 *Erguna-Xing'an massifs*

Early Jurassic igneous rocks in the Erguna-Xing'an massifs are mainly intermediate-silicic intrusive rocks, with subordinate intermediate-mafic volcanic rocks in the Erguna Massif (Appendixs 1 and 2; Wang W et al., 2015).

Early Jurassic granitoids in the Erguna-Xing'an massifs belong to the medium- to high-K calc-alkaline series (Figure 9a and b) and exhibit an affinity to I-type granites. The intermediate-mafic volcanic rocks also belong to the medium- to high-K calc-alkaline series (Wang W et al., 2015; Figure 9a and b) and are similar to arc-type igneous rocks (Gill, 1981; Wilson, 1989; Kelemen et al., 2003; Wang W et al., 2015). In addition, the coeval Wunugetushan porphyry Cu-Mo (183–178 Ma; Chen et al., 2011; Wang W et al., 2012) and Sankuanggou skarn Zn deposits (176 Ma; Ge et al., 2007) are found in the Erguna and Xing'an massifs, respectively. These lines of evidence indicate that the Early Jurassic igneous rocks in the Erguna-Xing'an massifs formed at an active continental margin.

These Early Jurassic calc-alkaline igneous rocks crop out as a NE-SW trending belt. Previous studies have proposed that they formed in an active continental margin setting related to the subduction of the Paleo-Pacific slab beneath Eurasian continent (Sui et al., 2007; Zhang Y L et al., 2010). However, the presence of coeval bimodal igneous rocks in the LXZR precludes the possibility that the Early Jurassic igneous rocks in the Erguna-Xing'an massifs are related to

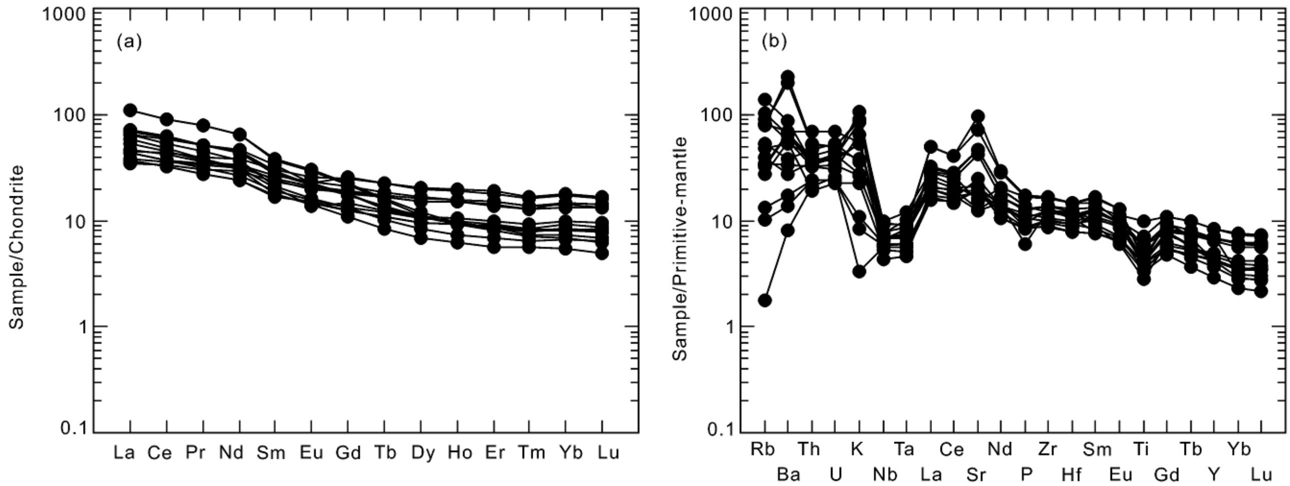


**Figure 10** (a) Chondrite-normalized REE patterns and (b) primitive-mantle-normalized trace element spidergrams for Early Jurassic igneous rocks in the EHJP.

subduction of the Paleo-Pacific slab. The Early Jurassic calc-alkaline igneous rocks are located along the southeastern side of the Mongol-Okhotsk suture belt, suggesting their formation in an active continental margin setting related to southward subduction of the Mongol-Okhotsk oceanic slab.

*4.3.4 Tectonic setting of the Early Jurassic igneous rocks*
The Early Jurassic calc-alkaline mafic-intermediate-silicic igneous rocks in the EHJP-Korean Peninsula-Hida Belt have similar geochemical characteristics to arc-type igneous rocks, whereas the coeval igneous rocks in the LXZR are bimodal. These rocks formed in active continental margin and back-arc extensional settings, respectively, thereby indicating that subduction of the Paleo-Pacific slab beneath Eurasian continent had begun in the Early Jurassic. This view is further supported by the Early Jurassic accretionary complexes at the continental margin. The Early Jurassic igneous rocks in the Erguna-Xing'an massifs are mainly intermediate-silicic intrusive rocks, along with minor amounts of intermediate-mafic volcanic rocks, which crop out in a NE-SW orientation. We conclude that these rocks formed in an active continental margin setting related to continued southward subduction of the Mongol-Okhotsk oceanic slab.

## 4.4 Middle Jurassic magmatism

Middle Jurassic igneous rocks at the continental margin of Northeast Asia are found mainly in the NCC and southern part of the Korean Peninsula, as well as in minor amounts in the Erguna-Xing'an massifs (Figure 11).

*4.4.1 Erguna-Xing'an massifs*
Middle Jurassic igneous rocks in the Xing'an Massif crop out mainly in the Heihe region, and minor amounts in the Nengjiang, Arongqi, and Chaihe areas. These rocks are granitoids (Appendixs 1 and 2; Figure 11; 175–164 Ma). Only one Middle Jurassic monzogranite pluton is found in the Manzhouli region of the Erguna Massif (171 Ma; Wang W et al., 2012).

Middle Jurassic muscovite granites (168 Ma) in the Xing'an Massif have an affinity to adakitic rocks, implying the presence of residual garnet in the magma source. Given this inference and the Middle Jurassic thrust-nappe structure in northern Hebei-western Liaoning provinces (Yanshanian; Zhang et al., 2007; Zhang et al., 2011) and Middle-Late Jurassic metamorphism in the northern part of the Xing'an Massif (Miao et al., 2015), we consider that crustal thickening in the Xing'an Massif took place during the Middle Jurassic (Li et al., 2015). Middle Jurassic igneous rocks in the Erguna-Xing'an massifs are distributed in a NE trending belt and are found only to the west of the Songliao Basin (drilling data show the existence of 165–161 Ma granitoids within the Songliao Basin; Appendix 1). No coeval magmatism has been found to the east of the Songliao Basin. As such, we conclude that Middle Jurassic crustal thickening and coeval magmatism in the Erguna-Xing'an massifs was related to the evolution of the Mongol-Okhotsk tectonic regime. The clockwise rotation of the Siberian Craton relative to the central Mongolian Massif indicates that a scissor-like, west-to-east closure of the Mongol-Okhotsk Ocean occurred during the Middle Jurassic (Zorin, 1999; Cogné et al., 2005; Tomurtogoo et al., 2005). Therefore, we conclude that the Middle Jurassic magmatism in the Erguna-Xing'an massifs formed in a compressional setting related to the closure of the Mongol-Okhotsk Ocean, and that closure of the Mongol-Okhotsk Ocean northwest of the Erguna Massif took place in the Middle Jurassic (Li et al., 2015).

*4.4.2 Northern margin of the North China Craton-Korean Peninsula-Liaodong Peninsula*
The Middle Jurassic igneous rocks at the northern margin of the NCC (including northern Hebei- western Liaoning pro-

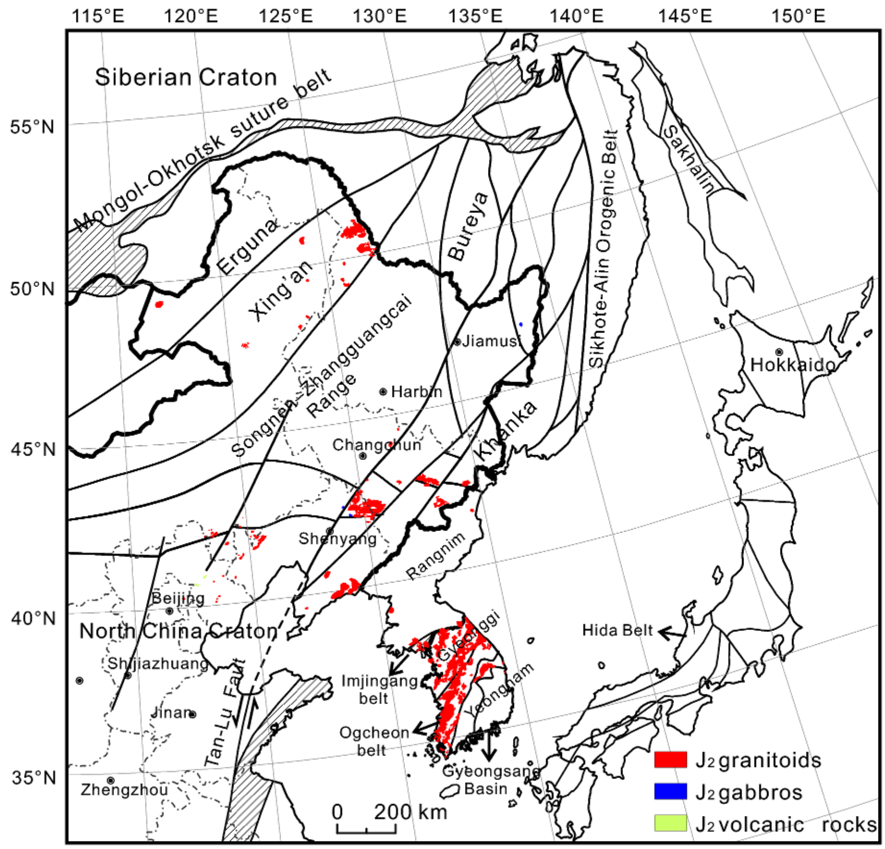


**Figure 11** (Color online) Distribution of Middle Jurassic igneous rocks at the continental margin of Northeast Asia.

vinces) are mainly granitoids with minor gabbros, diorites, and syenites (Figure 12; Zhang S H et al., 2014; Zhang H H et al., 2016), as well as minor andesites and rhyolites (Zhang S H et al., 2014). Most Middle Jurassic igneous rocks in this area have high $Al_2O_3$, $Na_2O$, and Sr contents, and low MgO, Y, and Yb contents, as well as high Sr/Y and $La_N/Yb_N$ ratios, similar to adakitic rocks derived by partial melting of thickened crust (Figure 13; Zhang S H et al., 2014; Zhang H H et al., 2016). These observations, combined with the occurrence of coeval adakitic rocks and garnet-bearing granites in the northern segment of the Great Xing'an Range and Middle Jurassic thrust-nappe structures in northern Hebei-western Liaoning provinces, indicate that Middle Jurassic crustal thickening occurred in this area. A number of observations provide insight into the tectonic regime that produced this crustal thickening. Firstly, Middle Jurassic magmatism did not take place in the eastern part of northeast China, indicating that a strike-slip regime existed between the continental margin of northeast China and the Paleo-Pacific slab during the Middle Jurassic. Secondly, the closure of the Mongol-Okhotsk Ocean took place during the Middle Jurassic. As such, we conclude that the Middle Jurassic magmatism at the northern margin of the NCC resulted from the far-field effects of the closure of the Mongol-Okhotsk Ocean.

