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Renewed profile of the Mesozoic magmatism in Korean Peninsula: Regional correlation and broader implication for cratonic destruction in the North China Craton

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Abstract Widespread Mesozoic magmatism occurs in the Korean Peninsula (KP). The status quo is poles apart between the northern and southern parts in characterizing its distribution and nature, with the nearly absence of any related information in North Korea. We have the opportunity to have conducted geological investigations in North Korea and South Korea during the past ten years through international cooperation programs. This led to the revelation of a number of granitoids and related volcanic rocks and thus facilitates the comparison with those in East China and Japan. Mesozoic granitoids in the KP can be divisible into three age groups: the Triassic group with a peak age of ~220 Ma, the Jurassic one of ~190–170 Ma and the late Early Cretaceous one of ~110 Ma. The Triassic intrusions include syenite, calc-alkaline to alkaline granite and minor kimberlite in the Pyeongnam Basin of North Korea. They have been considered to form in post-orogenic settings related to the Central Asian Orogenic Belt (CAOB) or the Dabie-Sulu Orogenic Belt (DSOB). The Jurassic granitoids constitute extensive occurrence in the KP and are termed as the Daebo-period magmatism. They correlate well with coeval counterparts in NE China encompassing the northeastern part of the North China Craton (NCC) and the eastern segment of the CAOB. They commonly consist of biotite or two-mica granites and granodiorites, with some containing small dark diorite enclaves. On one hand, Early Jurassic to early Middle Jurassic magmatic rocks are rare in most areas of the NCC, whilst Middle-Late Jurassic ones are not developed in the KP. On the other hand, both NCC and KP host abundant Cretaceous granites. However, the present data revealed contrasting age peaks, with ~130–125 Ma in the NCC and ~110–105 Ma in the KP. Cretaceous granites in the KP comprise the dominant biotite granites and a few amphibole granites. The former exhibit mildly fractionated REE patterns and zircon $\varepsilon_{Hf}(t)$ values from −15 to −25, whereas the latter feature strongly fractionated REE patterns and zircon $\varepsilon_{Hf}(t)$ values from −10 to −1. Both granites contain inherited zircons of ~1.8–1.9 or ~2.5 Ga. These geochemical characters testify to their derivation from re-melting distinct protoliths in ancient basement. Another Cretaceous magmatic sub-event has been entitled as the Gyeongsang volcanism, which is composed of bimodal calc-alkaline volcanic rocks of 94–55 Ma and granitic-hypabyssal granitic bodies of 72–70 Ma. Synthesizing the Mesozoic magmatic rocks across the KP, NCC and Japan can lead to the following highlights: (1) All Triassic granites in the NCC, KP and Japan have similar characteristics in petrology, chronology and geochemistry. Therefore, the NCC, KP and Japan tend to share the same tectonic setting during the Triassic, seemingly within the context of Indosinian orogensis. (2) Jurassic to earliest Cretaceous magmatic rocks in the NCC seem to define two episodes: episode A from 175 to 157 Ma and episode B from 157 to 135 Ma. Jurassic magmatic rocks in the KP span in age mainly from 190 to 170 Ma, whereas 160–135 Ma ones are rare. With the exception of ~197 Ma Funatsu granite, Jurassic magmatic rocks are absent in Japan. (3) Cretaceous granites in the KP have a peak age of ~110, ~20 Ma younger than those in the NCC, while Japan is exempt from ~130–100 Ma granites. (4) The spatial-temporal distribution and migratory characteristics of the

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Jurassic-Cretaceous magmatic rocks in Japan, KP, and NE China-North China indicate that the subduction of the Paleo-Pacific plate might not be operative before Late Cretaceous (~130–120 Ma). (5) Late Cretaceous magmatic rocks (~90–60 Ma) occur in the southwestern corner of the KP and also in Japan, coinciding with the metamorphic age of ~90–70 Ma in the Sanbagawa metamorphic belt of Japan. The magmatic-metamorphic rock associations and their spatial distribution demonstrate the affinities of sequentially subduction zone, island arc and back-arc basin from Japan to Korea, arguing for the Pacific plate subduction during Late Cretaceous. (6) This study raises another possibility that the Mesozoic cratonic destruction in the NCC, which mainly occurred during ~150–120 Ma, might not only be due to the subduction of the Paleo-Pacific Plate, but also owe much to the intraplate geodynamic forces triggered by other adjacent continental plates like the Eurasian and Indian plates.

Keywords Mesozoic granitoids, Korean Peninsula, Eastern China, Japan, Cratonic destruction

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1. Introduction

Mesozoic igneous rocks are widespread throughout NE Asia. Voluminous granitoid intrusions and related volcanic rocks constitute giant igneous provinces in the South China Block (SCB), eastern North China Craton (NCC), and NE China that encompasses the northeastern part of NCC and the eastern segment of the Central Asian Orogenic Belt (CAOB). By rough estimation, the Mesozoic granitoid rocks occupy about a half of rock outcrops in area, even two-thirds in NE China. In recent years, the study on Mesozoic igneous rocks has made great progress, especially across the eastern part of China. Huge amounts of data on mineralogy, petrology, geochemistry and chronology have been published (e.g. Wu et al., 2005a; Xu L J et al., 2013; Xu W L, 2013a, 2013b; Zhang X et al., 2008, 2014; Yang et al., 2007; Zhang S H et al., 2014). These advances have broadened the insights into the geotectonic evolution in NE Asia and spawned three important scientific issues. They are (1) Triassic magmatism and its bearing on Indosinian orogeny and Pangea supercontinent; (2) Jurassic-Cretaceous igneous rocks and their constraints on subcontinental lithospheric mantle (SCLM) or cratonic destruction; and (3) Granite petrogenesis and Phanerozoic continental crustal growth/reworking.

The Korean Peninsula (KP) is a key area for a thorough understanding of the geology in NE Asia. The study on the Mesozoic igneous rocks in South Korea has come a long way towards constraining important geological events (e.g. Chough et al., 2000; Ree et al., 2001; Oh et al., 2006; Chang and Zhao, 2012; Kim et al., 2008; Lee et al., 2003; Choi et al., 2005; Seo et al., 2010; Kim et al., 2011). The highlights include (1) if and/or how did the Dabie-Sulu Orogenic Belt (DSOB) extend eastward to the KP; (2) what is the geological significance of the Jurassic (Daebo-period) magmatism in the KP; (3) Cretaceous igneous rocks and their implication for linking the KP with the Pacific Plate. Given the absence of any information and data on Mesozoic igneous rocks in North Korea, however, the linkage is missing to fully understand the specific geology in the KP and general geotectonic framework in NE Asia. In this respect, we have the opportunity to have conducted geological investigations in North Korea and South Korea for the past ten years throughout executing individual international cooperation programs. The main cooperative partners from South Korea are Professor Chang-Wan Oh from the Chonbuk National University, Professor In-Chang Ryu from the Kyungpook National University and Professor Seon-Gyu Choi from the Korea University. The cooperative partners from North Korea are scientists from Institute of Geology, State Academy of Sciences of Democratic Republic of Korea. A lot of granitoid bodies and related volcanic rocks have been studied, thus facilitating the comparison with those in East China and Japan.

This paper aims to report new achievements and give a summary introduction of the Mesozoic granitoid bodies in the KP, with the key points including ages, types, distribution and nature of the granitoids in the KP, as well as and the comparison with granitoids in East China and Japan. Finally, we shall discuss their significance for constraining the cratonic destruction in the NCC. The detailed chronological and geochemical data and their interpretations are not specified here, which will be published soon in other papers of ours.

2. Geological background

East China, Korea and Japan are located in the easternmost part of Asia continent, constituting the circum-Pacific tectonic zone (Figure 1). During Late Mesozoic and Cenozoic, extension was widespread in East China and adjacent areas. Three rifting stages have been recognized (Ren et al., 2002), operating during the Late Jurassic-Early Cretaceous, Latest

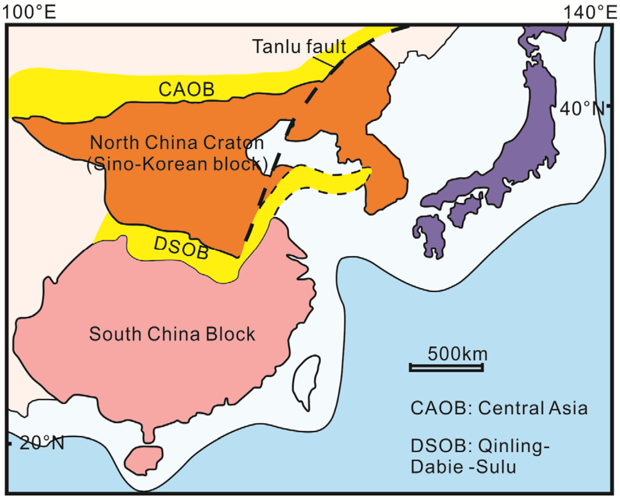


Figure 1 Sketch map of the tectonic elements in NE Asia.

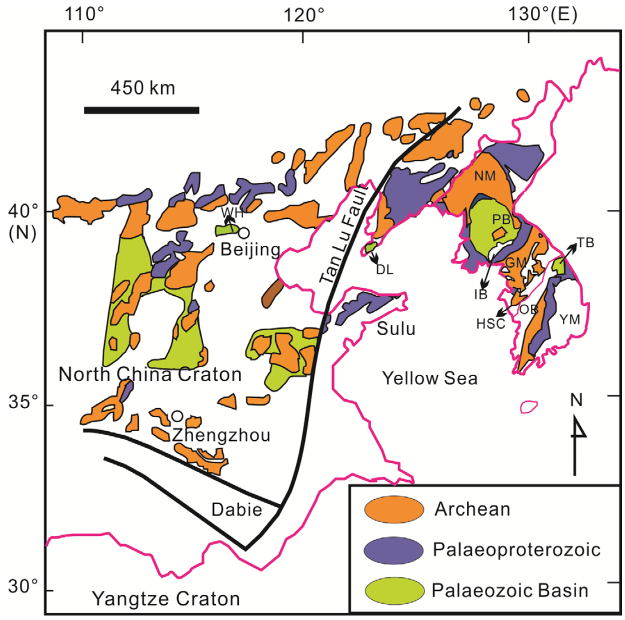


Figure 2 General map of the Sino-Korea craton. NM, Rangnim massif; GM, Gyeonggi massif; YM, Yeongnam massif; IB, Imjingang Belt; OB, Ogcheon Belt; HSC, Hongseon Complex; PB, Pyeongnam Basin; TB, Taebaeksan Basin; WH, Western Hill Basin; D, Dalian Basin.

Cretaceous-Paleogene and Neogene, respectively. The changes in convergence rates of India-Eurasia and Pacific-Eurasia may have resulted in NW-SE-trending extensional stress field dominating the rifting. Asthenospheric upwelling may have assisted the rifting process. The KP represents the denudation remnant of the deformed basement rocks and sedimentary successions as well as granitic intrusions and volcanic rocks, concealing a long history of basin formation and crustal deformation. It is an important tectonic link between East China and Japan.

In terms of geological and tectonic evolution, the KP has long been thought to be strongly tied with the mainland of China, with the NCC and KP collectively termed as the Sino-Korea Craton (Zhang, 1986; Qian, 1986; Lee, 1987; Paek, 1993). The tectonic correlation among Korea, China and Japan has also been discussed by some geologists (Oh et al., 2006; Ren et al., 2002; Mao et al., 2009), although such correlation suffered from the absence of relevant geological information and data in North Korea.

The KP comprises three major Precambrian massifs, i.e., Rangrim, Gyeonggi, and Yongnam massifs (Figure 2). The Rangrim and Gyeonggi massifs are separated by the Imjingang Fold Belt, while the Gyeonggi and Yongnam massifs are separated by the Ogcheon Fold Belt. Two main Paleozoic basins within the Rangnim and Gyeonggi massifs are the Phyongnam basin and Taebaeksan Basin that have a similar Paleozoic tectono-stratigraphy to the NCC. The Cretaceous Gyeongsang Basin in the southeastern corner of the KP contains gently eastward-dipping sedimentary successions (Chang, 1975; Lee, 1987; Paek, 1993; Choi, 1985; Ree et al., 1996) and probably formed in an island arc environment (Zhang Y B et al., 2012). A Tertiary sequence was deposited in the Pohang Basin in response to the back-arc opening in the Sea of Japan (East Sea named by the Korean people) (Chough et al., 1990; Yoon and Chough, 1995).

2.1 Precambrian units

The Rangnim Massif is located in the region to the north of the Imjingang Belt and to the south of the northern border of the KP. This massif can be divided into two sub-massifs, i.e. the Kwanmo sub-massif and Rangnim sub-massif on the basis of distinct rock associations (Choe, 2005). The Mushan Group and coeval granitic gneisses are distributed in the Kwanmo sub-massif and show typical characteristics of greenstone-granite terrain. The Mushan Group is composed of amphibolite/greenschist, banded iron formation (BIF) and mica schist/gneiss. They underwent amphibolite facies metamorphism. The Rangnim Complex and the Jungsan Complex developed in the Rangnim sub-massif, with high-grade regional metamorphism of up to granulite facies. The Rangnim Complex consists of composite orthogneisses and supracrustal rocks. The zircon U-Pb ages for cordierite-bearing gneiss from Huichon in the central part of the Rangnim Massif range from 2.5 to 2.58 Ga (Zhai M G et al., 2007). The supracrustal rocks are mainly composed of mica-quartzite, cordierite-bearing gneiss and hypersthene plagioclase gneiss. They underwent granulite facies metamorphism with partial melting. The zircon ages of the garnet sillimanite gneiss are 2160, 1980 and 1850 Ma (Paek, 1993; Choe, 2005). A porphyritic granite body intruding into the Jungsan Group has zircon U-Pb ages of ~1.83 and ~1.87 Ga (unpublished data). The Myohyanshan rapakivi batholith and gabbroic bodies in the north of the Phyongnam Basin are of anorogenic magmaticintrusions (Zhai M et al., 2007).

The Mesoproterozoic-Neoproterozoic sedimentary sequences have been termed as the Sangwon and Kuhyon systems. They were intruded by diabase sills at 890 Ma. LA-ICP-MS U-Pb dating on detrital zircons yielded ages of ca. 1000–2000 Ma with three peaks of 1000, 1200–1400 and 1800–1900 Ma.

The Gyeonggi Massif is situated between the Imjingang and Ogcheon belts, and consists mainly of Precambrian metamorphic rocks that are intruded by the Mesozoic granitoids. The Archean-Paleoproterozoic rocks are divided into basement complex (the Gyeonggi Complex) and supracrustal rocks (the Sosan Group) (Lee, 1987; Paek, 1993; Lee and Cho, 1995; Sagong et al., 2003). The Gyeonggi Complex consists of granitic and tonalitic gneiss, banded gneiss, migmatite, mafic granulite, BIF, amphibolite and metasedimentary rocks that include garnet sillimanite gneiss, graphite gneiss, marble, and fine-grained biotite gneiss (khondalite series rocks). A few garnet pyroxene granulite and garnet amphibolite are exposed along with metasedimentary rocks. The zircon ages of the metasedimentary rocks and hypersthene-bearing granites and Sm-Nd isochron ages of garnet granulites are ~1.80–2.0 Ga and 2.1–2.3 Ga, representing magmatic and metamorphic events, respectively (Lee et al., 1997; Kim et al., 1999; Sagong et al., 2003). Zhai et al. (2005) dated a rapakivi batholith in the northeastern Gyeonggi Massif at 1839±10 Ma using SHRIMP zircon U-Pb method.

The Yeongnam Massif is bounded by the Ogcheon Belt in the northwest and covered by thick Cretaceous sedimentary-volcanic rocks in the southeast. This massif is divided into the Sobaekson Complex and the Taebaeksan Group (or Yulri or Honam Group). All of them underwent poly-phase metamorphism and partly retrograded to greenschist facies (Lee, 1987; Paek, 1993; Kim and Cho, 2003). The Sobaekson Complex includes banded tonalitic gneiss, porphyroblastic granitic gneiss, migmatitic gneiss and granite. They yielded ages of 2.9–2.7, 2.59–2.47 and 1.83–1.91 Ga (Sagong et al., 2003; Zhai M G et al., 2007). The Taebaeksan-Group metasedimentary rocks include interbedded pelitic and psammitic-pelitic schists with penetrative foliations subparallel to lithologic layers (khondalite-series rocks). Their metamorphism is of up to granulite facies. A garnet leucogranite yielded a Pb-Pb isochron age of 1862 Ma and a Sm-Nd isochron age of 1926 Ma (Kim and Cho, 2003). Ilmenite-bearing anorthosite bodies occur in the southwestern Yeongnam Massif and yielded a Sm-Nd age of ca. 1792 Ma (Park et al., 2001).