Middle Jurassic igneous rocks of the Korean Peninsula mainly crop out in the Gyeonggi Massif, Ogcheon Belt, and Imjingang Belt, and are granitoid rocks (Figure 12). These granitoids can be subdivided into two groups based on their structure (i.e., gneissic and massive granites). Representative examples of such plutons include the Iksan (168 Ma; Oh et al., 2004), Jeonju (173 Ma; Hee et al., 2005), Seoul (170 Ma; Kwon et al., 1999; Hee et al., 2005), and Daebo (garnet-bearing) biotite granites and granodiorites (Appendixs 1 and 2). Most Middle Jurassic granitoids on the Korean Peninsula exhibit an affinity to adakitic rocks (Figure 13; Kim et al., 2015) and have high initial $^{87}Sr/^{86}Sr$ ratios (0.7048–0.7262), variable $K_2O$ contents (0.50–5.88 wt.%), and $K_2O/Na_2O$= (0.34–2.1), indicating that the primary magmas were not derived by partial melting of thickened crust (Kim et al., 2015). Geochemically, the Middle Jurassic igneous rocks on the Korean Peninsula belong to the high-K calc-alkaline series (Figure 12a and b). The granitoids are enriched in LILEs and depleted in HFSEs (e.g., Nb, Ta, Hf, and Ti; Mao, 2013; Kim et al., 2015), and are I-type granites, indicating their formation in a continental arc setting. In addition, Middle Jurassic folds and thrust faults within the Ogcheon Belt are NE trending, suggesting that NW-SE compression affected the Korean Peninsula during the Middle Jurassic (Hee et al., 2005). As such, we conclude that these Middle

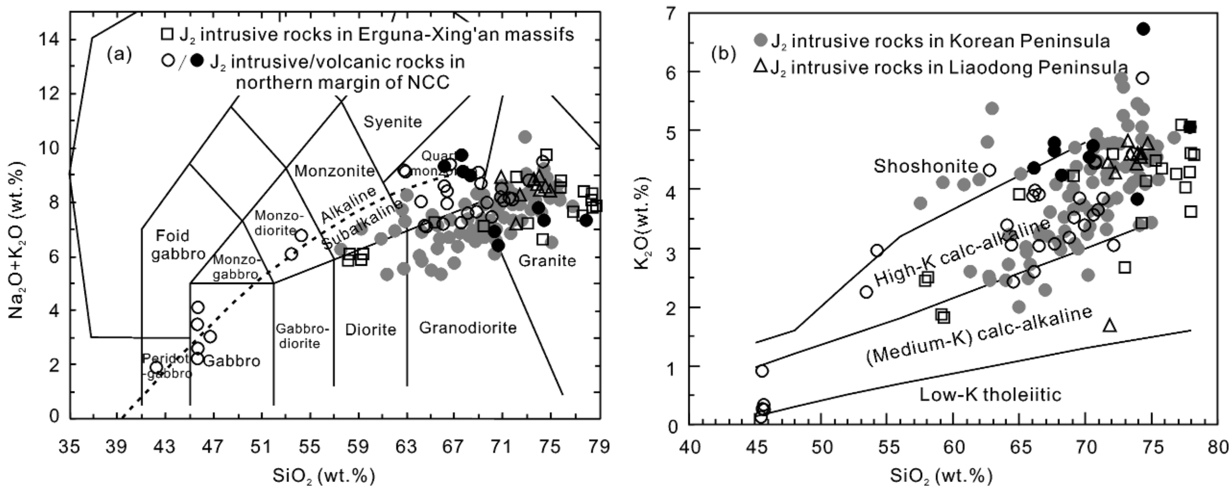


**Figure 12** (a) $SiO_2$ versus ($Na_2O$+$K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for Middle Jurassic igneous rocks at the continental margin of Northeast Asia.

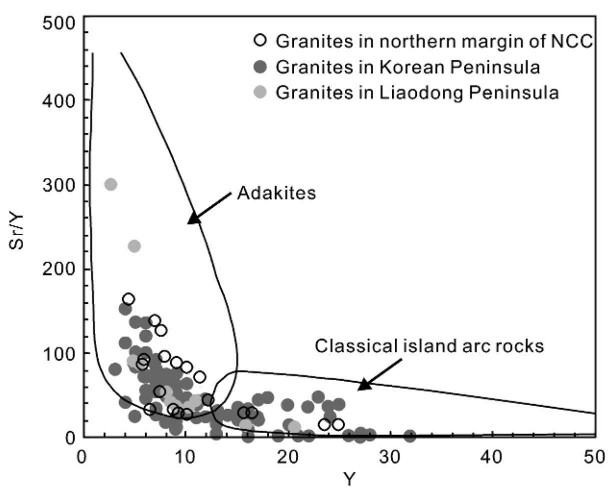


**Figure 13** Sr/Y versus Y diagram for Middle Jurassic granitoids at the northern margin of the NCC-Korean Peninsula-Liaodong peninsulas.

Jurassic igneous rocks formed in an active continental margin setting related to the subduction of the Paleo-Pacific slab.

The Middle Jurassic granitoids on the Liaodong Peninsula and eastern Jilin Province (located in the Paleozoic continental margin accretionary belt of the NCC) also have an affinity to adakitic rocks (Figure 13; Wu et al., 2005a). This observation, combined with the coeval adakitic rocks at the northern margin of the NCC and Korean Peninsula, indicate that the Middle Jurassic granitoids of the Liaodong Peninsula and eastern Jilin Province may be related to the far-field effects of Mongol-Okhotsk Ocean closure and/or northwestward subduction of the Paleo-Pacific slab.

#### *4.4.3 Tectonic setting of the Middle Jurassic igneous rocks*

Middle Jurassic igneous rocks in the Erguna-Xing'an massifs are mainly adakitic granitoids, implying that crustal thickening took place during the Middle Jurassic, which is also supported by the presence of Middle Jurassic thrust-nappe structures in northern Hebei-western Liaoning provinces and Middle-Late Jurassic metamorphism in the northern Great Xing'an Range. In addition, Middle Jurassic igneous rocks in northeast China are only found west of the Songliao Basin. Therefore, we conclude that this crustal thickening event was related to the evolution of the Mongol-Okhotsk tectonic regime, and not the circum-Pacific tectonic regime. Middle Jurassic igneous rocks in the Erguna-Xing'an massifs formed in a compressional environment related to the closure of the Mongo-Okhotsk Ocean. The coeval adakitic granitoids at the northern margin of the NCC may have resulted from the far-field effects of closure of the Mongol-Okhotsk Ocean. In contrast, the Middle Jurassic igneous rocks on the Korean Peninsula are mainly I-type granites, implying their formation in an active continental margin setting related to the subduction of the Paleo-Pacific slab beneath Eurasian continent.

### 4.5 Late Jurassic magmatism

Late Jurassic igneous rocks at the continental margin of Northeast Asia are located mainly in the Erguna-Xing'an massifs and NCC (Figure 14), and are characterized by outcrops of volcanic rocks over a large area.

#### *4.5.1 Erguna-Xing'an massifs*

The Late Jurassic igneous rocks in the Erguna-Xing'an massifs are composed of intermediate-silicic intrusive rocks and a suite of intermediate-mafic-silicic volcanic rocks (Appendixs 1 and 2). The former includes the Shiwei monzonites (155 Ma), the Mangui quartz monzonites (156–155 Ma), and the Badaguan syenogranites (155–150 Ma; Tang et al., 2015) in the Erguna Massif, and the Chaihe monzogranites (152–149 Ma; Shi et al., 2015), the Chabaqi mon-

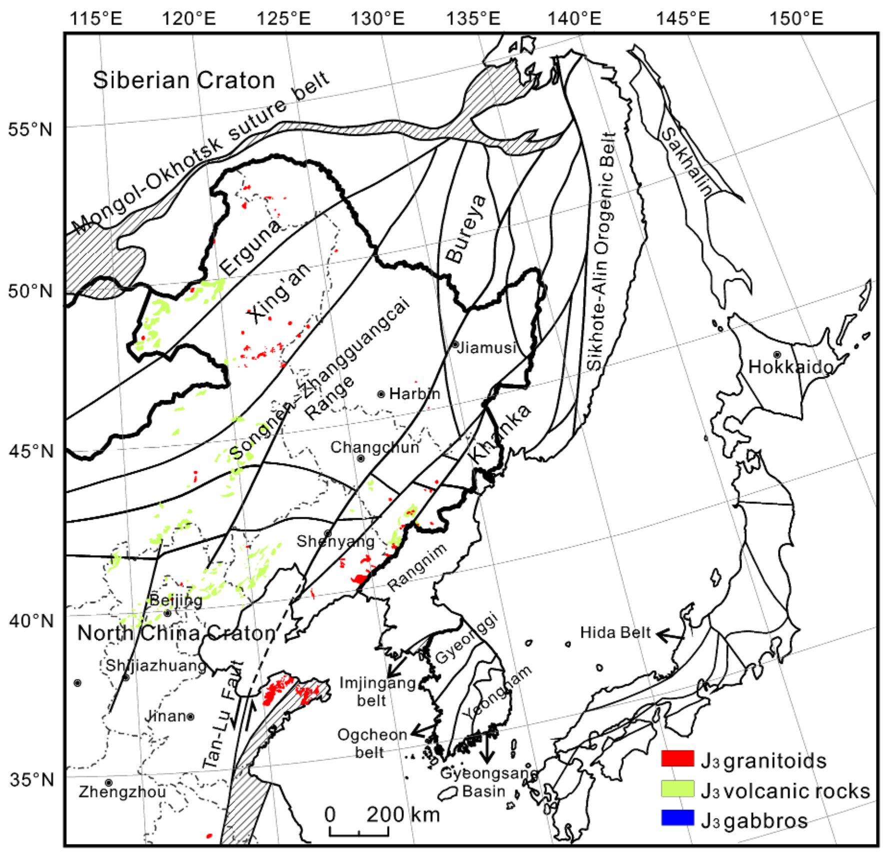


**Figure 14** (Color online) Distribution of Late Jurassic igneous rocks at the continental margin of Northeast Asia.

zogranites (151 Ma; Dong et al., 2016), and the Linxi syenogranites (149–148 Ma; Liu et al., 2005) in the Xing'an Massif. The latter mainly includes the intermediate-mafic volcanic rocks of the Tamulangou Formation (160–147 Ma; part of the Tamulangou Formation is Early-Middle Jurassic in age; Wang F et al., 2006) and silicic volcanic rocks of the Manketouebo Formation (160–152 Ma; part of the Manketouebo Formation is Early Cretaceous in age; Ying et al., 2010; Zhang C et al., 2014).

Geochemical data can be used to constrain the tectonic setting in which these Late Jurassic igneous rocks formed. Firstly, the Badaguan and Linxi syenogranites show large negative Eu anomalies and high 10000Ga/Al ratios, similar to A-type granites (Liu et al., 2005; Tang et al., 2015). Secondly, the Shiwei monzonites have high ($Na_2O$+$K_2O$) contents and belong to the alkaline series (Figure 15a and b; Tang et al., 2015). Thirdly, the Mangui quartz monzonites have high Sr contents and low Y and Yb contents, similar to adakitic rocks. Given this and high $Mg^{\#}$ values, it is plausible that the primary magmas were derived by partial melting of delaminated lower crust. These lines of evidence indicate that the Late Jurassic granitoids formed in an extensional environment. In addition, the Late Jurassic intermediate-mafic volcanic rocks from the Tamulangou Formation may have been derived from partial melting of enriched lithospheric mantle that was modified by subducted slab-derived fluids, in an extensional environment related to lithospheric thinning or rifting (Wang F et al., 2006; Ying et al., 2010; Meng et al., 2011). As such, we conclude that the Late Jurassic magmatism in the Erguna-Xing'an massifs occurred in an extensional environment.

Late Jurassic igneous rocks at the continental margin of Northeast Asia are mainly found west of the Songliao Basin in a NE-trending belt, whereas only two Late Jurassic silicic dikes have been found east of the Songliao Basin (147 Ma; Wu et al., 2011). No Late Jurassic igneous rocks are present in eastern Heilongjiang-Jilin provinces. Thus, Late Jurassic magmatism in the Erguna-Xing'an massifs appears to have been related to the evolution of the Mongol-Okhotsk tectonic regime rather than the circum-Pacific tectonic regime. As discussed above, the closure of the Mongol-Okhotsk Ocean to the northwest of the Erguna Massif took place in the Middle Jurassic and resulted in thickening of the lower crust (Li et al., 2015). Based on these observations, and the Middle Jurassic regional unconformity and Late Jurassic alkaline-subalkaline volcanic rocks from the Tiaojishan Formation in northern Hebei-western Liaoning provinces, we conclude that Late Jurassic magmatism in the Erguna-Xing'an massifs formed in an extensional environment related to the collapse or delamination of thickened crust after closure of the

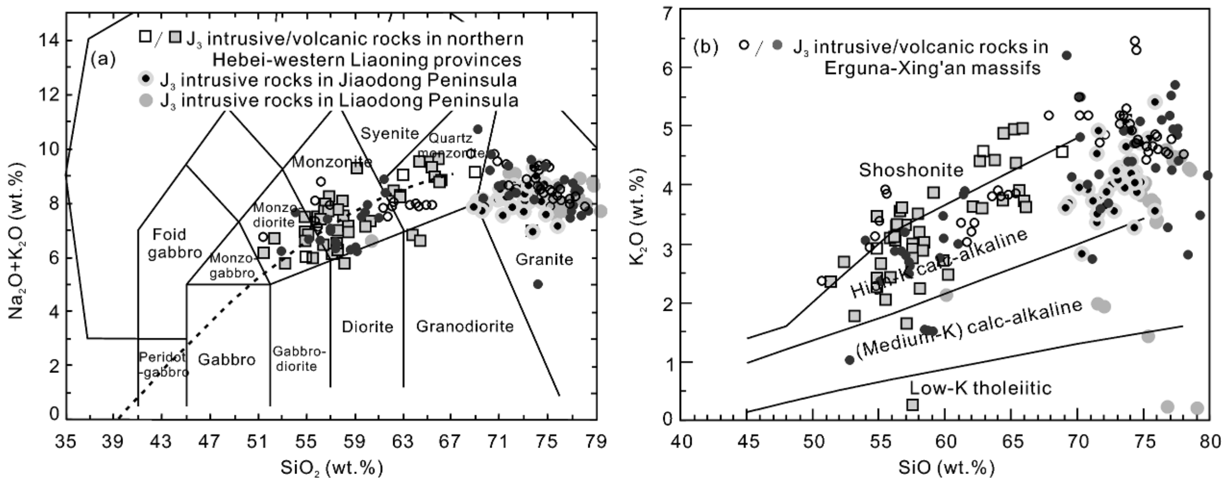


**Figure 15** (a) $SiO_2$ versus ($Na_2O+K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for Late Jurassic igneous rocks at the continental margin of Northeast Asia.

Mongol-Okhotsk Ocean.

### 4.5.2 *North China Craton*

Late Jurassic igneous rocks in the NCC are found mainly in northern Hebei-western Liaoning provinces, along with minor amounts on Liaodong and Jiaodong peninsulas (Figure 14).

The Late Jurassic igneous rocks in northern Hebei-western Liaoning provinces include intermediate-silicic volcanic rocks of the Lanqi and Tiaojishan formations (160–152 Ma), which are mostly alkaline rocks (Figure 15a and b). The volcanic rocks of the Lanqi Formation exhibit an affinity to adakitic rocks (Sr/Y=30–150; Ma et al., 2015). Ma et al. (2015) considered that the adakitic signature was most likely inherited from their source rocks, rather than reflecting derivation by partial melting of thickened lower crust.

The Late Jurassic igneous rocks on the Liaodong Peninsula include the Yutun mylonitic granites (157 Ma; Wu et al., 2005a), the Jiuliancheng monzogranites (157–156 Ma; Li et al., 2004; Wu et al., 2005a), and the Gaoliduntai plagioclase granites (156 Ma; Li et al., 2004). The Yutun mylonitic granites contain hornblende, similar to I-type granites. The Jiuliancheng monzogranites have A/CNK ratios of 1.0 to 1.1, are enriched in LREEs and Sr, and depleted in HREEs, similar to adakitic rocks. The Gaoliduntai granodiorites and trondhjemites have low REE abundances, positive Eu anomalies, and are highly fractionated (Wu et al., 2005a). On the Jiaodong Peninsula, representative Late Jurassic igneous rocks include the Linglong granitoids (160–153 Ma; Yang et al., 2012; Ma et al., 2013) and the Luanjiahe granites (158–154 Ma; Yang et al., 2012). These are slightly peraluminous I-type granites (Yang et al., 2012) and have high LREE and Sr contents as well as low HREE abundances, indicating an affinity to adakitic rocks (Yang et al., 2012; Ma et al., 2013). Most of the Late Jurassic granitoids from the Liaodong and Jiaodong peninsulas exhibit an affinity to adakitic rocks and have Sr/Y ratios of up to 378, high $SiO_2$ contents, high initial $^{87}Sr/^{86}Sr$ ratios (>0.710), and low MgO, Cr, and Ni contents, as well as negative $\varepsilon_{Nd}(t)$ values (Wu et al., 2005a; Ma et al., 2013), suggesting that their primary magma was derived from partial melting of thickened lower crust.

Several models have been proposed for the tectonic setting of the Late Jurassic igneous rocks in the NCC: (1) an active continental margin setting related to the subduction of the Paleo-Pacific slab (Zhou and Li, 2000; Wu et al., 2005a); (2) a post-collisional extensional environment after collision of the NCC with the YB (Mao et al., 2003; Yang et al., 2012); and (3) an extensional environment after the closure of the Mongol-Okhotsk Ocean (Xu et al., 2013a). Although Late Jurassic igneous rocks are found in the Sulu orogenic belt and adjacent areas, no coeval igneous rocks are present in the Dabie orogenic belt, indicating that the formation of Late Jurassic igneous rocks on the Liaodong and Jiaodong peninsulas was not related to post-collisional extension after the collision of the NCC with the YB. This inference indicates that Late Jurassic igneous rocks in the NCC formed in an extensional environment due to collapse of thickened crust, as also supported by the absence of Late Jurassic magmatism in the EHJP, Japan, and the Korean Peninsula, a regional unconformity in northern Hebei-western Liaoning provinces (Yu et al., 2016), and the occurrence of Late Jurassic adakitic rocks on the Liaodong and Jiaodong peninsulas. This tectonic setting was related to either the closure of the Mongol-Okhotsk Ocean or a change from a subduction to strike-slip regime between the Paleo-Pacific slab and Eurasian continent.