The above statements indicate that the three massifs in the KP probably have the same basement rocks. The main rock associations therein exhibited the traits of multi-stage crustal growth and reworking and consistently witnessed two important metamorphic events of ~2.5 Ga and ~1.9–1.8 Ga, corresponding to those in the NCC (Zhai M G et al., 2007; Zhai and Santosh, 2011). Therefore, we propose that the Rangnim, Gyeonggi and Yeongnam massifs most likely have a united Precambrian basement as in the NCC. The old units in the KP and North China collectively constitute the nuclei of the Sino-Korea Craton.

2.2 Paleozoic sediments

The Paleozoic Era in the KP is largely represented by the sedimentary rocks in two sedimentary basins, the Taebaeksan Basin in the central-eastern part and the Pyeongnam Basin in the central-northern part. The Paleozoic sequence consists of lower Paleozoic (Cambrian-Middle Ordovician) and upper Paleozoic (Late Carboniferous-Early Triassic) strata. An unconformity exists between two strata, representing a sedimentary gap of more than 100 Ma (Lee and Lee, 2003).

The Early Paleozoic sedimentary rocks are named as the Joseon Supergroup in the Taebaeksan Basin and the Hwagjiu Supergroup in the Pyeongnam Basin. They are exclusively of marine origin and consist of carbonate rocks with subordinate siliciclastic rocks. The general stratigraphic successions of two supergroups are strikingly similar.

The Middle Ordovician strata of the Taebaeksan and Pyeongnam Basins are unconformably overlain by or in fault contact with Middle Carboniferous strata. However, minor suspicious Devonian sedimentary rocks has been reported to occur in the northeastern edge of the Pyeongnam Basin (Paek, 1993).

The Middle Carboniferous-Early Triassic successions are well developed in the KP and termed as the Pyeongan Supergroup (or Daedong System). The sedimentation initiated in a marginal marine environment in Late Carboniferous, and was followed by a thick non-marine sandstone-shale succession during the Permian and Triassic.

The coal measures mainly appeared in the Late Carboniferous and Early Permian strata. The largest and most important coalfield in North Korea is located in the Pyeongnam Basin. The largest coalfield in South Korea is the Samcheok coalfield in the Taebaeksan Basin. The Early Permian strata contain coal-bearing cyclothems with pebble-bearing sandstone, shale and limestone.

In the NCC, the Paleozoic coal-bearing strata are Early-Middle Carboniferous Benxi and Taiyuan groups and Early Permian Shanxi and Xiahezi groups. The Benxi and Taiyuan groups are composed of sandstone and limestone with variable coal measures. The Shanxi and Xiahezi groups comprise various grained sandstone, shale, coal-seam and shale, showing multi-cycle deposits from shore to platform. Therefore, the coal-bearing sedimentary sequences in the KP and the NCC are similar.

2.3 Imjingang and Ogcheon belts

At present, the nature and tectonic significance of the Imjingang and Ogcheon belts remain controversial (e.g. Paek and Rim, 2005; Oh and Kusky, 2007). The Imjingang Belt lies between the Rangnim and Gyeonggi massifs and is a

~E-W trending fold and thrust belt characterized by the presence of the Devonian-Carboniferous Imjin Group with >2000 m thickness. The Imjin Group is surrounded by the Precambrian basement rocks in the south, east, west and northeast parts, and by the Paleozoic sediments in the north. The rocks near the margin of the Imjingang Belt commonly suffered strong deformation and mylonitization. The metamorphic grade of the Imjin Group increases from north to south and ranges from un-metamorphosed, sericite, garnet, staurolite to kyanite zones, defining a Barrovian-type facies series. The Imjingang Belt has been suggested to be a possible extension of the Sulu Collisional Belt in the KP (Lee and Cho, 1995; Ree et al., 1996; Cho, 2001). However, two North Korean geologists, Paek and Rim (2005) depicted the Imjingang Belt as a Middle Devonian to Early Carboniferous rift zone, with 15–30 km in width and several tens of km in length. They maintained that the belt did not run across the KP in the east, but belongs to the same continental block as the Rangnim and Gyeonggi massifs.

The Ogcheon Belt between the Gyeonggi and Yeongnam massifs is an east-northeast-trending fold belt. The Honam shear faults cut through the belt and has been considered to be its possible boundaries (Cluzel, 1992), although the Honam faults mainly recorded the Jurassic ages of dextral deformation corresponding to the Daebo event (Chough et al., 2000). The Ogcheon belt consists of the Neoproterozoic greenschist-amphibolite facies metamorphic rocks, namely the Ogcheon Group, and minor metamorphic rocks of uncertain ages. The Ogcheon belt is dominated by a stack of NE-trending nappes along its length (Cluzel, 1992; Kim, 1996; Fitches and Zhu, 2006). Oh (2006) correlated it with the Nanhua Basin and further with the Paleozoic orogenic events in the SCB and Japan. Chang and Park (2005) suggested that an early Triassic rift (the Hwanggangrni rift) should be separated from the Ogcheon Basin. The early Triassic rift-filling was initiated with the rapid deposition of the "pebble"-bearing phyllitic rocks on the Proterozoic rocks of ~750 Ma. Our investigation reveals that the traditional Ogcheon belt does not run through the KP from southwest to northeast. Instead, the Taebaeksan Basin occupies the eastern margin of the central KP.

2.4 Hongseong Complex

The eclogite-bearing Hongseong Complex (HSC) is located in the southwestern part of the Gyeonggi Massif and has been separated from the Gyeonggi complex (Guo et al., 2004; Oh et al., 2005). These eclogitic rocks are commonly associated with serpentinites, and occur as lenses in granitic gneiss. An eclogite sample yielded a metamorphic age of ~230 Ma and a protolith age of ~880 Ma. Its hosting granitic gneiss yielded an age of ca. 820 Ma. All these age records indicate that the Sulu Belt extends to the KP (Oh et al., 2006; Zhai M G et al., 2007; Oh and Kusky, 2007; Kim et al., 2006).

A main NNE-striking fault cuts through the Hongseong region, and separates the area into two parts that show a big difference in rock association, metamorphism and isotopic ages. The eastern part is composed of granitic gneiss and paragneiss metamorphosed to granulite facies. Conventional U-Pb zircon analyses of the paragneiss yielded an upper-intercept age of 1863+/−9 Ma corresponding to a major metamorphic event in the Gyeonggi Massif and the NCC (Kim et al., 2006). SHRIMP zircon U-Pb analyses on the granitic gneiss and paragneiss resulted in two age groups of 1.8–1.9 Ga and 2.4–2.6 Ga (Zhai M G et al., 2007; Kim and Cho, 2002). The western part is mainly composed of granitic gneiss with lenses of metabasite (retrograded eclogite) and ultramafic rocks. These lenses are tectonically emplaced in the granitic gneiss with a thin and strong ductile deformation contact zone. The granitic gneiss yielded ages of ca. 812 Ma and ca. 822 Ma for cores and ~235 Ma for rims using SHRIMP zircon U-Pb method (Cho, 2001). Zhai M G et al. (2007) have emphasized the eclogite-bearing complex in the western part of the Hongseong region as the HSC. The HSC is similar to the metamorphic complex in the Sulu UHP Belt in petrology, metamorphism and isotopic chronology.

Oh (2006) and Oh and Kusky et al. (2007) suggested that the HSC extends into the Odesan area, implying that the Gyeonggi massif might be subdivided into northern and southern Gyeonggi massifs. The northern Gyeonggi massif can be correlated with the North China block (NCB), while the southern Gyeonggi massif, Okcheon metamorphic belt, and Yeongnam massif can be related to the SCB. However, Zhai M G et al. (2007) maintained the uncertainty of how the HSC extends. With the eclogite-bearing complex outcropping only in the Hongseong area, they proposed a crustal detachment-thrust model. The model envisages that the collisional suture between the NCB and SCB might run along the Western Marginal Fault Zone of the KP, as supported by the geophysical study (Hao et al., 2002, 2007). The lower part of the UHP metamorphosed lithosphere of the SCB subducted eastwardly under the KP and its most part is not uplifted to the surface, with only modest part occurring in the Hongseong area.

2.5 Mesozoic magmatic rocks

Mesozoic granitoids and related igneous rocks are widely distributed in the northern and southern parts of the KP (Kim, 1996; Oh et al., 2006; Ishihara, 2007; Williams et al., 2009; Seo et al., 2010; Yi et al., 2012). They constitute unbroken expansion of the magmatic provinces in East China and Far East Russia.

We have investigated hundreds of Mesozoic intrusive bodies in the KP and collected a large number of samples for dating and geochemical analyses. Figure 3 shows spatial distribution of the Phanerozoic granitoid bodies in the KP, with all zircon U-Pb ages therein from our study. Measure-

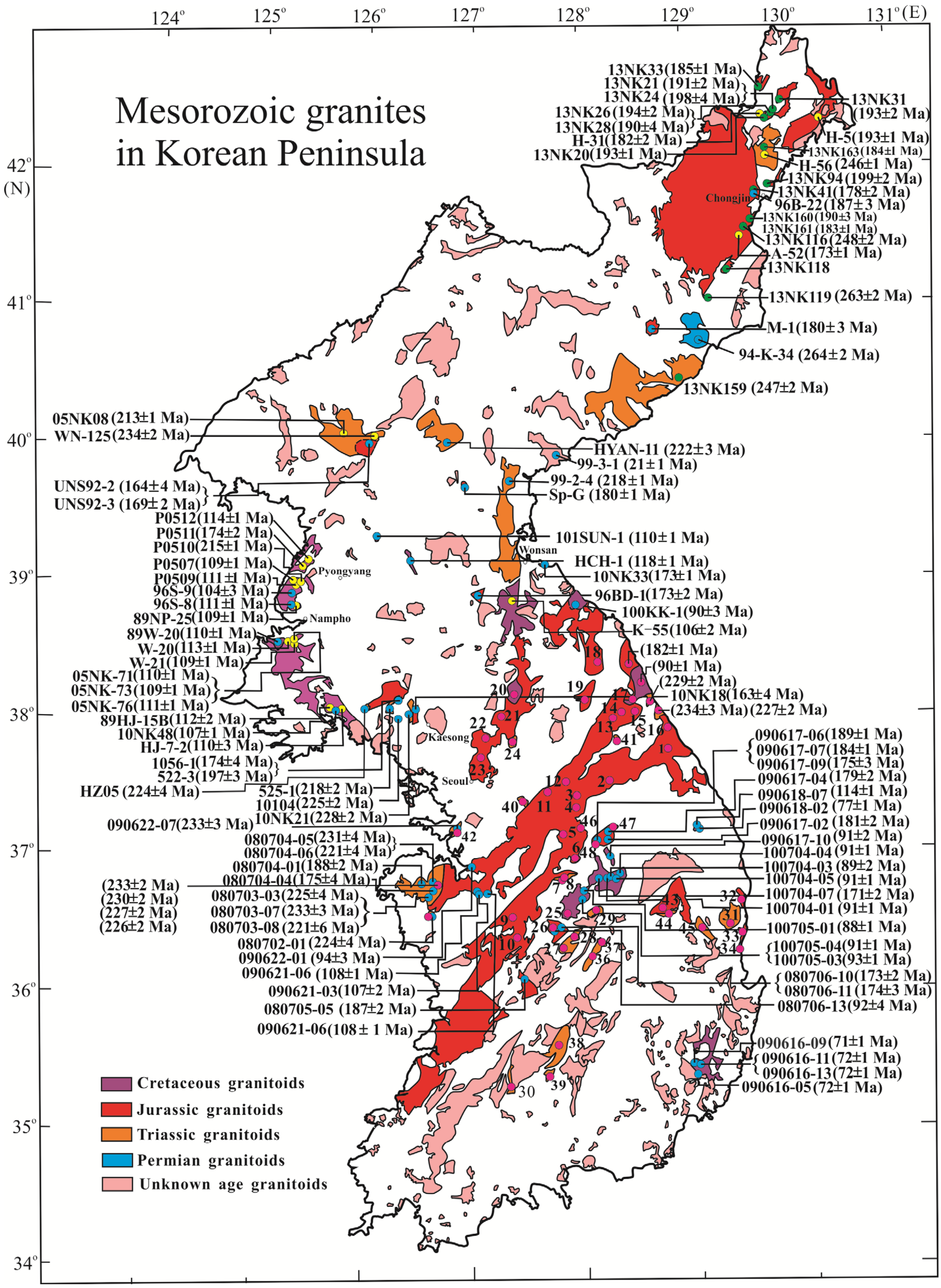


Figure 3 Sketch map for the Mesozoic granitoid bodies in the KP.

ments of U, Th and Pb on zircons were conducted using the Cameca IMS-1280 ion microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) and SHRIMP II instrument at Beijing SHRIMP Centre. The zircon Hf isotopic composition was analyzed by means of LA-ICPMS at IGGCAS. Except for several ages of 252–264 Ma, all data concentrated on the Mesozoic era. These Mesozoic granites can be classified into three age groups, i.e., Triassic granites with a peak age of ~220 Ma, Jurassic granites of ~170–180 Ma and Cretaceous granites of ~110 Ma. The Triassic bodies include syenite, calc-alkaline and alkali granites, with minor kimberlite in the Pyeongnam Basin of North Korea. The Triassic intrusions have been considered to form in post-orogenic settings affiliated with the CAOB or the DSOB by different researchers. The Jurassic granites are the most voluminous in the KP, termed as the Daebo-period magmatism. These granites are comparable to the Jurassic counterparts in NE China. They are commonly biotite or two mica granites and granidiorites, with some containing small dark diorite enclaves. Although abundant Cretaceous granites in the KP appear to resemble those in the NCC, our data revealed an obvious difference, i.e. the peak ages of ~130–125 Ma in the NCC and ~110–105 Ma in the KP. Two episodes of Cretaceous granites in the NCC and KP commonly contain inherited zircons of ~1.8–1.9 Ga or ~2.5 Ga, indicating their similar derivation from re-melting of ancient basements. A Late Cretaceous magmatic sub-event is designated as the Gyeongsang-period magmatism, as represented by the bimodal volcanic rocks of 94 to 55 Ma and the granitic-hypabyssal granitic bodies of 72–70 Ma.

3. Triassic magmatic rocks

3.1 Triassic granitoids and related rocks in the KP

Figure 4 shows the distribution of the granites dated by this study. The samples from Changang-Do, Hamgyongnam-Do and northern Pyongannam-Do in the Rangnim Massif are relatively few, since geological field works therein are restricted for military concerns. In general, the exposure of Triassic granitoid rocks shows an areal distribution. The zircon U-Pb ages range from 213 to 253 Ma, with a peak at ~220–230 Ma.

Triassic magmatic rocks are mainly of three types, including high-K calk-alkaline granites, syenites and a few kimberlites. In addition, there occur some small gabbroic and dioritic bodies. High-K calk-alkaline granites are widely distributed in three massifs and two fold belts, whereas syenites and kimberlites mainly occur in the Precambrian rocks in the southern part of the Rangnim Massif.

For these rocks, the related geochronological and geochemical data and their interpretations can refer to a few publications (e.g. Kim et al., 2011; Yi et al., 2014; Cho et al., 2008; Sagong et al., 2005). As demonstrated by their general geochemical features in Figure 5, most granitoids can diverge into calk-alkaline granite, quartz monzonite and quartz syenite. The analyzed samples are mostly subalkaline granites except for several dioritic samples. They show transitional character from metaluminous to peraluminous. Gabbroic samples from the Yangyang area in the Gyeonggi Massif and the Ogcheon Belt plot into the fields of hornblende gabbro or plagioclase-bearing hornblendite, and their U-Pb ages range from 226 to 231 Ma (Zhai M G et al., 2007; Williams et al., 2009).

The Hongseong (Gwangcheon) intrusions in the HSC have been widely documented due to the discovery of the Mesozoic eclogite outcrops therein (Seo et al., 2010; Oh et al., 2006; Kim et al., 2008). The rocks include mangerites and biotite granites. The mangerites consist mainly of K-feldspar (20–30%), orthopyroxene (1–10%), clinopyroxene (15–25%), plagioclase (10–25%), biotite (10–15%) and quartz (10–5%); accessory minerals include apatite, zircon, rutile, magnetite and ilmenite. Their SiO_2 contents range from 60% to 65%, plotting in a transitional field of syenite-granodiorite (Figure 6b) and having high Sr-Ba abundance (Figure 6a and d). Their chondrite-normalized REE patterns show distinct depletion in HREE with no or slight positive Eu anomalies. Biotite granites have SiO_2 of 67–78% and high K-contents, falling in the alkaline granite field in Figure 6b. They are relatively depleted in Sr and Ba (Figure 6a and f) and exhibit significant negative Eu anomalies.

Our samples of the Hongseong mangerites (080703-3 and 080702-01) yield zircon U-Pb ages of 225±4 Ma and 224±2 Ma. The biotite granite samples (080706-08 and 080707-08) give zircon U-Pb ages of 231±3 Ma and 231±2 Ma. Willianms et al. (2009) reported that the Hongseong granites in the western Gyeonggi Massif have initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7100 to 0.7140 and strongly negative $\varepsilon_{Nd}(t)$ values from −13.9 to −10.4. The Hongseong mangerites have slightly lower initial $^{87}Sr/^{86}Sr$ (0.7091) and $\varepsilon_{Nd}(t)$ (−14.1) values. The Nd model ages (T_{DM}) of the Hongseong intrusive samples range from 1.74 to 1.59 Ga. Figure 7 shows that most samples have negative $\varepsilon_{Hf}(t)$ values, with a range of −18 to −5 for mangerites and a main range of −24 to −18 for alkaline granites. The Nd-Sr-Hf isotopic compositions indicate that the Hongseong intrusions may have derived from re-melting of old lower crust.

Late Triassic syenite plutons in North Korea are known as the Phyonggang Complex in the Rangnim Massif (e.g. Paek, Gap & Jon, 1996). Two of the plutons occur in the northern Rangnim Massif, with a recently documented U-Pb zircon LA-ICPMS age of 234±2 Ma (the Unsan Pluton: Wu et al., 2007). More than ten syenite plutons and some satellite bodies have been revealed to distribute along the boundary to South Korea and termed the Tokdal Complex. The complex is unique in its incorporation of early pyroxenite cumulate in the clinopyroxene/amphibole/biotite/ nepheline-bearing syenite main body. From east to west, the syenite plutons change in composition from sodic to potassic. The fact that this pluton is characterized by rock types varying from pyroxenite, through gabbro, to clinopyroxene syenite with systematically changing mineral assemblages and compositions also suggests that they are differentiates through the same magmatic process, in contrast to extraneous origin for the pyroxenite. The detailed study has been given by Peng et al. (2008). A SHRIMP U-Pb zir-

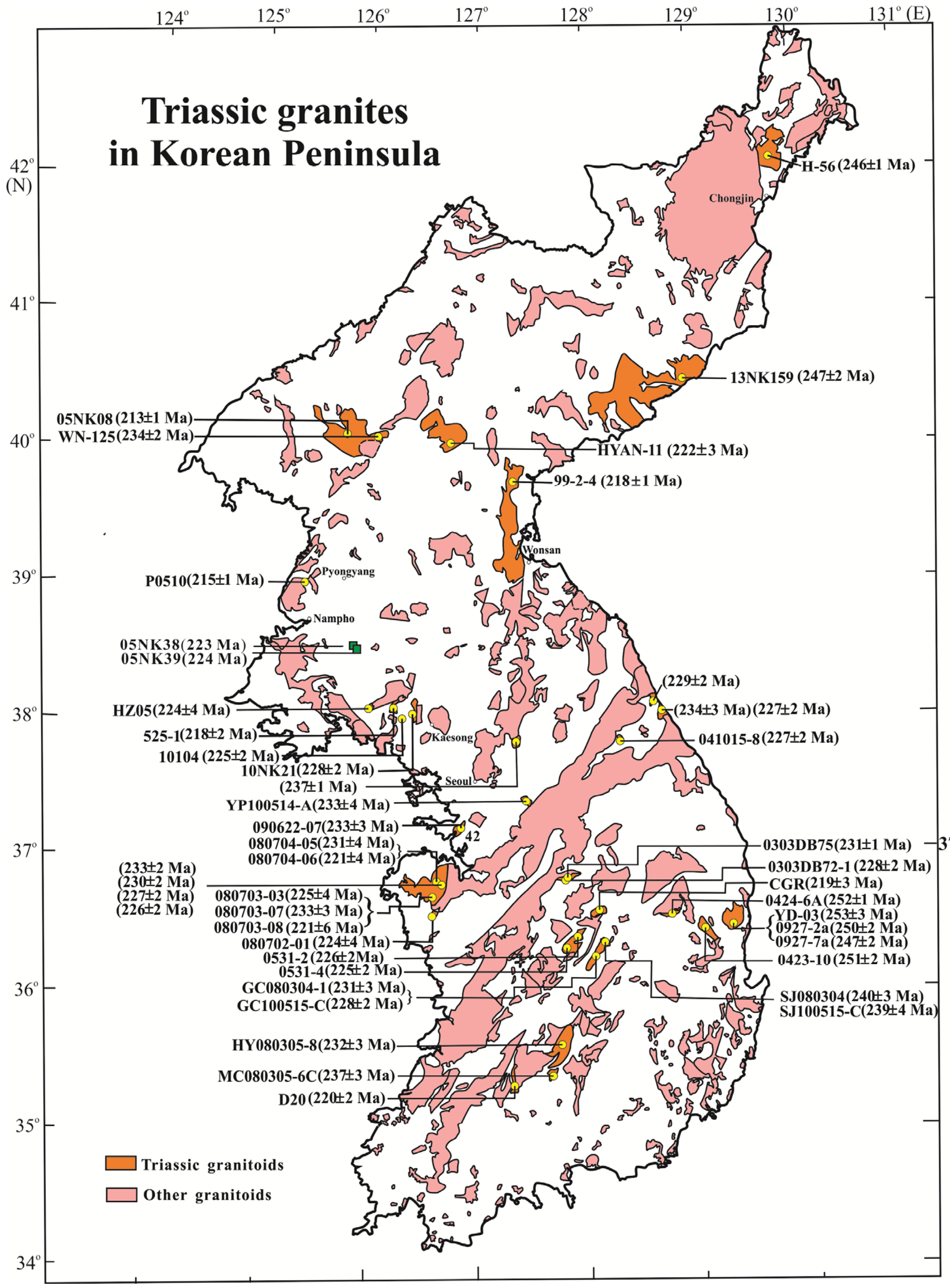


Figure 4 Sketch map for the Triassic granitoid bodies in the KP. Green square stands for kimberlite occurrence.

con age of 224±4 Ma was obtained from a biotite syenite sample. Clinopyroxene in pyroxenites is zoned, with either phlogopite and apatite inclusion or ilmenite and magnetite exsolution, and may have resulted from crystallization at high pressure in an active continental margin arc environment followed by ascent and decompression. The pyroxenite and syenite are enriched in light REE and large ion lithophile elements (LILEs), but strongly depleted in high field-strength elements (HFSEs), with $^{87}Sr/^{86}Sr_t$ values of ~ 0.7115 and $\varepsilon_{Nd}(t)$ values of −14 to −20. The Tokdal Complex could have originated from an enriched lithospheric mantle and undergone assimilation of juvenile materials during differentiation.

Several outcrops of kimberlites occur in the southwestern Rangnim Massif. The country rocks are the sedimentary rocks of Proterozoic Sangwon System. Abundant peridotite xenoliths are found in kimberlites. The host kimberlites contain phlogopite that yields a Rb-Sr isochron age of 223±7 Ma (Yang et al., 2010). The kimberlites have geochemical features similar to Group II kimberlites of Smith

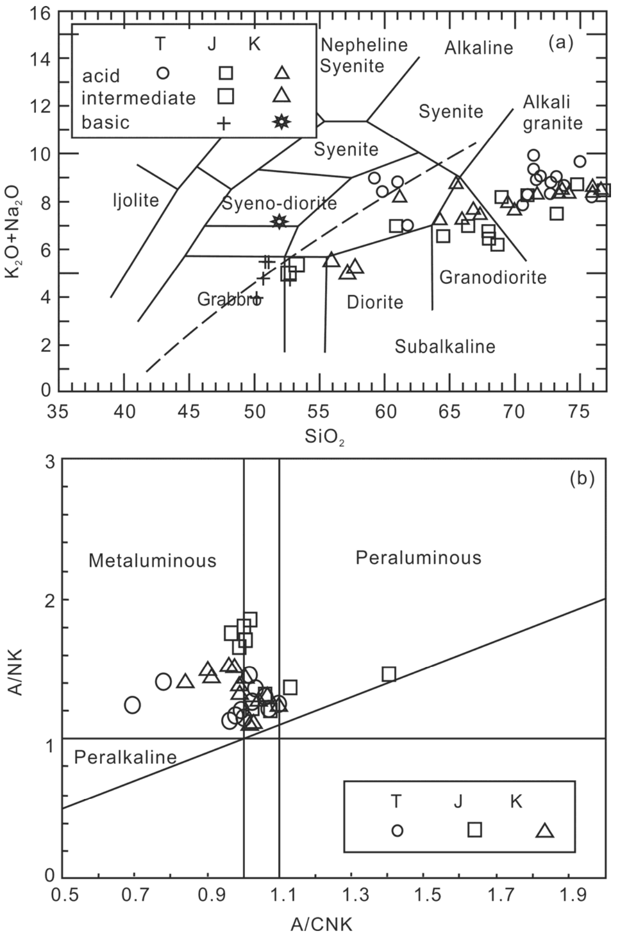


Figure 5 Diagrams of (Na_2O+K_2O)-SiO_2 (a) and A/NK-A/CNK (b) for the Mesozoic intrusive bodies. T, Triassic; J, Jurassic; K, Cretaceous.

(1983), with high initial $^{87}Sr/^{86}Sr$ (~0.7131) and negative $\varepsilon_{Nd}(t)$ (~–20) and $\varepsilon_{Hf}(t)$ (~–26). They are enriched in LILEs and LREEs with $(La/Yb)_{CN}$ ratios of 39.5–41.7, and depleted in HFSEs, indicating that their parental magmas were derived from small-degree partial melting of ancient lithospheric mantle.

Yang et al. (2010) reported the results of mantle xenoliths in the kimberlites. The mantle xenoliths are all spinel peridotites. They are generally large (to 30 cm across in largest dimension) and characterized by varying degrees of serpentinization. They contain clinopyroxenes and orthopyroxenes with relatively homogeneous CaO and equilibration temperatures of 991–1077°C (Yang et al., 2010). Olivine Mg numbers (%Fo) range from 89 to 91, clinopyroxene Na_2O from 0.46 wt.% to 2.10 wt.%, and spinel Cr# from 8.8 to 49. Bulk samples have platinum group element (PGE)+Re concentrations between 0.002 and 0.012 × CI chondrites (Horan et al., 2003), and are all characterized by relatively flat, chondrite-normalized patterns, with the exception of variable Re depletion. The peridotites have whole-rock Os isotope compositions with initial $^{187}Os/^{188}Os$ of 0.1245–0.1295. *In situ* Os isotope analyses of sulfides in the peridotites reveal that the sulfides have variable Os isotopic compositions that largely overlap with the bulk samples, but extend to suprachondritic ratios ($^{187}Os/^{188}Os_i$= 0.1221–0.1565). Clinopyroxenes in the peridotite have relatively unradiogenic Sr ($^{87}Sr/^{86}Sr_i$=0.7026–0.7040) and radiogenic Nd [$\varepsilon_{Nd}(t)$= +6.7 to +13.2] and Hf [$\varepsilon_{Hf}(t)$=+15.9 to +24.8] isotopic compositions.

The peridotite xenoliths contain no garnet, implying that they probably originated from mantle depths of < 80 km, based on the estimates of the spinel-garnet transition in such fertile rocks. Furthermore, the mineral and bulk compositions of the xenoliths suggest that the lithospheric mantle beneath North Korea during the Late Triassic was fertile and hot (918–1077°C). The range and distribution of Os isotope compositions of whole rocks, as well as the Sr-Nd-Hf isotope ratios of the pyroxenes, are within the range of modern convective mantle. The Os isotope compositions of sulfides are also consistent with the range of compositions reported for sulfides present in modern abyssal peridotites. Collectively, all of these geochemical and isotopic characteristics are consistent with the interpretation that the peridotites represent young (Phanerozoic) additions to the subcontinental lithospheric mantle. The fact that the North Korean Triassic lavas carry the juvenile lithospheric mantle xenoliths suggests that the lithospheric removal underlying North Korea occurred at least 50 m.y. earlier than the lithospheric removal to the west in the NCC.

The Late Triassic tectonic-magmatic activity in the KP was traditionally termed as the Songnim Movement (Kawasaki, 1925; Kim, 1976; Reedman and Urn, 1975). Previous studies have suggested different tectonic models for this movement, mainly including intracratonic deformation and post-collisional extension related to Indosinian orogeny. In terms of the former, the Songnim Movement can diverge into two stages (Kim, 1996). During the early stage, ductile shearing affected the southwestern part of the Ogcheon Belt and N-W trending folds in the Paleozoic sedimentary sequences. During the later stage, folding and thrusting prevailed in the Paleozoic rocks and produced N-W trending folds and thrusts that moved toward the southeast. Since Late Jurassic, the KP may have been influenced by the Pacific plate and other related plates.

Orogeny-related models attributed the formation of Late Triassic granitoids and associated rocks to post-collisional setting. Combining Triassic eclogite facies metamorphism and coeval granites, some researchers tend to consider that the DSOB extended eastward to the KP along the OB or IB, HSC and other paths (e.g. Ree et al., 1996; Cho, 2001; Sagong et al., 2005; Oh et al., 2006; Zhai M G et al., 2007; Kim et al., 2011; Chang and Zhao, 2012), although their models are distinct in detail. However, Triassic granites are minor in the DSOB. Instead, abundant coeval syenite and alkali granite bodies are exposed in the northern part of NCC. Therefore, it is possible that the Triassic intrusive bodies in the KP are related to the CAOB. In addition, the

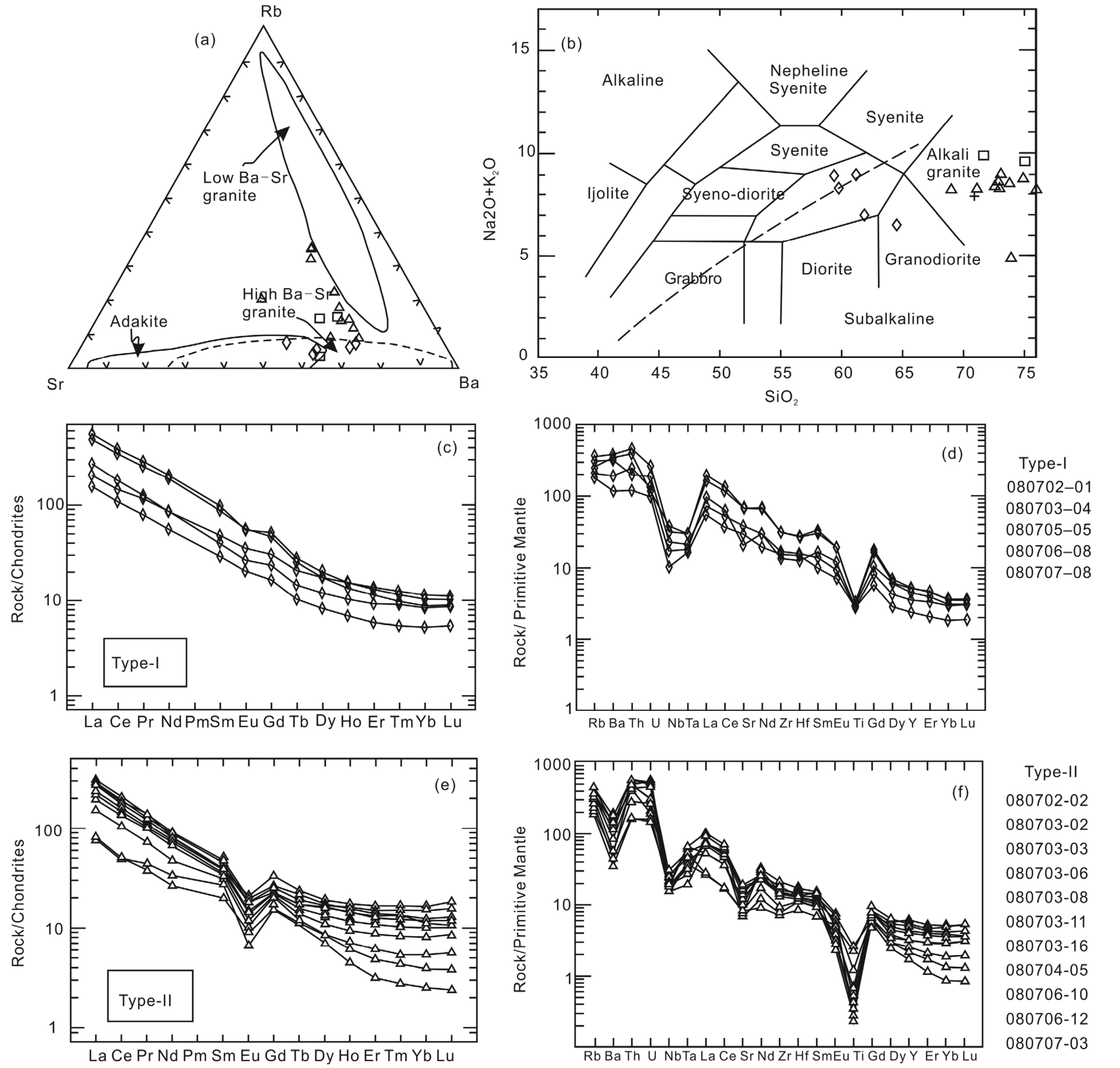


Figure 6 Diagrams of Rb-Sr-Ba (a), (Na_2O+K_2O)-SiO_2 (b) and Sr-Rb-Ba, REE patterns and trace element spider diagrams ((c)–(f)) for the granites in HSC.