### 4.5.3 *Tectonic setting of the Late Jurassic igneous rocks*

Late Jurassic igneous rocks at the continental margin of Northeast Asia are found mainly in the Erguna-Xing'an massifs and NCC. These rocks in the Erguna-Xing'an massifs include A-type granites, monzonites, and quartz monzonites of the alkaline series, and alkaline volcanic rocks of the Tamalangou and Manketouebo formations, implying their formation in an extensional environment related to the collapse or delamination of thickened crust after the closure of the Mongol-Okhotsk Ocean. Most of the Late Jurassic igneous rocks in the NCC have a geochemical affinity to adakitic rocks, also suggesting their formation in an extensional environment related to the collapse of thickened crust. The absence of Late Jurassic magmatism in Japan and the Korean Peninsula, as well as east of the Songliao Basin in northeast China, implies that the Late Jurassic magmatism was mainly related to the closure of the Mongol-Okhotsk Ocean, and that a strike-slip structure may have existed between the continental margin of Northeast Asia and the Paleo-Pacific slab in the Late Jurassic.

### 4.6 The early Early Cretaceous magmatism

The early Early Cretaceous (145–135 Ma) magmatism at the continental margin of Northeast Asia was located mainly in the Great Xing'an Range to the west of the Songliao Basin and at the northern margin of the NCC (Figure 16).

The early Early Cretaceous igneous rocks in the Great Xing'an Range and at the northern margin of the NCC are mainly silicic igneous rocks (Appendixs 1 and 2; Figure 16). Representative granitoids include alkali feldspar granite, biotite syenogranite, and granitic porphyry from the Hamagou Forestry Center (137–136 Ma; Shi et al., 2013), the Enhe syenogranites (137 Ma; Tang et al., 2015), and the Zhuolu granites (139 Ma; Zhang S H et al., 2014). These granitoids are A-type granites. Coeval volcanic rocks include A-type rhyolites and alkali rhyolites (Figure 17) from the Jixiangfeng (142 Ma; Zhang et al., 2008; Meng et al., 2011; Xu et al., 2011), Baiyingaolao (141 Ma; Wang et al., 2013), and Zhangjiakou formations (143–136 Ma; Wei et al., 2008). These A-type igneous rock associations indicate that an extensional environment existed in the Great Xing'an Range and northern margin of the NCC during the early Early Cretaceous.

Stratigraphic studies of the Mohe and Hailar-Tamsag basins within the Erguna Massif have shown that Lower Cretaceous rocks unconformably overlie Upper Jurassic rocks (Li et al., 1999a; Meng et al., 2012). In northern Hebei-western Liaoning provinces, metamorphosed basement rocks and Mesoproterozoic strata are thrust over the Upper Jurassic Tuchengzi Formation (Zhang et al., 2011). These regional unconformities represent north-to-south thrusting that occurred during the Late Jurassic and early Early Cretaceous (Yang Y T et al., 2015). The early Early Cretaceous volcanism took place after this thrusting event, implying that these volcanic rocks formed in an extensional environment related to the collapse or delamination of thickened crust (Wei et al., 2008; Xu et al., 2013b).

In summary, early Early Cretaceous magmatism is found only to the west of the Songliao Basin and in the central segment of the northern NCC in a NE-trending belt. There is no coeval magmatism in Japan, the Korean Peninsula, or the continental margin to the east of the Songliao Basin. As such, we conclude that the early Early Cretaceous magmatism took place in an extensional environment related to the collapse of thickened crust after the closure of the Mongol-Okhotsk Ocean, and was unrelated to the subduction of the Paleo-Pacific slab.

### 4.7 The late Early Cretaceous magmatism

The late Early Cretaceous magmatism occurred widely throughout the continental margin of Northeast Asia (Figure 18), and is mainly composed of granitoids and volcanic rocks.

The late Early Cretaceous igneous rocks in the Russian Far East are located mainly in the central Sikhote-Alin area, and include I-type granites (131 Ma; Jahn et al., 2015), dacites, and rhyolites (131–102 Ma; Figure 19a and b; Wu et al., 2017). The dacites and rhyolites are characterized by enrichment in LREEs and Sr, depletion in HREEs, and high Sr/Y (33–145) and $Na_2O/K_2O$ ratios (1.15–7.74), similar to adakites derived by partial melting of a subducted slab (Wu et al., 2017). The late Early Cretaceous igneous rocks in the Russian Far East formed in an active continental margin setting related to the subduction of the Paleo-Pacific slab, as also indicated by the presence of several late Early Cretaceous accretionary complexes in the Russian Far East (Zyabrev and Matsuoka, 1999; Safonova and Santosh, 2014).

The late Early Cretaceous magmatism in Japan occurs mainly in the Kitakami Mountains of northeast Japan and in Kyushu of southwest Japan (Figure 18). The former includes adakitic granitoids ($Na_2O/K_2O$ = 1.34–8.79, and typically>2) and medium-K calc-alkaline granites (Figure 19a and b), as well as minor gabbros and quartz diorites (125–108 Ma; Tsuchiya et al., 2007). Coeval basalts and high-Mg andesites are also present in these areas (121–100 Ma; Tsuchiya et al., 2005). The igneous rocks in the Kitakami Mountains were derived mainly by partial melting of a subducted slab. The coeval igneous rocks in Kyushu are mainly granitoids, along with andesites and rhyolites of the Kanmon Group (125–106 Ma; Mao, 2013). These granitoids have adakitic affinities and $Na_2O/K_2O$ ratios that are generally less than 1, which is different from the adakitic rocks of the Kitakami Mountains. These andesites and rhyolites have trace element patterns of typical arc volcanic rocks. The late Early Cretaceous magmatism in the Kitakami Mountains and Kyushu occurred in an active continental margin setting related to the subduction

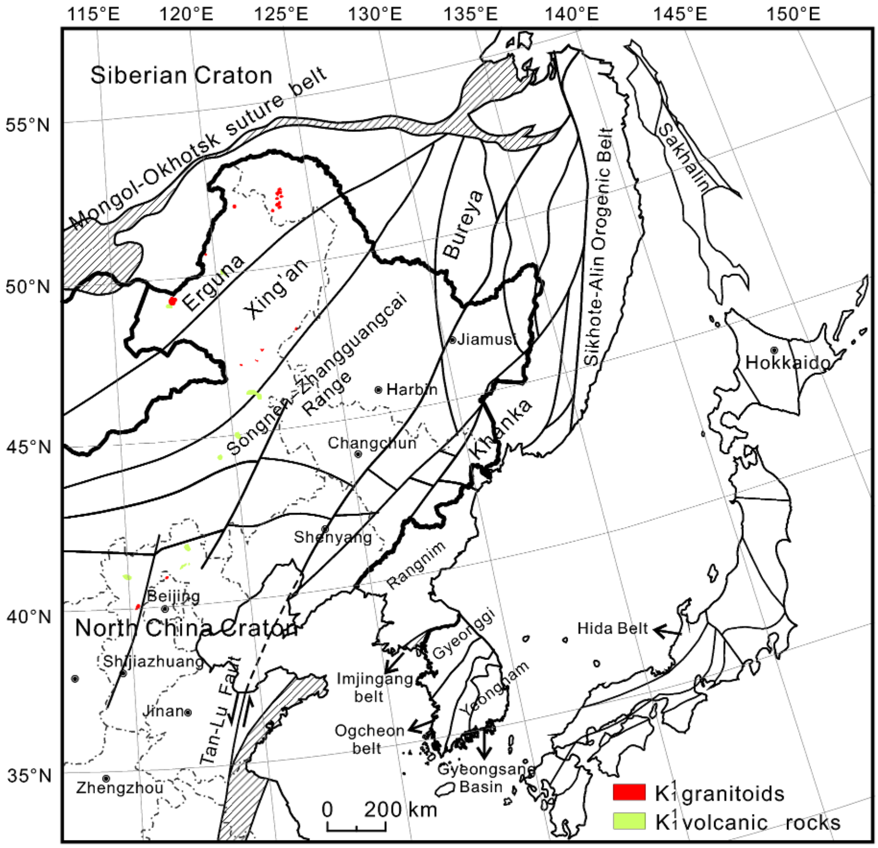


Figure 16 (Color online) Distribution of early Early Cretaceous igneous rocks at the continental margin of Northeast Asia.

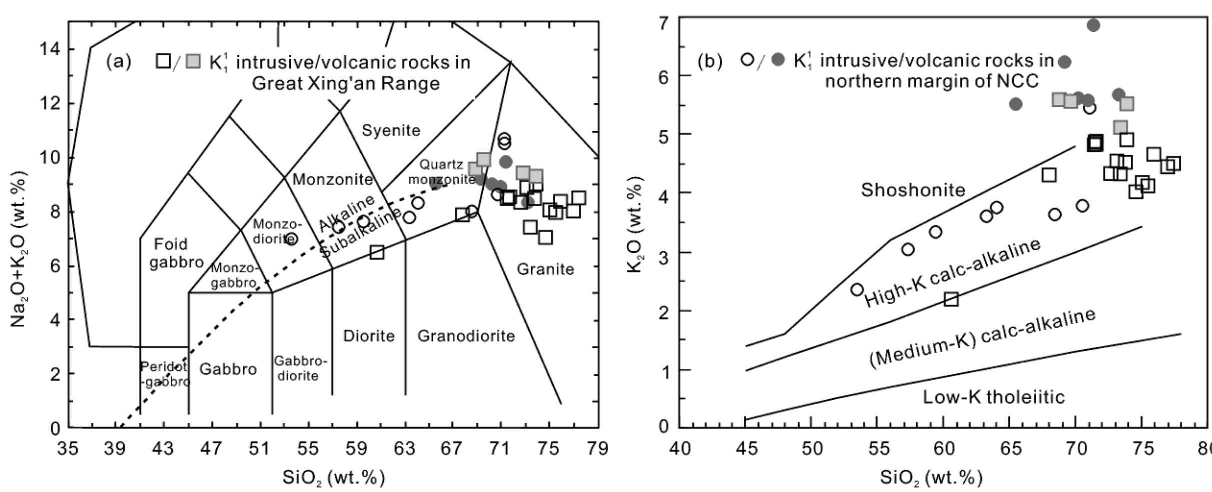


Figure 17 (a) $SiO_2$ versus ($Na_2O$+$K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for early Early Cretaceous igneous rocks from the continental margin of Northeast Asia.

of the Paleo-Pacific slab. The occurrence of Cretaceous accretionary complex belts (e.g., the Shimanto and Hidaka belts) in southwest and northeast Japan further demonstrates that subduction of the Paleo-Pacific slab took place beneath Eurasian continent in the Cretaceous (Saito, 1992).

A large area of late Early Cretaceous volcanic rocks occurs in northeast China (133–106 Ma; Xu et al., 2013b), including in the EHJP, the Great Xing'an Range, and faulted depression of the Songliao Basin. These volcanic rocks from different areas exhibit obvious compositional variations. In the EHJP, the representative strata, from north to south, include the Pikeshan, Peide, Dongshan, Jingouling, Ergulazi, and Guosong formations. Apart from several samples from the Jiamusi Massif, this group of volcanic rocks belongs to the

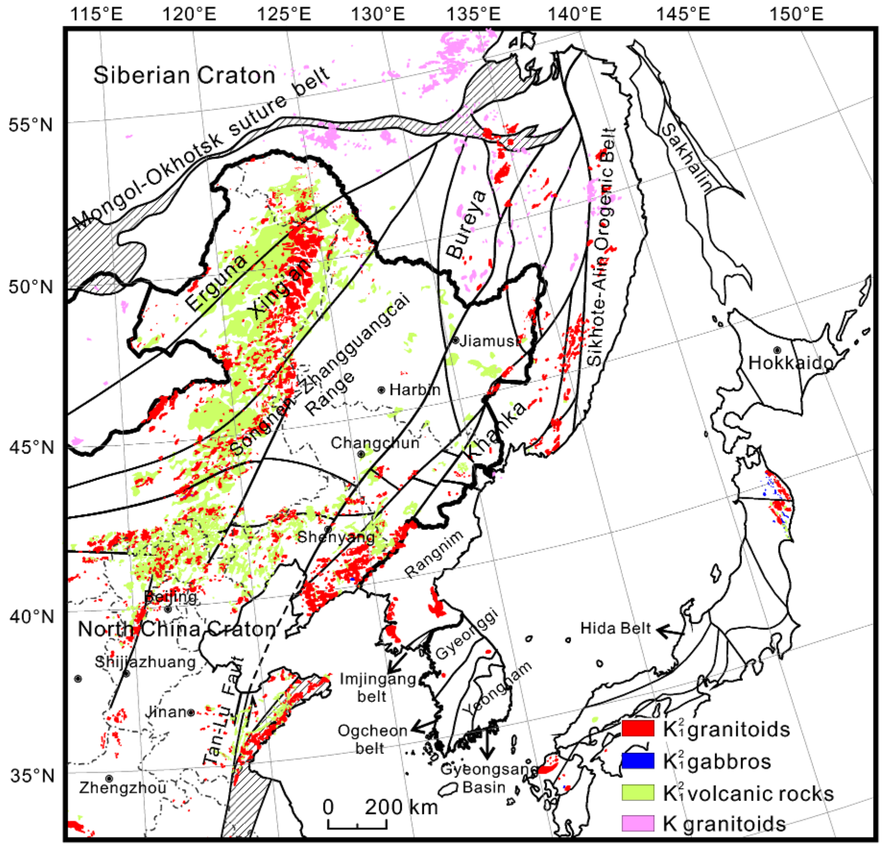


**Figure 18** (Color online) Distribution of late Early Cretaceous igneous rocks at the continental margin of Northeast Asia.

calc-alkaline series (Figure 19a and b; Yu et al., 2009), revealing that subduction of the Paleo-Pacific slab took place during the late Early Cretaceous. In contrast, coeval igneous rocks from the Songliao Basin and the Great Xing'an Range are bimodal volcanic rocks (Figure 19c and d; Wang F et al., 2006; Pei et al., 2008; Zhang J H et al., 2008, 2010) and alkali or alkali feldspar granites (Wu et al., 2011). From the continental margin to the intracontinental region, the increasing alkalinity of the coeval volcanic rocks suggests the westward subduction of the Paleo-Pacific slab. The early Early Cretaceous (147–130 Ma) tectonic exhumation of the Raohe accretionary complex further demonstrates that the westward subduction of the Paleo-Pacific slab beneath Eurasian continent occurred during the Early Cretaceous (Zhou et al., 2014; Wang Z H et al., 2015).

The late Early Cretaceous volcanic rocks in the NCC are found mainly in the eastern-central part of the craton. Most of the granites are A-type (Wu et al., 2005b; Sun and Yang, 2009), and syenites, monzonites, and trachytes belong to the alkaline series (Figure 19e and f), indicating their formation in an extensional environment. In addition, numerous coeval metamorphic core complexes are present in the eastern part of the NCC (Yang et al., 2007), including the Yunmengshan, Miyun, and Chengde metamorphic core complexes in northern Hebei Province (Davis et al., 2001), the Louzidian-Dachengzi metamorphic core complex in western Liaoning Province (133–118 Ma; Zhang et al., 2002), and the Xiaoqinling metamorphic core complex at the southern margin of the NCC (127–107 Ma). This shows that an extensional environment related to lithospheric thinning characterized the eastern-central part of the NCC during the late Early Cretaceous (Yang et al., 2008; Sun and Yang, 2009; Liu et al., 2012), and that the extension was related to the subduction of the Paleo-Pacific slab (Wu et al., 2005b; Zhu et al., 2012).

There were two magmatic hiatuses in the Mesozoic, during 170–115 and 155–115 Ma in the northern and southern Korean Peninsula, respectively (Kiminami and Imaoka, 2013). Thus, the late Early Cretaceous igneous rocks on the Korean Peninsula formed between 115 and 100 Ma, are restricted in extent, and are mainly granitoids as compared with coeval igneous rocks from other regions at the continental margin of Northeast Asia (Wu et al., 2007b; Zhai, 2016). In the southern Korean Peninsula, late Early Cretaceous igneous rocks are located mainly within pull-apart or extensional basins (Lee, 1999; Chough et al., 2000) and are A-type granites (Kim and Kim, 1997). Furthermore, coeval low-angle normal faults have been found on the northern Korean Peninsula. These lines of evidence suggest that the late Early Cretaceous igneous rocks of the Korean Peninsula formed in an extensional environment related to the sub-

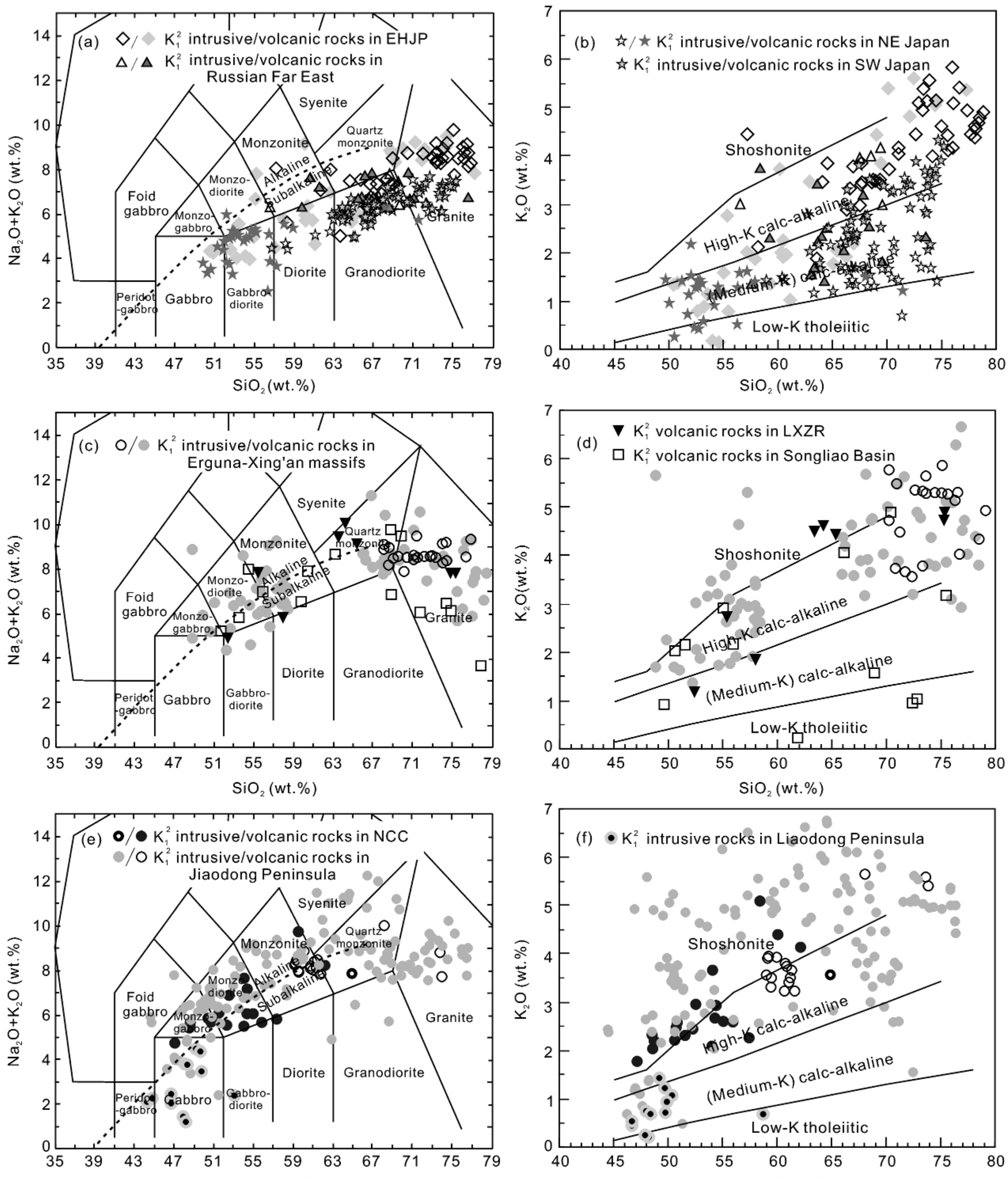


**Figure 19** $SiO_2$ versus ($Na_2O+K_2O$) and $SiO_2$ versus $K_2O$ diagrams for late Early Cretaceous igneous rocks at the continental margin of Northeast Asia. (a)–(b), EHJP, Russian Far East, and Japan; (c)–(d), Erguna-Xing'an massifs, LXZR, and Songliao Basin; (e)–(f), North China Craton, and Jiaodong and Liaodong peninsulas).

duction of the Paleo-Pacific slab (Wu et al., 2007b).