Triassic syenites and alkaline granites have been advocated to form in an intracratonic setting and dominantly derive from partial melting of ancient lower crust (e.g. Jiang et al., 2009). Their parental magmas prove to be similar to I-type magmas and to have undergone extensive fractionation during their ascent.

3.2 Triassic granitoids and related rocks in East China and Japan

In South China, the Late Triassic granites locally occur in the central-northern part. The granitoid rocks can be divided into two types. One is peraluminous leucogranites and the other metaluminous granites. The former are commonly associated with uranium mineralization. Their petrogenetic models include re-melting of ancient crust (e.g. Zhou and Li, 2000), subduction of Paleo-Pacific Plate (e.g. Sun et al., 2012), Indosinian Orogeny (e.g. Wang Y et al., 2013) or the complicated effects from more convergent blocks (Mao et al., 2014a). The granitoid rocks are poorly distributed in the DSOB. The Jiazishan complex is an example that has been suggested to represent post-collisional magmatism of the Sulu ultra-high-pressure belt. The complex includes gabbro (211–213 Ma) and syenite (209–215 Ma) (Guo et al., 2005;

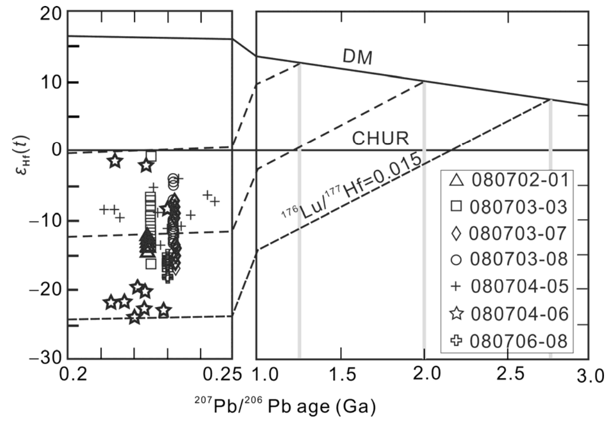


Figure 7 Diagram of $\varepsilon_{Hf}(t)$-$^{207}Pb/^{206}Pb$ age (Ga) for the Hongseong intrusive rocks.

Yang et al., 2005). Some Triassic granites sporadically occur in the South Qinling terrane in the Qinling Orogenic Belt to the west of Dabieshan. The ca. 245–215 Ma granites have lower Sr and Ba contents, while the 220–210 Ma granites show high-K characteristics. These two episodes of granites have been interpreted to be linked with syn-collisional and post-collisional processes, respectively.

The southern margin of the NCC is also home to the Late Triassic intrusive rocks, with their occurrences recently documented in the western North Qinling Terrane of the Qinling Orogenic Belt (Wang X X et al., 2013). The North Qinling Terrane has generally been thought to have a consistent tectonic affinity with the NCC (Dong et al., 2011). The Triassic intrusions therein are metaluminous-peraluminous and middle- to high-K granites, with high-Sr and low-Y character. Their zircon U-Pb ages range from 245 to 215 Ma. These high-Sr-low-Y granites have been considered to be derived from thickened lower crust in syn- to post collisional processes between the North and South Blocks. Another group of granites have zircon U-Pb ages of 217–200 Ma. They are rapakive granites and highly differentiated granites with high-K characters, and probably formed in a post- orogenic extensional setting.

Abundant Triassic granitoids and related rocks are widely distributed in the northern part of the NCC, spanning from NW Shanxi Province and southern Inner Mongolia to eastern Liaoning Province and constituting an E-W trending zone. They can be classified into three types, i.e., adakitic granites, high-K granites and quartz syenites-syenites. The adakitic granites are characterized by high Sr and Na_2O (~4.0%), low Y and HREEs. These features are similar to modern adakites from island arcs and Archean high-Al tonalite-trondhjemite-granodiorite (TTG). However, they are relatively K-rich and their evolved Sr-Nd-Hf isotopic compositions and inherited zircon ages coincide with those of the Archean granulites and the Hannuoba granulite xenoliths (Jiang et al., 2007). Such features cannot readily be explained with previous petrogenetic models of adakites and TTGs. Three adakitic grainitic bodies in northwestern Hebei Province have been studied, their magmatic zircon U-Pb ages are 236–220 Ma and inherited zircon ages are ~2.5 Ga. Jiang et al. (2007) proposed that these adakitic granites formed by partial melting of ancient lower crust, with the restites represented by some of the Hannuoba granulite xenoliths. This implies that crustal anatexis may be one of the major processes controlling the chemical differentiation of the continental crust (Jiang et al., 2007). Other researchers (Yang et al., 2005; Jiang et al., 2009; Zhang S H et al., 2012) further documented the alkali granites and syenites in the northern part of the NCC. Some alkali granites have geochemical characteristics of A-type granites or highly fractionated granites. The zircon U-Pb ages range from 238 to 211 Ma for A-type granites and from 226 to 220 Ma for syenites. Like adaketic granites, these A-type granites and syenites contained old inherited zircons with U-Pb ages of 2.5 Ga and 1.7–1.9 Ga. Together with their whole-rock $\varepsilon_{Nd}(t)$ values from −11 to −6, zircon $\varepsilon_{Hf}(t)$ values from −25 to −10 and Hf model ages (T_{DM}) of up to 1.99 Ga (Han et al., 2004; Zhang S H et al., 2012), these features point to ancient crustal sources. The syenites are usually associated with small mafic-ultramafic complex (Ren et al., 2009), as exemplified by the Xiaozhangjiakou mafic-ultramafic body in a syenitic-mafic-ultramafic complex (Tian et al., 2007). While the zircon U-Pb age of ~220 Ma is interpreted as the emplacement time for the mafic body, the zircons of ~2.45–2.5 Ga may have been trapped from country rocks. The body features whole-rock $\varepsilon_{Nd}(t)$ values of –2.9~+1.66 and zircon $^{176}Hf/^{177}Hf$ ratios from 0.282557 to 0.282690. For the formative regimes of these magmatic rocks, two prevalent hypotheses are post-orogenic extension related to the CAOB or intracontinent rifting within the NCC.

The Mesozoic granites are well-developed in NE China (Figure 8, after Wu et al., 2011). The Triassic granites are mainly distributed in two zones. One extends from Mohe in the north to Erguna in the south, and the other spans from Heihe via Jiamusi-Mudanjiang to Yanji. Moreover, the Songliao basin has a granitic basement (Wu et al., 2011). Therefore, the Triassic to middle Jurassic granites may be widespread in the whole NE China, although their spatial distribution is ambiguous due to heavy forest coverage. The Triassic granites can be roughly classified into two age groups: 255–235 Ma and 235–200 Ma. They probably correspond to syn- collisional and post-collisional processes. Xu W L et al. (2013a, 2013b) and Tang et al. (2015) summarized the data on the granites and volcanic rocks in NE China and further suggested that the Triassic granites can be subdivided into three stages at ~246, ~225, ~205 Ma in Erguna, constraining the history of southward subduction of the Mongol-Okhotsk oceanic plate. Zhang X H et al. (2012) reported three Middle to Late Triassic ferroan granitoid suites from northwestern Liaoning within a junction area of the NCC and the CAOB. The Middle Triassic

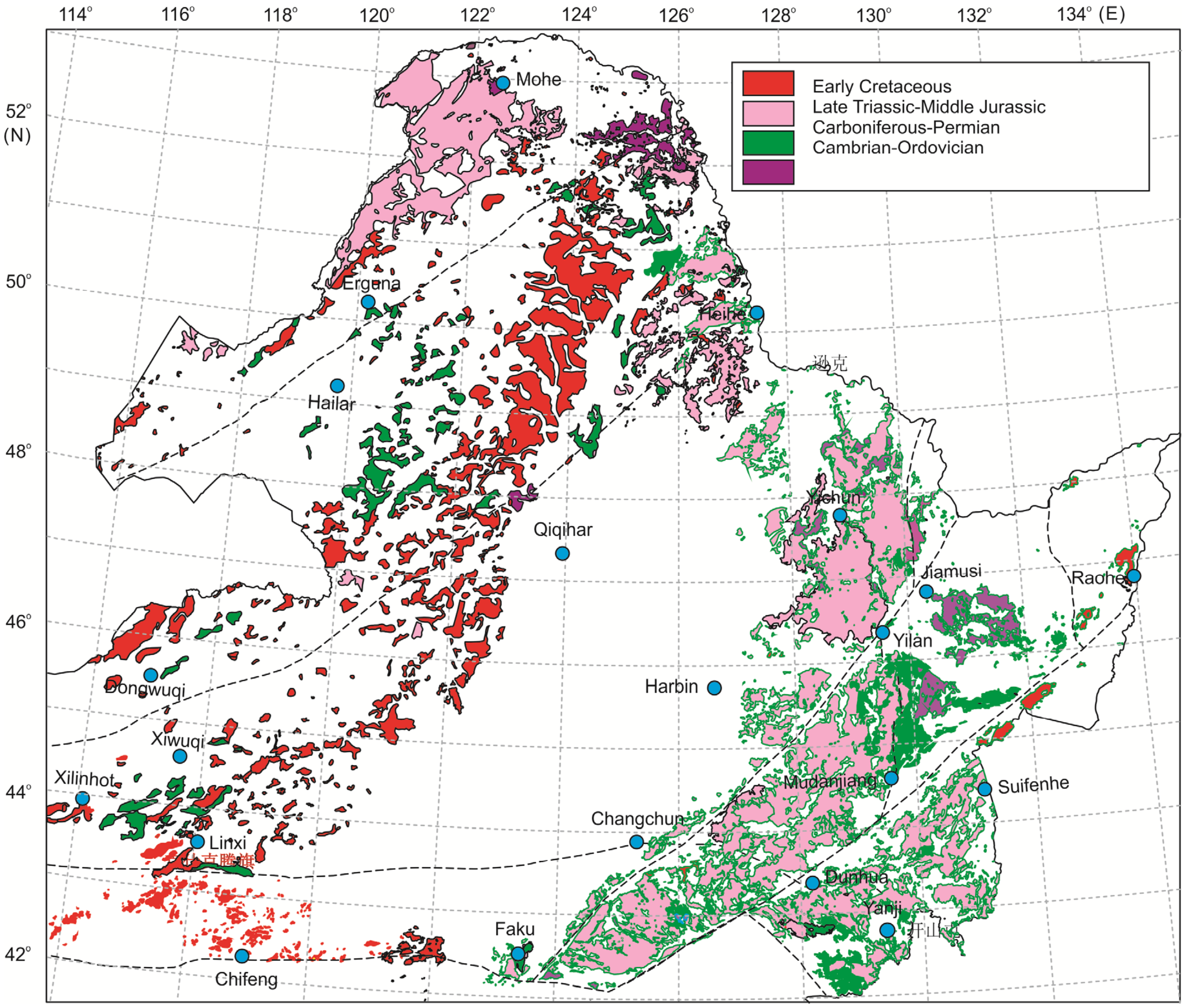


Figure 8 Temporal-spatial distribution map of Phanerozoic granitoids in NE China (after Wu et al., 2011).

(ca. 238 Ma) Ping'andi granites are mainly calc-alkaline and peraluminous. Their radiogenic whole-rock Nd and zircon Hf isotopic signatures argue for an origin consistent with partial melting of a preliminary quartz-feldspathic crust formed by prior mantle-derived magmatic underplating and their differentiations. By contrast, the Late Triassic (ca. 220 Ma) Dashaoleng and Sijiazi suites show an evolved character from alkali-calcic to alkali and from metaluminous to peraluminous. Their variably evolved whole-rock Sr-Nd and mixed zircon Hf isotopic compositions suggest that both suites were formed by variable mixing between depleted mantle-derived mafic magma and old crust-derived felsic magma, with distinctively higher input from juvenile components in the Dashaoleng suite. These contrasting ferroan granitoid suites not only provide a spatial marker for monitoring juxtaposition of the NCC and the CAOB along a lithospheric-scale boundary fault in the region, but also present a temporal snapshot that records a southwardly-progressing crustal growth scenario possibly in response to lithospheric dripping within a post-orogenic extensional regime.

The occurrence of Triassic granites in Japan is only documented in the Hida Belt (Figure 9) and is not associated with any contemporaneous volcanic rocks (Tatsumi et al., 2002; Kimura et al., 2003; Taira, 2001; Mao et al., 2009). Geochemically, these granites are metaluminous and their spatial distribution shows typical zoning. The "old" augen granites along the northwestern side near the Japan Sea (East Sea by the Korean people) show an increasing zoning of acidity in chemical composition from inside to outside and have gneissic structure. In contrast, the "young" Funachu granites, which are located along the southeastern side near the Pacific Ocean, show a decreasing zoning of acidity from inside to outside and are free from gneissic foliations. Zircons from the "old" granites yielded U-Pb ages of 245–248 Ma, while zircons from the "Young" granites yielded U-Pb age of 197±3 Ma and inherited ages of 241±4 Ma (Mao et al., 2009). Moreover, a sample of metamorphic rock from the Hida Belt exhibited three zircon U-Pb ages of ~320, 250 and 200 Ma. These ages have been