In summary, we conclude that the late Early Cretaceous igneous rocks at the continental margin of Northeast Asia were related to the subduction of the Paleo-Pacific slab beneath Eurasian continent. The igneous rocks in the Russian Far East, Japan, and EHJP of northeast China formed at an active continental margin, whereas coeval igneous rocks from the Songliao Basin, Great Xing'an Range, NCC, and Korean Peninsula formed in an intracontinental extensional environment related to lithospheric thinning resulting from the subduction of the Paleo-Pacific slab.

### 4.8 Late Cretaceous magmatism

Late Cretaceous igneous rocks are only present at the eastern continental margin of Northeast Asia, including the Russian Far East, southwest Japan, South Korea, northeast China, and eastern north China (Figure 20).

Late Cretaceous igneous rocks in the Russian Far East, including intermediate-silicic intrusive rocks (93–66 Ma; Appendixs 1 and 2; Jahn et al., 2015; Tang et al., 2016b) and volcanic rocks (80–67 Ma; Appendixs 1 and 2; Zhao et al., 2017), are located mainly in the eastern SAOB. Most of the Late Cretaceous igneous rocks are calc-alkaline (Figure 21a and b), indicating their formation in an active continental margin setting related to the subduction of the Paleo-Pacific slab.

Late Cretaceous magmatism was extensive in southwest Japan and includes a gabbro-diorite-granitoid association that formed at a convergent plate margin (Mao, 2013). Coeval volcanic rocks include the Abu rhyolites and dacites, and the Nohi rhyolites (Yuge et al., 1998; Sonehara and Harayama, 2007). These Late Cretaceous igneous rocks belong to the medium- and high-K calc-alkaline series (Figure 21a and b), implying their formation in an active continental margin setting.

Late Cretaceous igneous rocks on the southern Korean Peninsula are located mainly in the Gyeongsang Basin and Ogcheon belt. Late Cretaceous granitoids in the Gyeongsang Basin are part of the high-K calc-alkaline series, similar to those from continental margin arc settings (Mao, 2013), and the coeval mafic-intermediate-silicic volcanic rocks belong to the medium- and high-K calc-alkaline series (Appendix 2; Figure 21a and b), also typical of an active continental margin setting. Late Cretaceous granitoids in the Ogcheon belt are calc-alkaline and slightly to strongly peraluminous granites (Lee et al., 2010). As such, we conclude that Late Cretaceous igneous rocks of the southern Korean Peninsula formed in an active continental margin setting related to the subduction of the Paleo-Pacific slab.

Late Cretaceous igneous rocks in northeast China include calc-alkaline series volcanic rocks at the continental margin (Dongning-Hunchun area) and alkaline series igneous rocks in the intracontinental region (Figure 21a and b). The former includes andesites and dacites of the Suifenhe and Tuntianying formations (97–88 Ma; Ji et al., 2007; Xu et al., 2013a), and the latter comprises the Datun alkaline basalts near Changchun (92 Ma; Zhang et al., 2006) and shoshonite series monzogabbros in the Shuangyashan area (98 Ma; Zhang et al., 2009). From the continental margin to intracontinental region, the increasing alkalinity of these igneous rocks indicates that subduction of the Paleo-Pacific slab beneath Eurasian continent occurred during the Late Cretaceous.

Late Cretaceous volcanic rocks are present in the eastern NCC, including the Qujiatun alkaline basalts in southern Liaoning Province (82 Ma; Wang W et al., 2006), intermediate-silicic volcanic rocks of the Daxingzhuang Formation in western Liaoning Province (81 Ma; Bing et al., 2003), the Fuxin alkaline basalts in western Liaoning Province (92–85 Ma; Xu et al., 1999; Wang et al., 2002), the Laohutai alkaline basalts in Fushun City (70 Ma; Kuang et al., 2012), the Daxizhuang alkaline basalts on Jiaodong Peninsula (73 Ma; Yan et al., 2003), and trachyandesites and trachydacites of the Laiyang Basin (93–91 Ma; Guo et al., 2005). These Late Cretaceous volcanic rocks belong to the alkaline series (Figure 21a and b) and formed in a back-arc extensional environment related to the subduction of the Paleo-Pacific slab.

In summary, Late Cretaceous igneous rocks along the eastern continental margin of Northeast Asia are related to the subduction of the Paleo-Pacific slab. In the Late Cretaceous, the east of northeast China, Russian Far East, southwest Japan, and southern Korean Peninsula were parts of an active continental margin, whereas the intracontinental region of northeast China and eastern NCC was in a back-arc setting. From the late Early Cretaceous to Late Cretaceous, the extent of igneous rocks narrowed eastward (i.e., from the intracontinental region to the foreland), suggesting the eastward drift of Eurasian continent and rollback of the Paleo-Pacific subducted slab.

### 4.9 Paleogene magmatism

Small amounts of Paleogene igneous rocks are found in northeast China, the Russian Far East, Japan, and South Korea (Figure 22). The early Paleogene I-type granitoids in the Russian Far East belong to the high-K calc-alkaline series, have arc-like geochemical features, and formed in an active continental margin setting related to subduction of the (Paleo) Pacific slab (57–56 Ma; Jahn et al., 2015; Tang et al., 2016b). In addition, early Paleogene granodiorites in the Fujin area (Sanjiang Basin) of northeast China are high-K, calc-alkaline, I-type granitoids (Figure 23a and b), and have high Sr, low Y, and no Eu anomalies, similar to adakitic rocks derived by partial melting of lower continental crust (54 Ma; Wang Z H et al., 2016). The early Paleogene (58–55 Ma) andesites in the Yanbian area are geochemically similar to high-Mg adakites ($Mg^{\#}$=65–70; Sr=2013–2282 ppm; Y=10–11 ppm) and formed by magma mixing in an extensional environment (Guo et al., 2007). The early Paleogene volcanic rocks at the eastern and northern margins of the NCC include the Luanshishanzi alkaline basalts in eastern Liaoning Province (58 Ma; Wang W et al., 2006) and tholeiites of the Laohutai Formation in Fushun City (60 Ma;

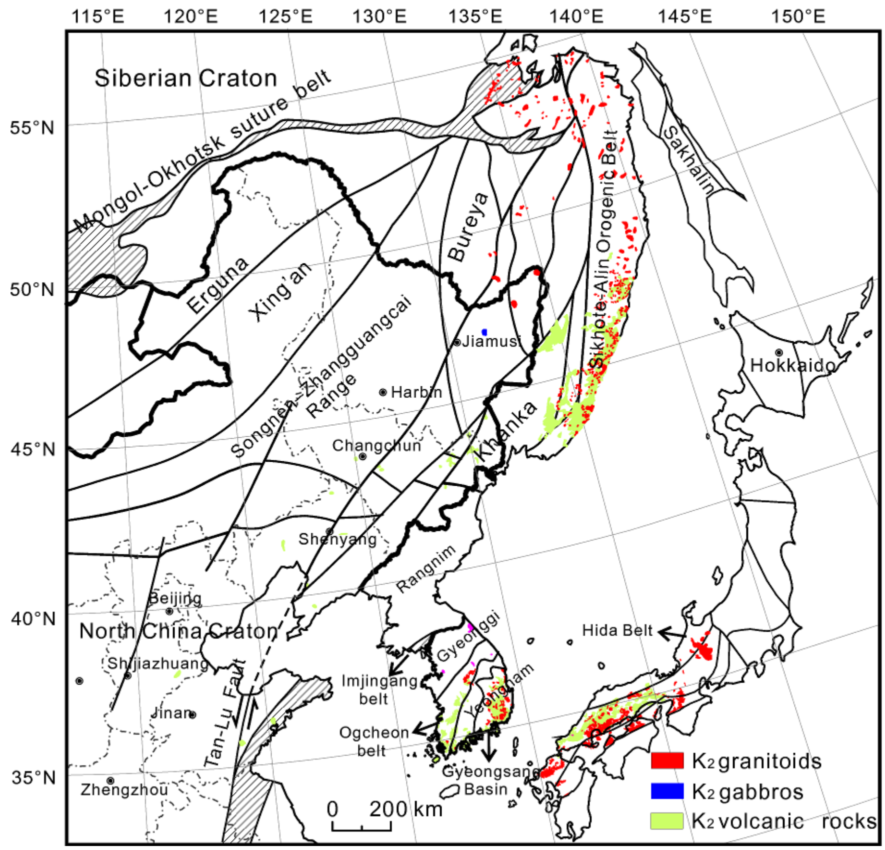


**Figure 20** (Color online) Distribution of Late Cretaceous igneous rocks at the continental margin of Northeast Asia.

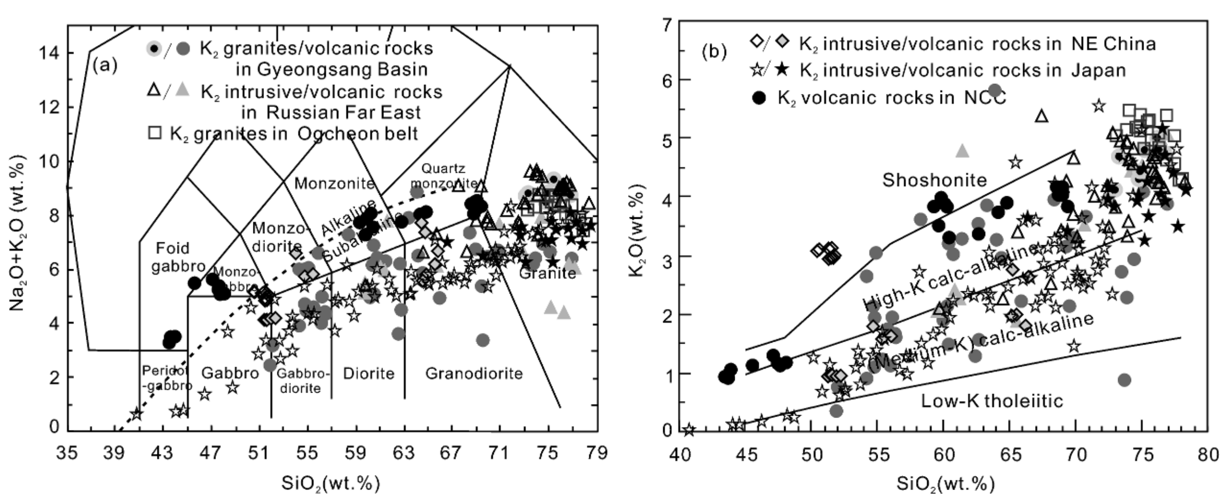

**Figure 21** (a) $SiO_2$ versus ($Na_2O+K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for Late Cretaceous igneous rocks at the continental margin of Northeast Asia.