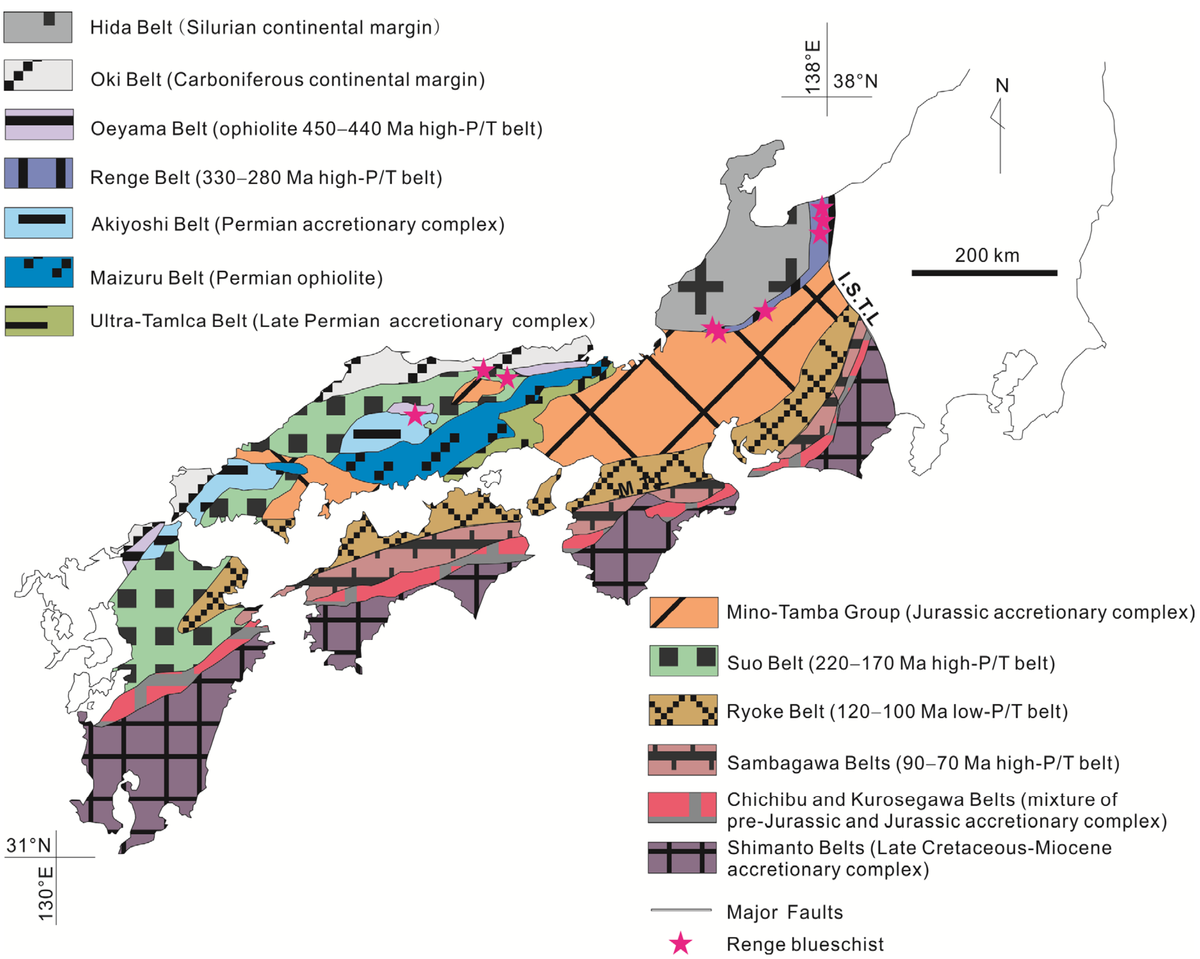


Figure 9 Sketch map showing geotectonic subdivisions of southwestern Japan (modified after Tsujimori, 2002). The timing of accretion generally gets younger oceanwards. MTL, Median Tectonic Line; I.S.T.L, Itoigawa-Shizuoka Tectonic Line.

suggested to represent regional high-temperature metamorphism, large-scale ductile shearing and contact metamorphism related to the intrusion of the Funachu granites, respectively (Tsujimori et al., 2006; Arakawa et al., 2000; Sano et al., 2000; Otoh et al., 2003). Oh (2006) proposed a "new paradigm". It envisions that (1) the Hida Belt in Japan grew as a continental margin or continental arc while subduction was ongoing on the margin of the North China Block; (2) the collision between the North and South China blocks began in Korea during Permian (290–260 Ma) and propagated westwards until Late Triassic (230–210 Ma), culminating in the sinistral Tan-Lu fault in China and the dextral fault in the Hida marginal belt in Japan.

4. Jurassic magmatic rocks

4.1 Jurassic granitoids and related rocks in the KP

Abundant Jurassic granitic intrusions and large-scale ductile shearing deformations represent one of the most important tectonic-magmatic events in the KP, termed as the Daebo Event. Two major shear zones are the Imjingang shear zone in the north and the Honanm shear zone in the south, which strongly affected the distribution and structural nature of the IB and OB. The Daedong Basin in the Gyeonggi massif has been proposed to result from the formation of graben or half-graben (Cluzel, 1992; Kim, 1996). A series of deformational phases between the latest Triassic Songnim stage and the earliest Daebo stage are characterized by the inversion structures. During the Daebo stage, distinct brittle to ductile deformations occurred along the contact boundary between the GM, OB and RM (Figure 2). It was presumed to be reactivation of pre-existed deep basement fractures. Brittle deformation with northeast- or southwest-plunging fold axial traces overprinted on the mylonite zone. Although previous studies suggested that the shear zones of the Daebo stage formed in Late Triassic to Early Jurassic, Kim et al. (2009) reported the SHRIMP U-Pb zircon ages from the mylonitic orthogneiss and hornblende-biotite granitoid near the Myeongho area within the Yecheon Shear Zone, a representative segment of the Honam Shear Zone. The core and overgrowth parts of the zircons from the foliated hornblende-biotite granitoid yielded ages of ca. 187 Ma and ca. 178 Ma, respectively. The former is interpreted as the emplacement timing, whereas the latter as the timing of subsequent mylonitization, similar to zircon overgrowth age of ca. 179 Ma in the mylonitized quartz-feldspar orthogneiss. Muscovite and biotite K-Ar ages range from 162–168, 148–155, and 136 Ma for the mylonitized basement rocks and foliated granitoids. Synthesizing these geochronological results with previous structural studies leads to the suggestion that the Honam Shear Zone initiated during Middle Jurassic Daebo Movement (or early Yanshanian) and lasted possibly as late as Early Cretaceous.

Jurassic volcanic rocks constitute local occurrence in the Paleozoic-Mesozoic basins. The Bansong Group (Daedong Supergroup) in the Taebaeksan Basin has long been considered to be an important temporal marker for the Songnim orogeny (the collision of the North and South China blocks) and experience deformation during the Middle Jurassic Daebo event. However, Han et al. (2006) offered another explanation for the origin of the Bansong Group and associated faults on the basis of structural and geochronological data. With the SHRIMP U-Pb zircon ages of 186±2 and 187±2 Ma from two felsic pyroclastic rocks in the Taebaeksan Basin, it was proposed that the Bansong Group deposited during the late Early Jurassic rather than Late Triassic (Han et al., 2006). The inherited zircon U-Pb ages of ca. 1.9 Ga are in agreement with the present basement ages.

Jurassic intrusive rocks are the largest magmatic unit in the KP (Figure 10). Following the Triassic granites related to the Indosinian orogeny, the Jurassic granites have been usually interpreted to exhibit tectonic affinity with the Songnim orogeny. Their ages range from 199–175 Ma to 175–165 Ma, with no obvious age zoning in spatial distribution. It is noteworthy that the Middle-Late Jurassic granites and related rocks (~165–145 Ma) are scarce.

In general, the Jurassic granitoids exhibit high-K calc-alkaline character and vary from metaluminous to peraluminous (Figure 5a and b), as manifested by the well-studied granitoid plutons in the central GM and northern OB (Kim et al., 2011). The granitoids therein can be divided into two categories according to mineralogy and occurrence: biotite granites and diorites. The former occur as batholiths, whereas the latter as small-scale stocks or blebs within the former. Micro-mafic enclaves are common, whilst xenoliths from country rocks are rare. The zircon grains from biotite granites yielded concordant $^{206}Pb/^{238}U$ ages from 184 to 167 Ma. The biotite granites vary in SiO_2 from 60.7 wt.% to 72.9 wt.%, in Al_2O_3 from 14.3 wt.% to 17.6 wt.%, in K_2O from 2.88 wt.% to 5.73 wt.%, Na_2O from 3.10 wt.% to 4.45 wt.%, total Fe_2O_3 from 1.29 wt.% to 5.93 wt.%, CaO from 0.95 wt.% to 5.28 wt.%, TiO_2 from 0.17 wt.% to 1.06 wt.% and MgO from 0.24 wt.% to 2.50 wt.%. All the samples have highly negative $\varepsilon_{Nd}(t)$ values from −21.1 to −13.4, with late Archean to early Proterozoic Nd model ages (2.97–2.27 Ga). Two granites contain old inherited zircons with ages of ~1.8–2.5 Ga. These characteristics resemble those of temporally and spatially coexisting Jurassic-Triassic granites in the central-northern NCC, and their petrogenesis can be attributed to partial melting of ancient crustal rocks in multi-stage reworking (Jiang et al., 2009). Another example is the deformed biotite granite complex at Haemi of the HSC. The granitic complex contains later small-scale veins and is associated with a hornblende gabbroic body. A granite sample (080705-05) yields a zircon age of 187±2 Ma. Zircon $\varepsilon_{Hf}(t)$ values range from −23 to −19, indicative of a possible old crustal source (Figure 11). For two gabbro samples collected from a nearby locality, the zircons in them yield U-Pb ages of 188±2 Ma (080704-1) and 175±4 Ma (080704-04); while zircon $\varepsilon_{Hf}(t)$ values range from −7 to +2 (Figure 11). These gabbros can be explained to have derived from ancient enriched mantle, with certain crustal contamination.

Most Jurassic granitoids were affected by ductile deformation. They may have become foliated as a result of Middle Jurassic dextral strike-slip faulting along the Honam shear zone (Lee et al., 2003) between the OB and YM in the south and along the Imjingang dextral shear zone between the IB and GM in the north (Paek and Rim, 2005). Although the Jurassic granitoids are spatially associated with coeval shear zones, no evidence is available to support the genetic relationship between granite emplacement and tectonic shearing. The Middle-Late Jurassic granitoids is outnumbered by Early-middle Jurassic ones. In general, the Early-Middle Jurassic granites tend to form earlier than ductile shear zones that started to operate since 170 Ma. The Daebo Event should be restricted to Middle-Late Jurassic deformation. If the Early-Middle Jurassic granites in NE China turned out to be the result of the Late Triassic post-orogenic extension in the CAOB, the Daebo Event could be related to the Farallon-Izanagi Plate subduction as suggested by Oh (2006) and Kim et al. (2005). The Honam shear zone may have been active from 170 to 140 Ma, owing to a transform fault related to the subduction. The above-mentioned models failed to reconcile the coincident activities in the Imjinggang shear zone and the Tanlu Fault in East China. Equally noteworthy is the contradiction between the rarity of magmatic activity in the KP during Middle-Late Jurassic and the subduction of Farallon-Izanagi Plate supposedly at that time.

4.2 Jurassic granitoids and related rocks in East China and Japan

Mesozoic tectonic-magmatic activity in East China has attracted much attention from geologists for a long time. It was termed as the Yanshanian Movement by Wong (1927) and reiterated as crustal reworking by Chen (1960, 1985). Episodes A and B in the Yanshanian Movement are marked by the unconformity beneath the andesitic rocks of the Tiaojishan Formation with an age of ca. 160 Ma and the unconformity beneath the volcanic rocks of the Zhangjiakou Formation with an age of ca. 135 Ma for their baseline

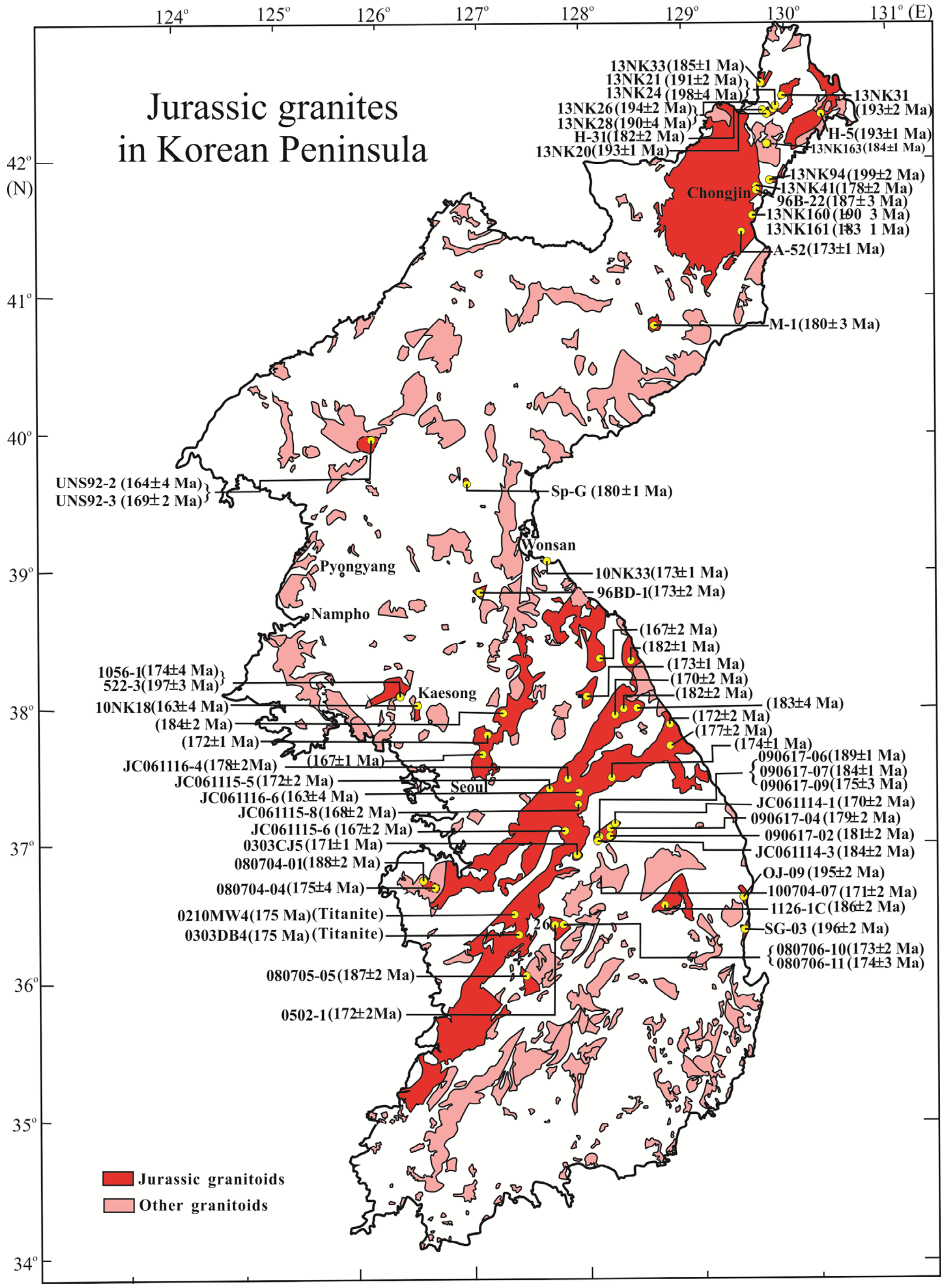


Figure 10 Sketch map for the Jurassic granitoid bodies in the KP.

boundary in the Yanshan Basin in the northwestern-central part of the NCC, respectively (Zhao et al., 2004); while they are 158–153 Ma and 136 ~134 Ma in the Chengde Basin in the northern NCC, respectively (Liu et al., 2006).

Figure 12 shows the distribution of Mesozoic igneous rocks in the SCB (after Li X H et al., 2012, 2014) and depicts a rough zoning with the rock ages increasing from southeast to northwest. Jurassic granitoids occupy over 60–70% of the Mesozoic granitoids in the SCB. Some adakatic granites are present in the Middle and Lower Yangtze Area and usually associated with Cu-Mo deposits. The diorite porphyrites in Jiangxi and Zhejiang provinces have zircon U-Pb ages of 176–165 Ma and 150–142 Ma (Mao et al., 2009). In the SE part of the SCB, i.e., Cathaysian Block, most granites are S-type with a calc-alkaline character. They outcrop in two zones, i.e. the E-W trending zone along the Nanling mountains and the NE trending zone along the Wuyishan Fold Belt (Mao et al., 2009). Jurassic granites have a peak range of zircon U-P ages from 177 to 155 Ma. They were usually associated with W-Sn-REE mineralization (Wang Y et al., 2013). A number of them are highly fractionated granites enriched in

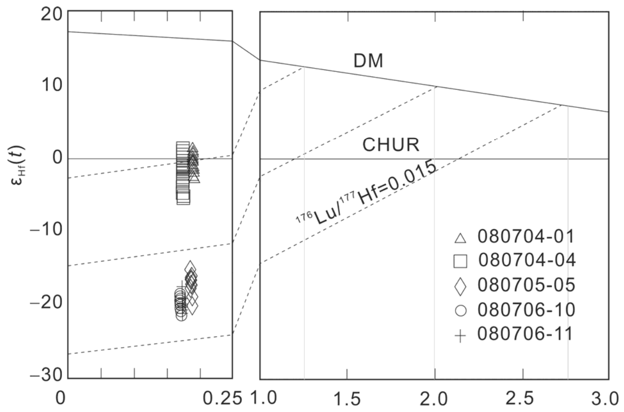


Figure 11 Diagram of $\varepsilon_{Hf}(t)$ via age (Ga) for the Jurassic deformed granite and hornblende gabbro samples from Haemi. The samples of 080705-05, 080706-10 and 080706-11 were collected from the same location.