Kuang et al., 2012). Early Paleogene (66–47 Ma) A-type granites in the Kyeongju region of the Gyeongsang Basin on the southern Korean Peninsula formed in an extensional environment (Kim and Kim, 1997). As such, we conclude that the early Paleogene igneous rocks from northeast China, eastern NCC, and southern Korean Peninsula formed in an extensional setting related to rollback of the (Paleo) Pacific subducted slab, whereas coeval arc-like magmatism only occurred in the Russian Far East.

Late Paleogene (46–39 Ma) igneous rocks are present mainly in the Russian Far East and are composed of a suite of mafic-intermediate-silicic volcanic rocks (Appendixs 1 and 2). The intermediate-silicic volcanic rocks are geochemically similar to adakites (Wu et al., 2017). In addition, minor late

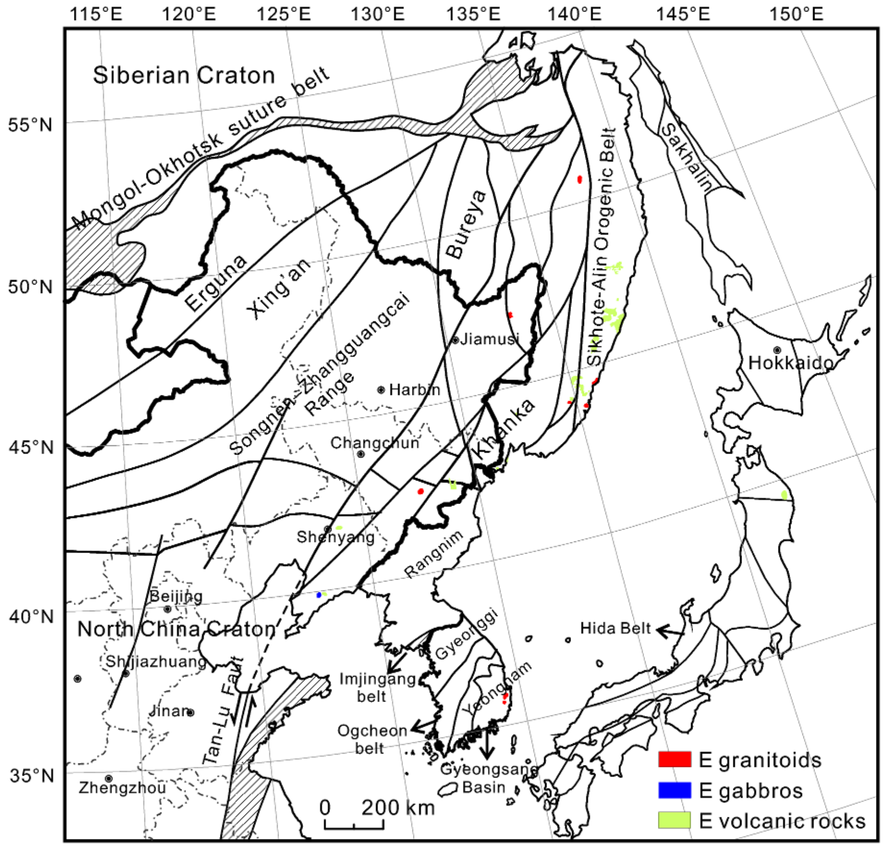


**Figure 22** (Color online) Distribution of Paleogene igneous rocks at the continental margin of Northeast Asia.

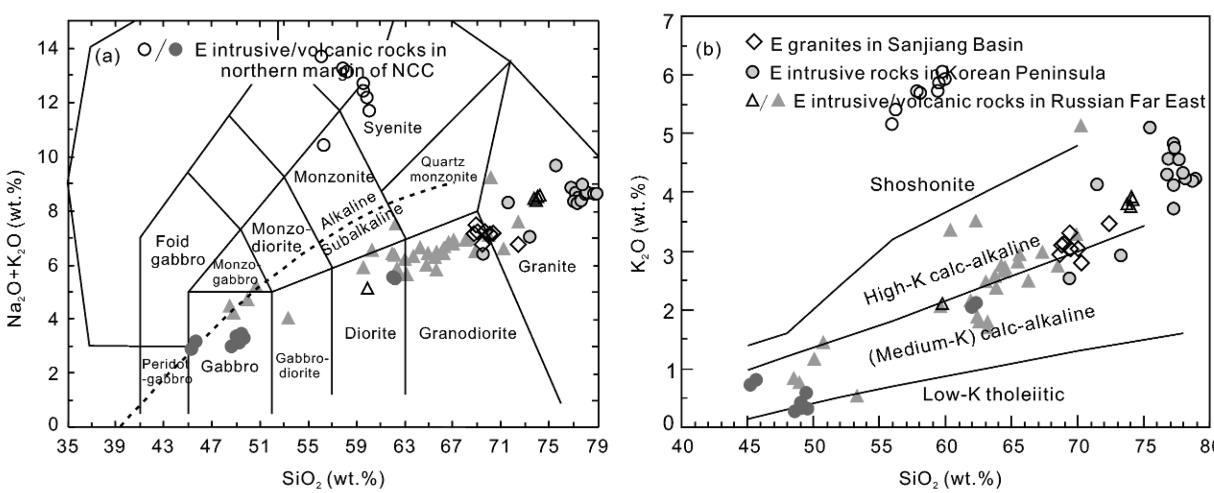


**Figure 23** (a) $SiO_2$ versus ($Na_2O+K_2O$) and (b) $SiO_2$ versus $K_2O$ diagrams for Paleogene igneous rocks at the continental margin of Northeast Asia.

Paleogene igneous rocks are found in northeast China, including the Yongsheng aegirine-nepheline syenite in the Huadian area (31 Ma; Yuan et al., 2003) and the Yinmawanshan gabbro in eastern Liaoning Province (32 Ma; Yuan et al., 2003). In the Kitakami region of northeast Japan, late Paleogene (44–38 Ma) high-Mg andesites were derived from the interaction of subducted slab-derived melts with mantle peridotite (Tsuchiya et al., 2005). Typical arc-like magmatism was absent in Northeast Asia during the late Paleogene. Therefore, we consider that late Paleogene igneous rocks in the east of northeast China, the Russian Far East, and northeast Japan formed in an extensional environment related to the eastward drift of Eurasian continent and further rollback of the (Paleo) Pacific subducted slab.

## 5. Mesozoic-Paleogene subduction history of the Paleo-Pacific slab beneath the continental margin of Northeast Asia

The timing of subduction initiation of the Paleo-Pacific slab beneath Eurasian continent has been controversial. At present, three hypotheses have been proposed: in the Permian (Ernst et al., 2007; Sun et al., 2015; Yang H et al., 2015), Triassic (Peng and Chen, 2007; Zhou et al., 2014; Wilde, 2015), and Early Jurassic (Xu et al., 2009, 2013a; Safonova and Santosh, 2014; Guo et al., 2015; Wang et al., 2017). The Mesozoic-Paleogene igneous rock associations at the continental margin of Northeast Asia and their spatial-temporal distribution provide important insights into the initial timing and history of Paleo-Pacific slab subduction as well as its spatial influence (Figure 24).

**Triassic:** Triassic igneous rocks in the Erguna-Xing'an massifs are mainly high-K, calc-alkaline, I-type granitoids in a NE-trending belt parallel to the Mongol-Okhotsk suture belt. These rocks formed in an active continental margin setting related to the southward subduction of the Mongol-Okhotsk oceanic slab. Triassic igneous rocks at the northern margin of the NCC are mainly adakitic and alkaline igneous rocks in an E-W trending belt along the Solonker-Xra Moron-Changchun-Yanji suture belt, which formed in orogenic and post-orogenic extensional settings related to the closure of the Paleo-Asian Ocean, respectively. Triassic igneous rocks of the Jiaodong-Liaodong-Korean peninsulas belong to the alkaline series and form a NE-trending belt parallel to the Sulu belt. These rocks formed in a post-orogenic extensional setting related to deep subduction and collision between the NCC and YB. Late Triassic igneous rocks in the EHJP and LXZR comprise bimodal volcanic rocks, A-type granites, and A-type rhyolites (Xu et al., 2013a; Wang F et al., 2015) that, along with the coeval passive continental margin sedimentary formations (Zhang et al., 2015), suggest an extensional environment that may have been related to either the southward subduction of the Mongol-Okhotsk oceanic slab or final closure of the Paleo-Asian Ocean. As such, we conclude that Triassic magmatism at the continental margin of Northeast Asia was not related to the circum-Pacific tectonic regime (i.e., the Paleo-Pacific slab was not subducted during the Triassic).