Al and Si but depleted in Mg and Ca, with high initial $^{87}Sr/^{86}Sr$ ratios and $\varepsilon_{Nd}(t)$ values. The structural analyses demonstrate that two tectonic inversions from compression to extension happened at 175–165 Ma and 145–135 Ma (Zhang Y Q et al., 2012). There are hot debates for the Jurassic tectonic setting in the SCB, with main opinions including intra-continental orogeny, Paleo-Pacific subduction and post-collisional regime related to Indosinian orogeny (e.g. Zhou and Li, 2000; Wang Y et al., 2013; Mao et al., 2009; Li X H et al., 2012; Zhang et al, 2013; Sun et al., 2012).

Early Jurassic-earliest Middle Jurassic granitoids remain a local occurrence in the southern Yanbian and Liaodong areas of the northeastern NCC. Typical intrusions include diorite-granodiorite-granite plutons with zircon U-Pb ages of 190–170 Ma (Zhang S H et al., 2014). Early Jurassic volcanic rocks, assigned to the Nandaling and Xinglonggou formations in the northern NCC, are distributed only in the Western Hills of Beijing, the Chengde area in northern Hebei province (biotite $^{40}Ar/^{39}Ar$ plateau age of 180±2 Ma, Davis et al., 2001) and the Beipiao and Nanpiao areas in western Liaoning province ($^{40}Ar/^{39}Ar$ plateau age of 188±7 Ma, Chen et al., 1997). In contrast, Middle-Late Jurassic igneous rocks are widely distributed in the Yanshan Belt in the northern NCC, the Liaodong area and eastern Shandong Peninsula in the eastern NCC and the southern Yanbian-Liaobei area in the northeastern NCC. Middle-Late Jurassic intrusive rocks consist mainly of monzodiorite, syenite, diorite, mozonite and granite, while coeval volcanic rocks are mainly composed of andesite, basaltic andesite, andesitic tuff, trachy andesite with minor basalt, rhyolite and rhyolitic tuff. Most of these magmatic rocks exhibit adakite-like geochemical signatures with high contents of Al_2O_3, Na_2O and Sr, low contents of MgO, Y and Yb, high Sr/Y and La_N/Yb_N ratios, depletions of HFSE (e.g., Nb, Ta, Ti, Zr, Hf), low to moderate initial $^{87}Sr/^{86}Sr$ ratios and significant negative $\varepsilon_{Nd}(t)$ values. They have been generally considered to be derived from the partial melting of an old lower crust or thickened mafic lower crust (e.g., Li et al., 2001; Zhang et al., 2001; Rapp et al., 2002; Davis, 2003). The granitoids have zircon U-Pb ages of 165–150 Ma, and commonly contain inherited zircons of ~2.5 Ga or 1.8–1.9 Ga (e.g. Wu et al., 2006; Qiu et al., 2002; Hu et al., 2004; Ding et al., 2010; Zhang S H et al., 2014). Middle-Late Jurassic granites in the NCC are mainly classified as I-type with minor as A-type. Some of the granites in the Jiaodong Peninsula belong to S-type (Zhang T and Zhang Y Q, 2007). Geological and Sr-Nd-Hf-Pb isotopic data indicate that the intermediate- felsic magmatic rocks are mainly crustal-derived (e.g., Yang et al., 2006; Yang and Li, 2008), while the mafic rocks derive from partial melting of an EMI-type sub-continental lithospheric mantle (e.g., Guo et al., 2007).

Unlike the Triassic-Early Jurassic igneous rocks that are only distributed along cratonic margins, Middle-Late Jurassic magmatism affected a broader region of the eastern NCC. Some researchers noted that Middle-Late Jurassic magmatic rocks are mainly calc-alkaline in composition and exhibit similar petrological and geochemical characteristics to those in the Andes arc and the active continental margin of western North America (e.g., Deng et al., 2000) and further advocated that they likely formed in an active continental margin in response to the Paleo-Pacific plate subduction (e.g., Zhao et al., 2004; Wu et al., 2006). However, other researchers argued that the magmatic distribution, deformation patterns, multiple tectonic systems and multi-directed contractions in the NCC during Middle-late Jurassic might record far-field effects of synchronous convergence of three different plates toward East Asian continent, with the Siberian plate in the north, the Paleo-Pacific plate in the east and the Lhasa Block in the southwest (Zhai et al., 2004a). This Middle to Late Jurassic intraplate orogeny and pervasive shortening preceded lithospheric attenuation and thinning in East China at earliest Cretaceous (e.g., Zhang Y et al., 2008).

NE China is home to voluminous Jurassic granitoids. With the Jurassic granitoids mainly developed in the east and the Cretaceous granitoids in the west (Figure 8), their spatial distribution seems to show a westward younging trend (Wu et al., 2011). Three genetic types of granitoids have been identified in the area. S-type granitoids have only been discovered in the Nadanhada Terrane in the easternmost part of NE China, A-type granitoids are sparsely distributed in the Xing'an, Songliao and Liaoyuan terranes, with aluminous and peralkaline sub-types. The aluminous A-type granitoids are composed of quartz, alkali feldspar, plagioclase, biotite and local hornblende, and are difficult to distinguish from highly fractionated I-type granitoids. The peralkaline A-types consist of quartz, alkali feldspar, albite, biotite, arfvedsonite and riebekite. The most widely distributed rock types across the area are hornblende-bearing gabbro, diorite, granodiorite, monzogranite and syenogranite. Geochemically, these granitoids vary from metaluminous,

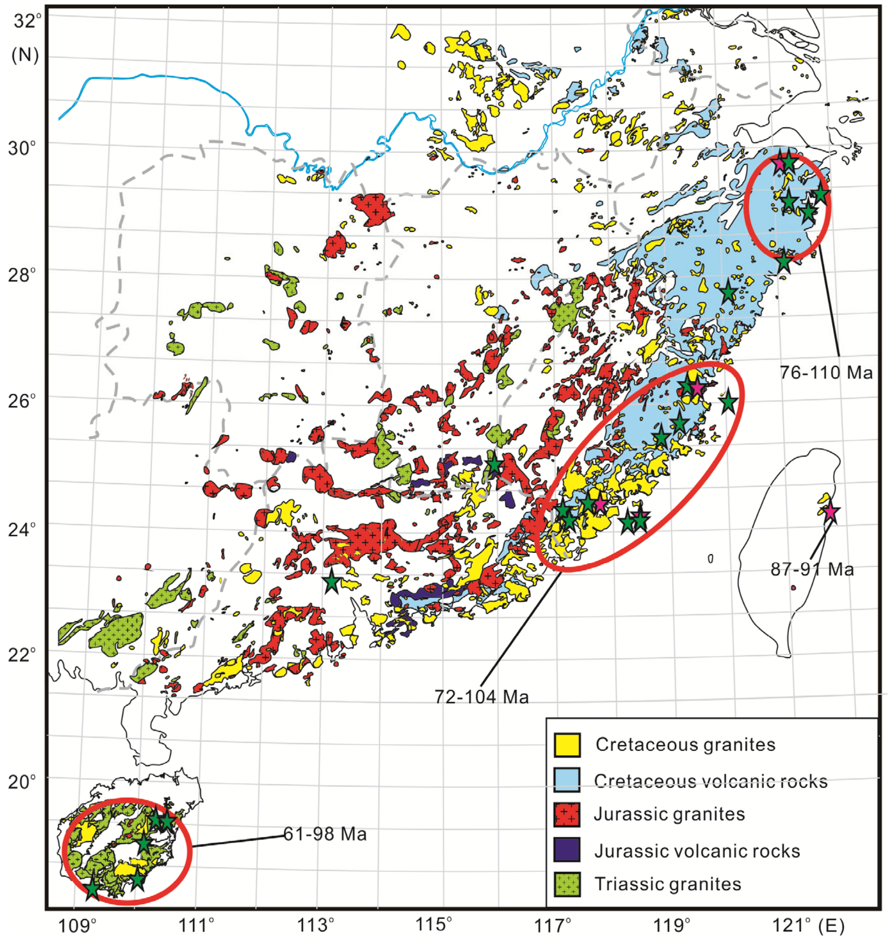


Figure 12 Sketch map showing distribution of the Mesozoic igneous rocks in the SCB (after Li X H et al., 2012).

peraluminous to peralkaline. Over hundred samples have been dated (Wu et al., 2011). The resultant zircon U-Pb ages concentrated in a range of 200–170 Ma, with a few ages of 160–150 Ma. Geochronologically, Jurassic granitoids in NE China are somewhat similar to those in the KP but different from those in the NCC. Combining granitoids in other areas in the CAOB (Jahn, 2004; Jahn et al., 2000), Jurassic granitoids in NE China could be attributed to the subduction of the Pacific plate, whereas contemporaneous ones in the Erguna Massif might be related to the subduction and subsequent closure of the Mongo-Okhotsk Ocean (Wu et al., 2011).

A conspicuous fact is that there were hardly any Jurassic magmatic rocks in Japan. A magmatic lull might last ~70 Ma from 195–125 Ma (Nishiro and Yoshida, 2014), indicating the Japanese Island might not be affected by the subdution of the Paleo-Pacific Plate before ~125–120 Ma (Mao et al., 2009).

5. Cretaceous magmatic rocks in the KP

5.1 Cretaceous granitoids and related rocks in the KP

Widespread Cretaceous granites in the KP are similar in magmatic affinity to those in the NCC (Figure 13). Obvious difference lies in the fact that the former are younger. Our zircon U-Pb data for these granites range from 114 to 92 Ma with a peak of ~110 Ma. This age range is also documented by detrital zircons from the river sands in North Korea (Figure 14). The Late Cretaceous (or to early Paleogene) tectono-magmatic event is termed as the Bulgugsa Movement or Orogeny (Kim, 1996), as represented by E-W trending thrust faults, large-scale upright folds and NNE-trending strike-slip faults with dextral sense. Intense volcanism and plutonism coincided with the sedimentation in the Gyeongsang Basin. The late stage of basin evolution is characterized by the transition into transpression due to sinistral strike-slip motion (Seo et al., 1979; Kim, 1996).

The granitoids of the Bulgugsa Movement include granodiorites, granites and a few diorites. They are mostly subalkaline and vary from metaluminous to peraluminous in Figure 5, as represented by the Sokrisan, Weolaksan and Muamsa plutons in the OB. Their major and trace elements, and Sr-Nd isotopic data have been reported for evaluating the source characteristics and petrogenesis (Lee et al., 2010; Oh, 2006). The Sokrisan and Weolaksan plutons are batholith-scale complexes and consist of biotite granite, with

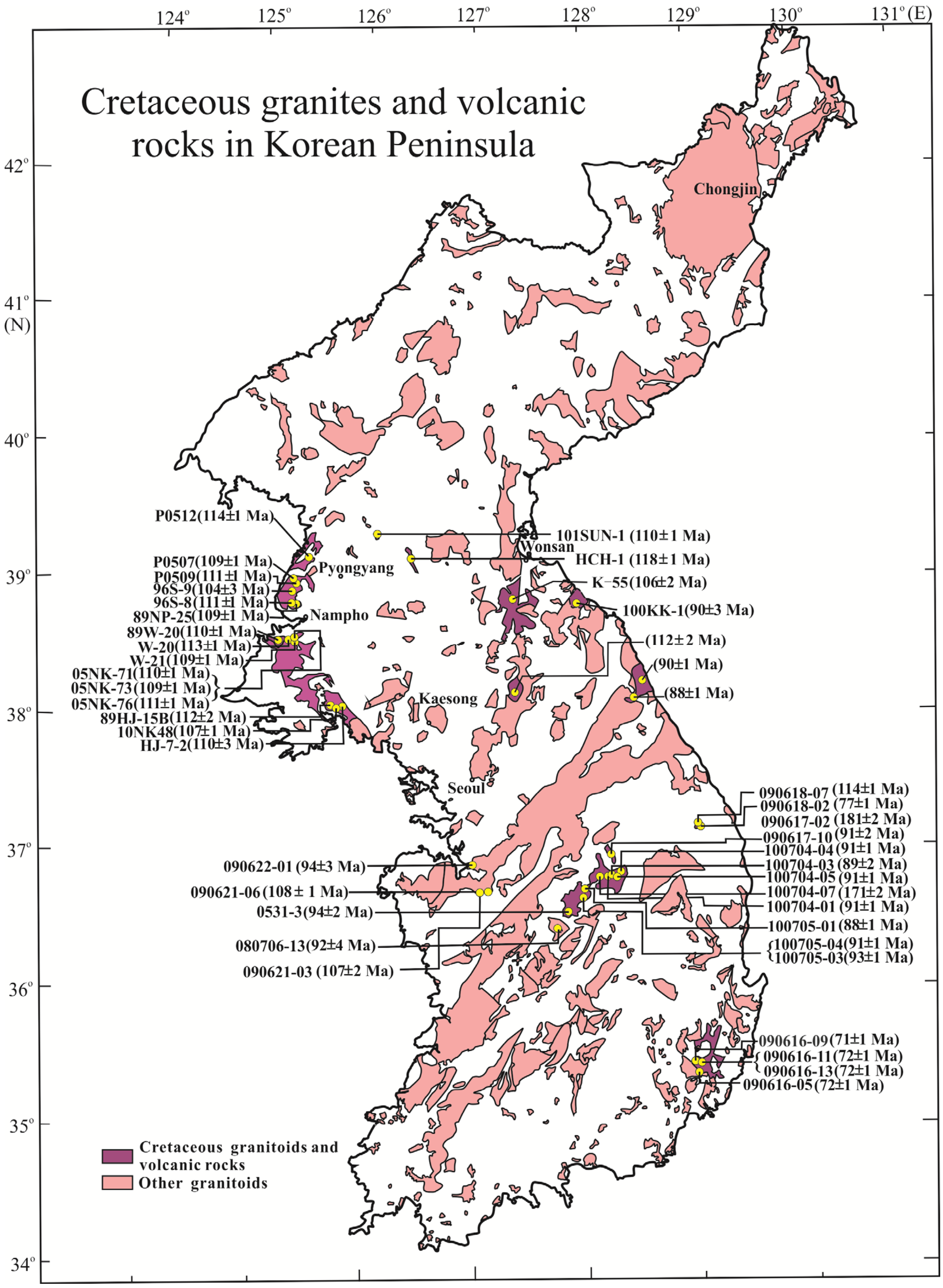


Figure 13 Sketch map for the Cretacous granitoid bodies and volcanic rocks in the KP.

hornblende-biotite granite in the eastern part. The Muamsa pluton is a stocky biotite granite. Three granites all have miarolitic texture. Geochemically, they have high SiO_2, FeOt/MgO, K_2O+Na_2O, and LREE contents. They are mostly depleted in P_2O_5, TiO_2, Ba and Sr, with strongly negative Eu anomalies. These geochemical characteristics reflect dual affinities of A-type and highly-fractionated granite. The chondrite-normalized REE patterns and PM-normalized spider diagrams are similar to those of anorogenic A-type granites. The Muamsa granite has initial $^{87}Sr/^{86}Sr$ ratio of ca. 0.7139, while those for the Weolaksan and Sokrisan granites are ca. 0.7132 and 0.7084, respectively. The $\varepsilon_{Nd}(t)$ values for the granites range from −13.3 to −15.8. These elemental and isotopic features indicate that three granites might have derived from chemically similar crustal sources. In tectonic discrimination diagrams, the granites fall in the scope of syn-collisional to within-plate granites.

Epithermal Au-Ag mineralization in the KP took place between ca.100 and 70 Ma, overlapping with shallow mag-

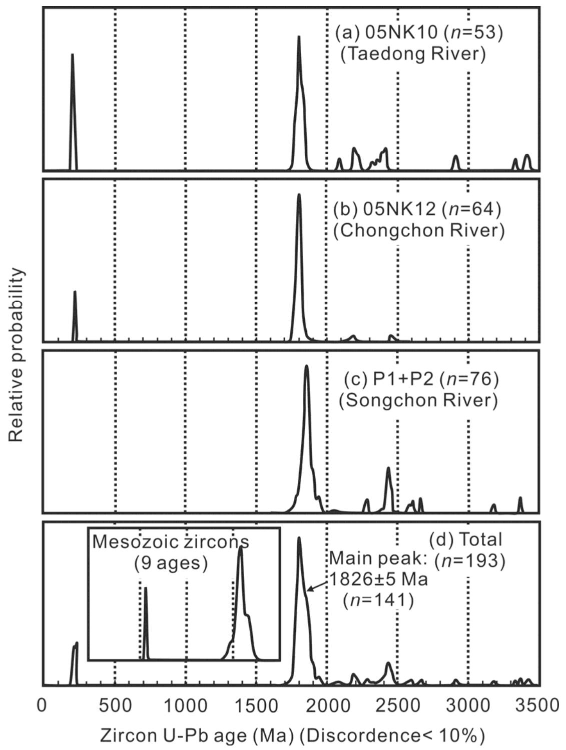


Figure 14 Detrital zircons from the river sands in North Korea.

matic activities (Choi et al., 2005). Styles of epithermal Au-Ag deposits in the KP include the Mugeug-type found in the sediment-dominated basins in the central segment and the Haenam-type in the volcanic-dominated basins in the southwest. Epithermal Au-Ag deposits associated with the volcanic-dominated basins in the southern KP generally formed at very shallow crustal levels (<0.5 kbar) and relatively low temperatures (<300°C) from fluids containing large components of less-evolved meteoric waters than those associated with the sediment-dominated basins. This Au-Ag metallogenesis in the KP is different in mineralization age and type from the Au metallogenesis in the eastern Shandong of the NCC. It is possible that several Au-bearing granites in the KP occur near the Yalu River in the Rangnim Massif (Song et al., 2009), which has not yet been studied in detail.

The Gyeongsang Basin is the largest non-marine sedimentary basin in the KP. Its sedimentary setting, magma source, tectonic affinity and formation age are important for understanding the Mesozoic tectonic evolution of the KP and even the Northeast Asia. The Gyeongsang Supergroup, the basin fill, is divided into the Sindong, Hayang, and Yucheon Groups in ascending order. The Sindong and Hayang Groups are composed of sandstone, shale, minor amounts of conglomerate, and marl deposited in a non-marine environment, whereas the Yucheon Group is characterized by the dominance of volcanic rocks (Chang, 1977, 1988). These volcanic rocks vary from basalt-trachyandesite-andesite-trachyte for the Chusasan Subgroup to basalt-dacite-rhyolite for the Unmunsa Subgroup. They are all of high-K calc-alkaline series (Figure 15a and b). Geochemically, the rocks possess similar REE patterns, but with variable amounts of HREE depletion and variable negative Eu anomalies. Their trace element patterns show a relatively strong depletion of Nb, Ta, P, and Ti, and a wide range in Rb, Ba, and Sr. Initial $^{87}Sr/^{86}Sr$ ratios of these rocks are generally lower than 0.7070 (Hwang, 1997). Zircons from the volcanic rocks (andesite and ash-flow tuff) in the Chusasan Subgroup yield ages from 94 to 88 Ma; while zircons from dacite in the Unmunsa Subgroup give U-Pb ages of ~74–63 Ma (mainly 70–65 Ma), earlier than Ar-Ar plateau ages of 57±1 Ma and 56±3 Ma for basalt samples. The associated granites around the Gyeongsang Basin have zircon U-Pb ages from 91 to 72 Ma. Four granite samples associated with the volcanic rocks in the Gyeongsang Basin give ages of ~72 Ma. Twenty inherited/xenocrystic zircons

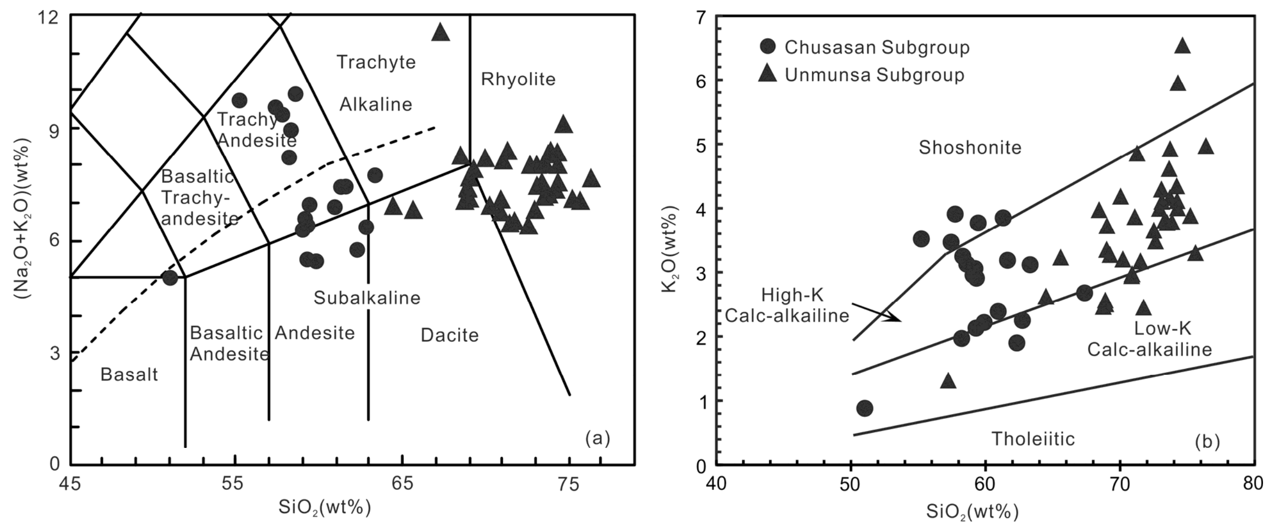


Figure 15 Plots of (a) (Na_2O+K_2O) (wt.%) vs. SiO_2 (wt.%) and (b) K_2O (wt.%) vs. SiO_2 (wt.%) for the volcanic rocks from the Chusasan and Unmunsa Subgroups, Gyeongsang Basin (after Zhang Y B et al., 2012. Late Cretaceous volcanic rocks and associated granites).

from these rocks give Archean ages ranging from 2.5 to 2.6 Ga (Figure 16), suggesting the existence of late Archean rocks in the Yeongnam Massif (Zhang Y B et al., 2012).

These data attest to a major Gyeongsang magmatic event during Late Cretaceous. In comparison with the Sambagawa metamorphic belt, the Jurassic Chichibu accretionary complex with Cretaceous strike-slip basin sediments, and the Cretaceous Shimanto mélange zone in southwest Japan, it is likely that above-mentioned complexes constitute the trace of a continuous island arc system in SE Korea extending from SW Japan during the period of 94–80 Ma (Figure 17). The Gyeongsang basin tends to change in tectonic affinity from an island arc to a back-arc with bimodal volcanic rocks of ~70–55 Ma.

From 160 to 110 Ma, there was a significant magmatic

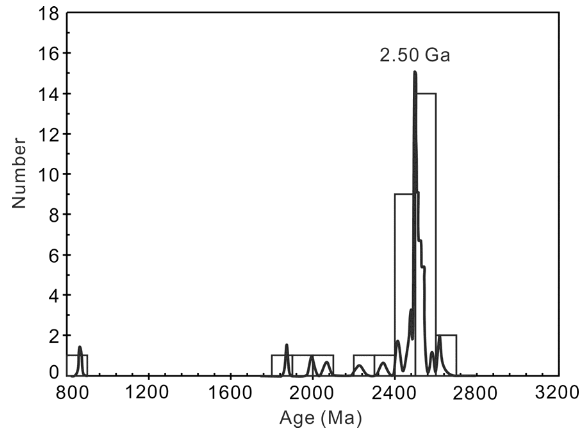


Figure 16 Inherited zircon ages from the volcanic rocks in the Gyeongsang Basin.

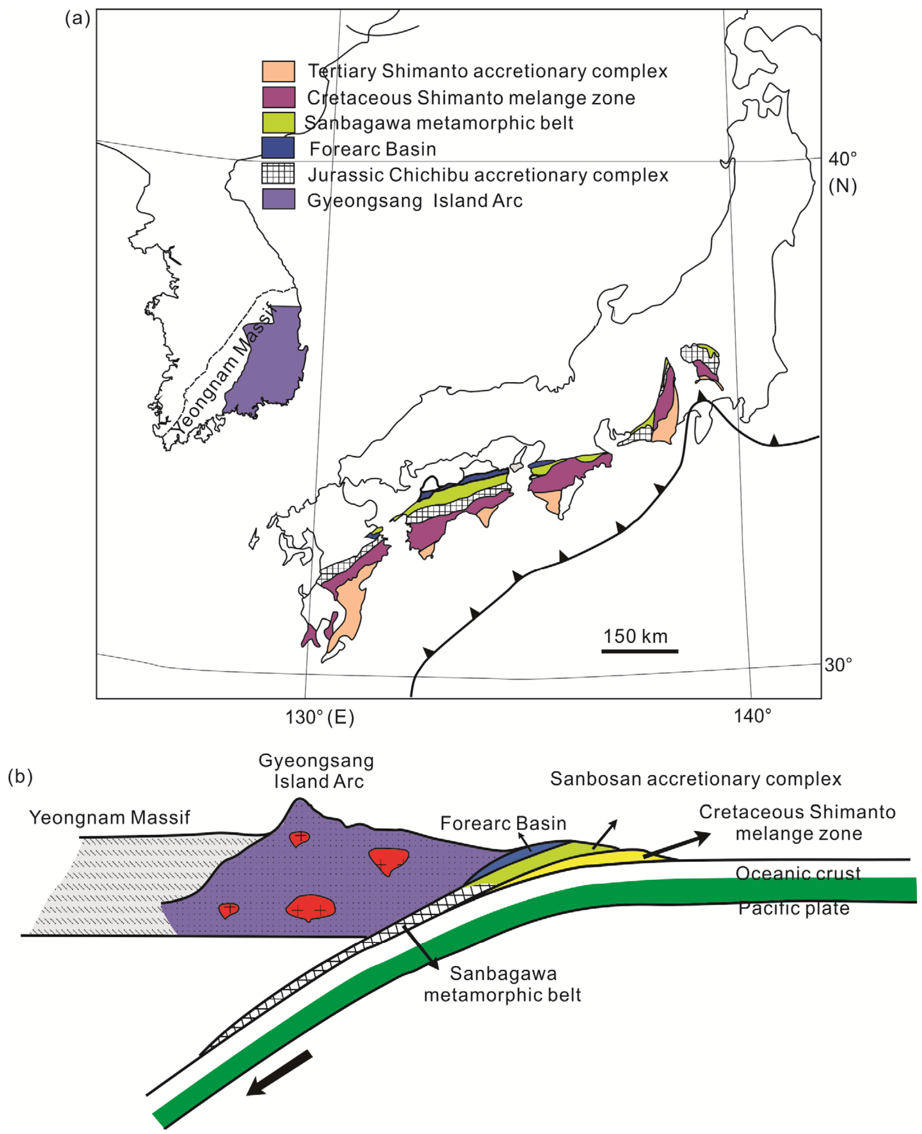


Figure 17 (a) Simplified diagram of geotectonic profile of the Gyeongsang Basin and Japanese island. Geology of Japan after http://www-odp.tamu.edu/publications/190196SR/205/images/05_f04.gif; (b) simplified model of the Late Cretaceous Japanese island arc system (after Zhang Y B et al., 2012. Late Cretaceous volcanic rocks and associated granites).

lull of ca. 40 Ma in Korea (Zhai M G et al., 2007; Mao et al., 2009), whereas large-scale magmatism and metallogeny happened in East China during Early Cretaceous. Therefore, various models have been proposed for this magmatic gap, including (1) change in angle of convergence, (2) change in convergence rate and (3) change in subduction angle (e.g., Kim, 1996; Sagong et al., 2005; Choi et al., 2005; Oh, 2006; Lee et al., 2010). It is evident that the specific magmatism in the KP linking to the subduction of the Paleo-Pacific Plate might occur since Late Cretaceous.

5.2 Cretaceous granitoids and related rocks in East China and Japan

Cretaceous magmatic rocks in the SCB can be subdivided into two groups, i.e. Early-Middle Cretaceous (145–125 Ma) and Late Cretaceous (120–85 Ma) (Mao et al., 2014a, 2014b). They are roughly distributed in the middle and lower reaches of Yangtze River, the Qinhang zone in the Nanling Range and the China's South-East coastal area. Two volcanic episodes along the latter have been recognized. The lower series dominantly consists of a set of high-K and calc-alkaline intermediate-acid volcanic rocks with minor sedimentary layers. The upper series is a set of bimodal volcanic rocks interlayered with red sediments. High-K granodiorite-granites usually intruded into two series. They have zircon U-Pb ages of 94–85 Ma (Chen C H et al., 2004). The volcanic rocks in two series yielded zircon U-Pb ages of 143–130 and 104–99 Ma, respectively (Guo et al., 2012). The intrusive rocks in the middle and lower reaches of Yangtze River and Nanling Range range in age from Late Jurassic to Early Cretaceous (150–120 Ma), and a few granites formed in 110–93 Ma (Zhou et al., 2012; Li X H et al., 2013, 2014). The Cretaceous granites are considered as typical of ancient crust reworking (Zheng et al., 2013). However, much controversy exists concerning its geodynamic mechanism, like intra-continental orogeny and subduction of the Paleo-Pacific Plate (Zhang Y Q et al., 2012; Mao et al., 2014a).

Numerous recent studies have established close linkage between Cretaceous magmatism and cratonic destruction in the NCC. The shallow response to lithosphere thinning and crust-mantle interaction spawned large amount of granitoid intrusion, volcanic eruption and corresponding fluid-mineralization. Three main periods of granitoid formation are 160–140, 130–110 and 100–80 Ma, with the strongest period of 130–110 Ma and a peak of 125 Ma (Zhai et al., 2004b; Wu et al., 2008; Xu W L et al., 2013b; Zhu R et al., 2012). The magmatism is directly related to the most gold-productive region of China (Zhai et al., 2001, 2002; Li S R et al., 2013; Zhu et al., 2015). Mesozoic granitoid intrusion and gold mineralization occur not only in the eastern Shandong, but also in the western Shangdong and the Taihangshan area in the hinterland of NCC. Most gold deposits formed within a few million years in the Early Cretaceous (130–120 Ma), coeval with the widespread occurrence of bimodal magmatism, rift basins and metamorphic core complexes that marked the peak of lithospheric thinning and cratonic destruction. Stable isotope data and geological evidence indicate that ore-forming fluids and other components were largely exsolved from reworking crust and cooling magma/or derived from mantle degassing during lithospheric extension.

Liaodong Peninsula in the northeastern part of the NCC is one of the important areas hosting Mesozoic granitoids and gold deposits. Although Late Triassic and Jurassic intrusions are also present in the Peninsula, Early Cretaceous turns out to be the most important period of granitic magmatism (Wu et al., 2005b). Early Cretaceous intrusions have zircon U-Pb ages of 131–117 Ma. They usually occur as large batholiths and consist of numerous rock types, like dolerite, diorite, monzonite, porphyritic granite, highly fractionated alkali feldspar granite and A-type granite. Magma mixing is extensively developed between diorite and granite. The gold deposits in the Liaodong Peninsula have the same mineralization ages and types as those in the eastern Shandong (Song et al., 2009). We argued that two Cretaceous granite-gold mineralization regions have once behaved as a united mineralization province, only separated by the Bo Sea since its opening in Cenozoic (Zhai et al., 2001, 2002; Zhai and Santosh, 2013).

Cretaceous granitoids in the NE China are distributed in a NNE-trending zone from Linxi in the south to Elunchun in the north and to Mohe in the east, called the LE zone (Figure 8). Cretaceous granites sparsely occur in the Jurassic granite zones. Wu et al. (2011) reported that 135–120 Ma granitoids tend to occur in the western side of the LE zone, whereas ~115 Ma granitoids in the eastern side. Most of the Cretaceous granitoids are quartz monzodiorite, porphyritic monzogranite, alkali-feldspar granite and alkaline granite. They have similar emplacement ages, ranging from 129 to 123 Ma in Linxi (Great Xing'an Range). A composite batholith in the Liaoyuan area in the southeastern NE China can be identified as four episodes, which are Late Permian (ca. 285 Ma), Early Triassic (249–245 Ma), Jurassic (192–168 Ma) and Cretaceous. Zircons from Cretaceous granites yielded ages of 119–116 Ma. Other Cretaceous intrusive bodies include gabbro and syenogranite that commonly contain alkali minerals. Xu W L et al. (2013a, 2013b) and Tang et al. (2015) summarized Cretaceous volcanic rocks in NE China, with three stages of early Early Cretaceous (145–138 Ma), late Early Cretaceous (133–106 Ma) and Late Cretaceous (97–88 Ma). However, three-staged volcanic rocks show no distributional regularity. Early Cretaceous and Late Cretaceous volcanic rocks are small and mainly occur in the Yanji area in the central-eastern margin of NE China. The early Early Cretaceous volcanic rocks are mainly composed of A-type rhyolite and alkaline rhyolite. The late Early Cretaceous volcanic rocks are calc-alkaline and bimodal in nature, and commonly associated with

Au-polymetallic mineralization. Xu W L et al. (2013b) suggested that the early Cretaceous alkaline rhyolites indicated an extensional environment related to the collapse of the thickened crust after the closure of the Mongol-Okhotsk Ocean. The late Early Cretaceous calc-alkaline volcanic rocks in the eastern Heilongjiang-Jilin provinces indicate an active continental margin setting, and the coeval bimodal volcanic rocks in the Great Xing'an Range and the Songliao Basin suggest an intracontinental extensional environment related to the low-angle subduction of the Paleo-Pacific Plate beneath the Eurasian continent.