**Early Jurassic**: Early Jurassic calc-alkaline igneous rock associations with arc-like geochemical features in the EHJP-Korean Peninsula-Hida Belt imply their formation in an active continental margin setting, whereas the Early Jurassic bimodal igneous rocks and A-type granites in the LXZR formed in an extensional environment (Yu et al., 2012; Wang et al., 2017). The Early Jurassic igneous rocks show compositional differences from the continental margin to intracontinental region that reveal the Early Jurassic onset of subduction of the Paleo-Pacific slab beneath Eurasian continent (Xu et al., 2013b), which is also supported by the presence of Early Jurassic accretionary complexes at the eastern margin of Eurasian continent. In contrast, Early Jurassic calc-alkaline igneous rocks in the Erguna-Xing'an massifs form a NE-trending belt parallel to the Mongol-Okhotsk suture belt, and formed in an active continental margin setting related to the southward subduction of the Mongol-Okhotsk oceanic slab. The spatial influence of Paleo-Pacific slab subduction on northeast China extended to east of the Songliao Basin.

**Middle Jurassic to early Early Cretaceous**: In northeast China, Middle Jurassic to early Early Cretaceous igneous rocks are found mainly to the west of the Songliao Basin. Middle Jurassic igneous rocks are mainly adakitic rocks that formed in an orogenic setting related to the closure of the Mongol-Okhotsk Ocean. Late Jurassic to early Early Cretaceous magmatism was mainly of the alkaline series, bimodal igneous rocks, and A-type granites, which formed in a post-orogenic extensional setting related to the closure of the Mongol-Okhotsk Ocean. In contrast, no coeval magmatism took place in the EHJP, implying that a strike-slip tectonic regime existed between the continental margin of Northeast Asia and the Paleo-Pacific slab during the Middle Jurassic to early Early Cretaceous.

Middle Jurassic adakitic rocks at the northern margin of the NCC may have resulted from the far-field effects of the closure of the Mongol-Okhotsk Ocean. In contrast, the Late Jurassic to early Early Cretaceous igneous rocks in the NCC formed in an extensional environment related to either the collapse of thickened crust after the closure of the Mongol-Okhotsk Ocean or a strike-slip structure between the eastern margin of Eurasian continent and Paleo-Pacific slab.

Abundant Middle Jurassic adakitic rocks on the Korean Peninsula may have formed in an active continental margin setting related to the subduction of the Paleo-Pacific slab. The absence of Late Jurassic to early Early Cretaceous magmatism on the Korean Peninsula further indicates that subduction of the Paleo-Pacific slab did not take place at this time. As such, we conclude that a strike-slip regime existed between the continental margin of northeast China and the Paleo-Pacific slab during the Middle Jurassic to early Early Cretaceous. However, in the southern part of the Korean Peninsula, subduction of the Paleo-Pacific slab and a strike-slip structure existed during the Middle Jurassic and Late Jurassic to early Early Cretaceous, respectively.

**The late Early Cretaceous:** Voluminous late Early Cretaceous calc-alkaline volcanic rocks, I-type granitoids, and adakitic rocks are present in the EHJP, the Russian Far East, and Japan, related to the subduction of the Paleo-Pacific slab beneath Eurasian continent, as also indicated by the presence of Early Cretaceous accretionary complexes (Saito, 1992; Zyabrev and Matsuoka, 1999; Safonova and Santosh, 2014; Wang Z H et al., 2015; Zhou et al., 2015). In contrast, coeval

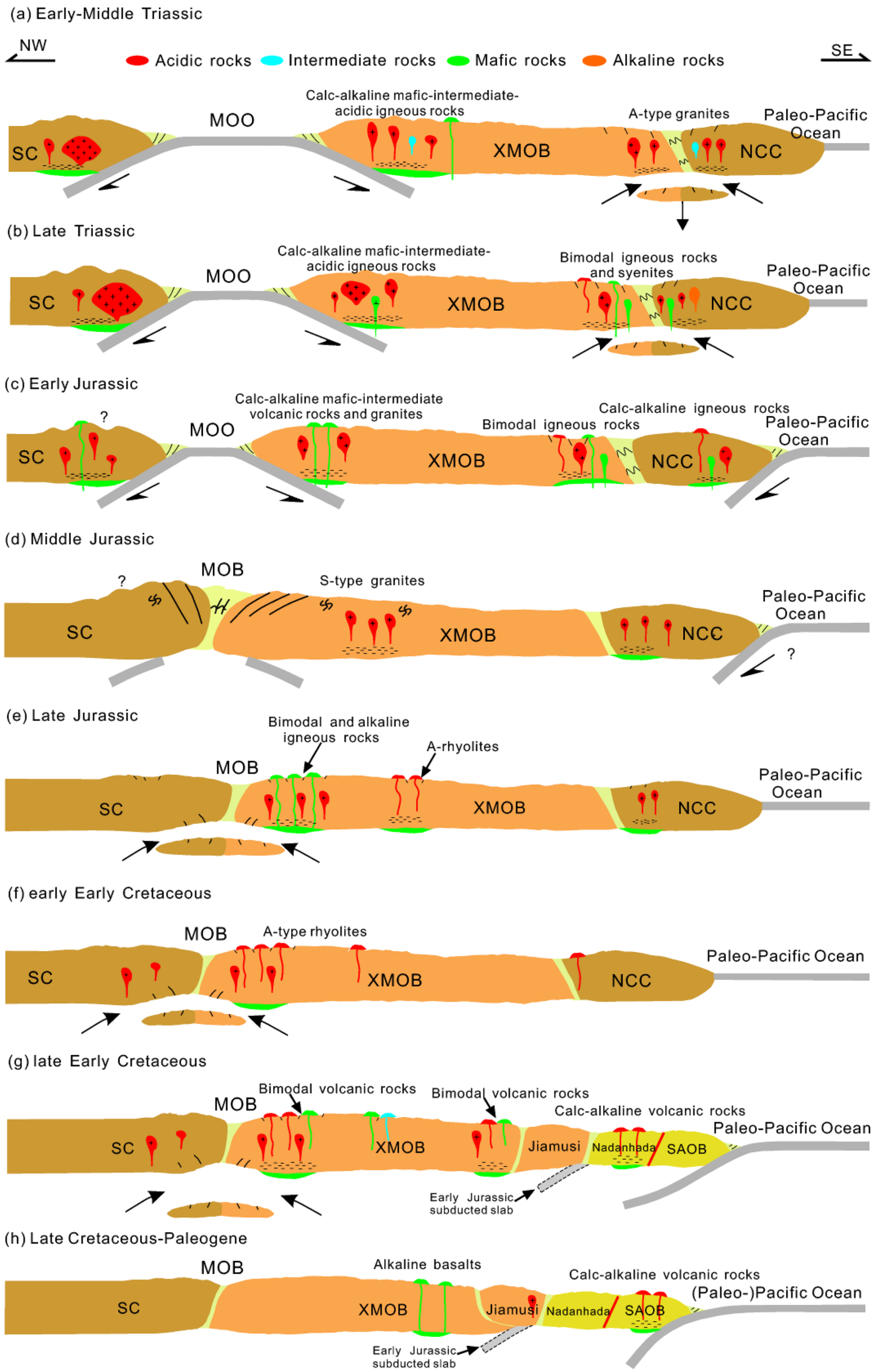


**Figure 24** Mesozoic tectonic evolution of the Paleo-Pacific slab (MOO=Mongol-Okhotsk Ocean; MOB=Mongol-Okhotsk suture belt; NCC=North China Craton; SAOB=Sikhote-Alin Orogenic Belt; SC=Siberia Craton; XMOB=Xing-Meng Orogenic Belt).

A-type granites, alkaline rocks, and metamorphic core complexes in the Songliao Basin, Great Xing'an Range, NCC, and Korean Peninsula indicate an intracontinental extensional environment related to the subduction of the

Paleo-Pacific slab. From continental margin to intracontinental region, the increasing alkalinity of the late Early Cretaceous volcanic rocks further indicates that low-angle, westward subduction of the Paleo-Pacific slab occurred during the late Early Cretaceous. The late Early Cretaceous magmatism mainly took place east of the Great Xing'an Range-Taihang Mountain-Wuling Mountain gravity gradient belt, implying that the spatial influence of the Paleo-Pacific slab subduction extended to this belt.

**Late Cretaceous to Paleogene:** Late Cretaceous igneous rocks are located along the continental margin of Northeast Asia. The eastern part of northeast China, the Russian Far East, southwest Japan, and the southern Korean Peninsula were an active continental margin during the Late Cretaceous. Paleogene arc-like magmatism only occurred in the Russian Far East, and no arc-like magmatism was produced in the late Paleogene. From the Late Cretaceous to Paleogene, the extent of magmatism reduced eastward, suggesting the eastward drift of Eurasian continent and further rollback of the Paleo-Pacific subducted slab.

## 6. Conclusions

Based on Mesozoic-Paleogene igneous rock associations at the continental margin of Northeast Asia and their spatial-temporal distribution, along with information from accretionary complexes, sedimentary formations, and regional unconformities, we draw the following conclusions.

(1) Mesozoic-Paleogene magmatism can be subdivided into nine episodes in the Early-Middle Triassic, Late Triassic, Early Jurassic, Middle Jurassic, Late Jurassic, early Early Cretaceous, late Early Cretaceous, Late Cretaceous, and Paleogene.

(2) Triassic magmatism was related to the closure of the Paleo-Asian Ocean and southward subduction of the Mongol-Okhotsk oceanic slab, but had no relationship with the Paleo-Pacific tectonic regime.

(3) The onset of subduction of the Paleo-Pacific slab beneath Eurasian continent took place in the Early Jurassic.

(4) A strike-slip regime existed between the eastern margin of Northeast Asia and the Paleo-Pacific slab in the Middle-Late Jurassic and early Early Cretaceous.

(5) Low-angle subduction of the Paleo-Pacific slab beneath Eurasian continent took place during the late Early Cretaceous. The effects of subduction of the Paleo-Pacific slab reached the Great Xing'an Range-Taihang Mountain-Wuling Mountain gravity gradient belt in the late Early Cretaceous.

(6) The eastward narrowing of the region of magmatism from the late Early Cretaceous to Paleogene suggests the eastward drift of Eurasian continent and rollback of the Paleo-Pacific subducted slab.

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