Late Cretaceous magmatic rocks are well distributed in Japan. Early Cretaceous granites (120–110 Ma) are limited, only found in NE Japan to the east of the Tanakura Tectonic Line (Ishihara, 2007). The Kitakami Mountains are quartz diorite-tonalitic in the west, granodiorite in the middle, adakitic in the east (Zone II), and granodiorite and granitic with equivalent effusive facies in the easternmost zone (Zone I). These granitoids become magnetic toward the east, including a strongly magnetic belt in the eastern offshore belt shown clearly in the aeromagnetic map. The representative strata are the Kuji and Noda Groups in the Noda area in the central-northern Japan. The Late Cretaceous Kuji Group unconformably overlies the Late Cretaceous (121–110 Ma), and documented a fission track age of 71±2 Ma indicating the upper formation (Nishiro and Yoshida, 2014). Sasaki and Tsuchiya (1999) pointed out the magmatic resemblance between the volcanic rocks in the Rebun-Kabato Belt and the Harachiyama Formation (Cretaceous volcanic rocks) near Kuji Basin. This volcanic belt is considered to form in the Berriasiane Cenomanian time, designating before the onset of the Kuji Group, on the basis of the isotopic ages of volcanic rocks and radiolarian fossils from the mudstones intercalated in the volcanic rocks (Nagata et al., 1986; Kondo, 1993). Furthermore, the age of the Harachiyama Formation is 119–93 Ma (Shibata et al., 1978) and the Late Cretaceous Campanian-Maastrichtian volcanic rocks, which yielded an age of 71±2 Ma ($^{40}Ar/^{39}Ar$ dating), were also reported (Takigami, 1991). Late Cretaceous granites mainly formed in 100–60 Ma, and <60 Ma granites occur in the Hokkaido area (Mao et al., 2009). Late Cretaceous granites occupy ~70% in volume of granite outcrops in Japan. The Sambagawa belt (90–70 Ma) is located on the southern side of the median tectonic line (MTL) (Tsujimori et al., 2000). Summarizing the above information and data boils down to the duration of Late Cretaceous magmatic activity in Japan into Middle Eocene (45 Ma). Most researchers attributed this period of magmatism to the subduction of the Pacific Plate. Kinoshita (1995) noted the migration of igneous activities in SW Japan during Late Cretaceous-early Tertiary. In the inner zone of SW Japan, the northern part of the MTL, granites and their volcanic equivalents formed in large quantities during Late Cretaceous to Early Tertiary (Figure 9). They show a migratory trend in age along the MTL, coinciding with the general direction of strikes in SW Japan. From the age distribution and the cooling histories of the bodies, it was concluded that the magmatism migrated eastward along the MTL with a rate of 30 km/Ma Such migration can be extrapolated to the Mesozoic igneous rocks in the East Asian continental margin, where two magmatic belts ranging in age from Cretaceous to Paleogene are found to become younger northeastwardly along the margins. This can be ascribed to the subduction of the Farallon- Izanagi and Kula-Pacific ridges.

6. Discussion and summary

6.1 Geological and geophysical profile of the Mesozoic tectonic evolution in NE Asia

Synthesizing the available geological and geophysical information can outline the Mesozoic tectonic evolution in NE Asia in three aspects.

(1) All or most of the KP belongs to a part of China-Korea continent (Sino-Korea Craton) since Paleoproterozoic or Neoarchean (Oh, 2006; Zhai M G et al., 2007). Systematic geological and geophysical study suggested that the Sino-Korea (or the NCC) and South China (or the Yangtze) blocks were collided together along the Paleo-Tethys orogenic belt (the Qinling-DSOB) during 255–230 Ma (Taira, 2001). Meanwhile, the CAOB between the Sino-Korean and Siberian cratons was under way, leading to the amalgamation of the Sino-Korea Craton with multiple terranes in NE China. A Proto-Japan might usher in with the Jurassic accretionary prisms and occupy an extensive area in the Japanese arc system and even in East Asia (Kojima and Kametaka, 2000), although there was no typical magmatic record for an arc system (Ishihara, 2007). It has been documented by Carboniferous-Permian basaltic rocks, Carboniferous-Permian-Triassic reef limestones, Permo-Triassic red to green ribbon cherts and shales, and Jurassic turbidites (Matsuoka, 1992; Nakae, 2000). Therefore, main geological units, including Korea, Japan, North China, South China and NE China, were in proximity to one another and constituted a coherent East China-Korea-Japan geotectonic pattern of NE Asia since Late Permian-Triassic on.

(2) It is suggested that the subduction of the Izanagi plate might continue from Triassic to Late Jurassic along the southern margin of the SCB with subduction of the Izanagi-Kula ridge starting in the east during Late Jurassic (ca. 150 Ma) and moving northeastwards during Early Cretaceous (ca. 120 Ma). This resulted in extensive Jurassic-Cretaceous magmatism (Kinoshita, 1995; Maruyama et al., 1997; Kusky et al., 2007). Oh (2006) suggested that the Mesozoic batholithic granitoids in South Korea are part of this extensive magmatic belt along the East Asian continental margin during the Mesozoic that extends from the southern portion of Guangxi in South China via the KP to the Far East Russia. After regional intrusion of Jurassic

granitoids, the Hida belt was thrust over the inner zone of SW Japan, while additional Jurassic and Cretaceous accretionary complexes were added to Japan. However, the suggestion still lacks the support from magmatism (Kinoshita, 1995; Nishiro and Yoshida, 2014).

(3) The Japan Sea and Yellow Sea were suggested to open in Miocene (~15 Ma). Respective tectonic effects of continental collision in Asia and back arc spreading are considered either as independent or closely related. The collision of India could have tectonic influence as far north as Japan and Sakhalin, determining the geometry of back arc opening therein and diffuse extrusion (Jolivet et al., 1994). The rhombohedral shape of the Japan Basin and the specific tectonic behaviors in both eastern and western margins could be explained by an Early Eocene-Oligocene rifting of a pull-apart basin that accommodated along two large dextral shear zones, east of Korea and west of NE Japan-Sakhalin. It is followed by the main opening of the Japan Basin as a mega pull-apart, during Upper Oligocene/Lower Miocene. Subsequent back-arc spreading might relate to the subduction processes, leading to the formation of the Yamato and Tsushima Basins at the end of Lower-Middle Miocene. From 1–2 Ma to the present, compression seems to prevail along the eastern margin of the Japan Sea (Lallemand and Jolivet, 1986).

6.2 Comparison of Mesozoic granites and related rocks in NE Asia

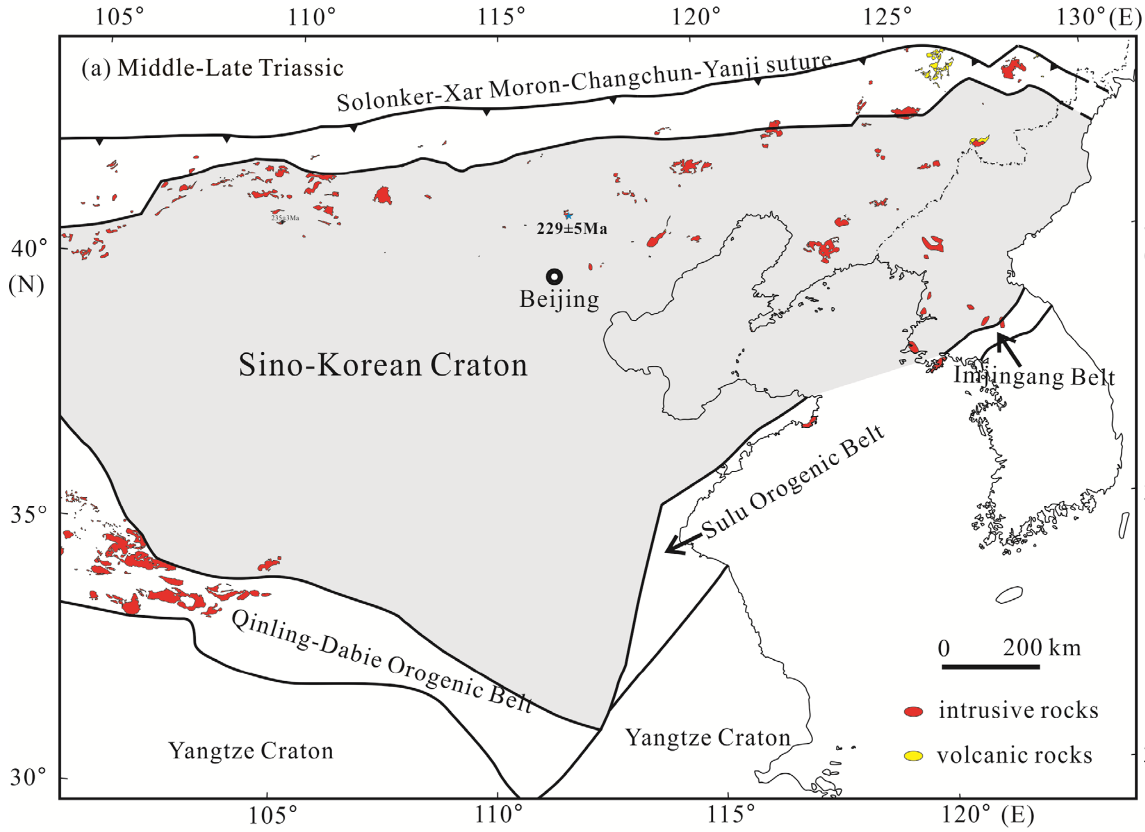
As stated in the introduction, the spatial-temporal distribution of Mesozoic granitoids and related rocks in NE Asia is clear. The following chart outlines it in the main terranes in NE Asia (Figure 18).

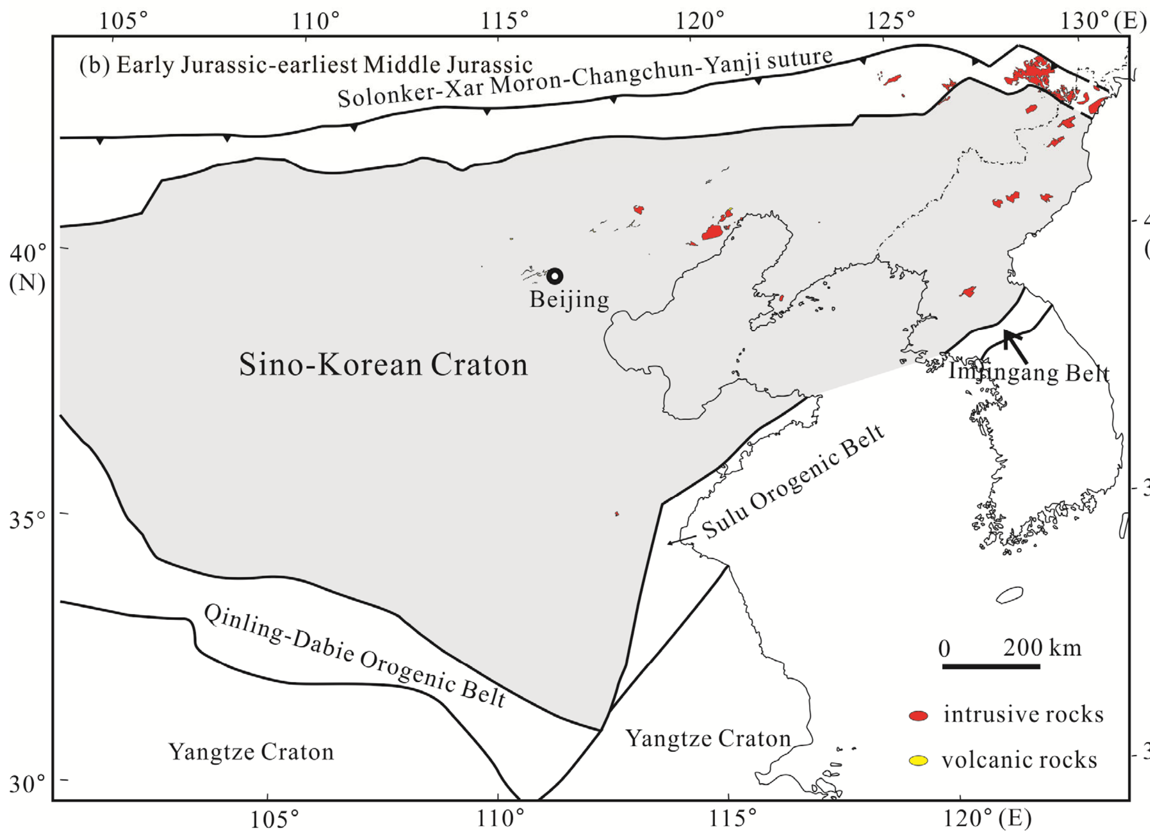
During the Triassic period of 250–205 Ma, granitoids and related rocks are distributed in all terranes in NE Asia, along with the metamorphic rocks of similar ages. All these magmatic and metamorphic rocks are interpreted as the result of Indosinian orogeny, linking to the CAOB or Qinling-DSOB. Figure 18a shows Middle-Late Triassic magmatic rocks in the NCC. They are well-developed in its northern margin and northern-central part. The Triassic syenite/A-type granite zone in the latter has been argued to form in an intracontinental setting (e.g., Mu et al., 2001; Shao et al., 2003). The Mesozoic syenite-alkaline granite zone in North Korea seems to relate to the CAOB, although some researchers ascribed it to the DSOB (e.g., Peng et al., 2008). The Triassic granites and mangerites in South Korea are more likely associated with the DSOB. It is clear that both Indosinian orogenic belts played an important role in the tectonic evolution of the KP. The "old" augen granites in the Hida and Suo belts (220–170 Ma) along the inner zone of SW Japan (Tsujimori, 2002) were regarded to be the result of Indosinian orogeny when Japan was located near KP at ~250 Ma (Oh, 2006), although other researchers suggested that Proto-Japan took shape in Jurassic. For all such different views, a consistent theme is that all terranes in NE Asia were situated in the same geotectonic setting in Triassic and it was Indosinian orogeny that have led to the formation of the Mesozoic NE Asia continent.

A big difference existed in the spatial-temporal distribution between Early Jurassic-early Middle Jurassic and Middle Jurassic granitoids in various terranes of NE Asia. Intense Daebao-period granitoids intruded during 197–175 Ma and associated volcanics erupted with rifting characteristics. It was followed by weak early Middle Jurassic tectonic-magmatic events including 173–165 Ma granites and ductile deformation. A few volcanic rocks of ~188 Ma in the Taebaeksan Basin consist of a rhyolitic pyroclastic unit, including lapilli tuff and tuff breccia and overlying the basal conglomerates, and possibly formed in a small basin controlled by faults (Han et al., 2006). Unlike the Triassic ones, Early Jurassic-early-Middle Jurassic magmatic rocks are limited in East Asia. They occur in NE China and locally in Hida of Japan, but are nearly absent in the NCC and SCB (Figure 18b) (several such rocks have recently been reported in SCB, Ye et al., 2013 and references therein). The Middle Jurassic magmatic rocks are distributed in the NCC, SCB and NE China (Figure 18c), but not in Japan. Their spatial distribution is inconsistent with an arc-arc-back basin system from Japan via Korea to East China as suggested by the previous study (Oh, 2006). The Middle-Late Jurassic volcanic rocks mainly occur in the Yanshan or northern Hebei areas to the north of Beijing (Figure 19c). The middle Jurassic volcanic rocks and granites mainly occur in the central part of the SCB. The middle-Late Jurassic magmatism in the NCC and SCB has been suggested to represent intra-continental crustal reworking or distant effects of the subduction from Paleo-Mongol-Okhotsk Ocean or Paleo-Pacific Ocean.

The Early Jurassic and early Middle Jurassic granites are extensively distributed in NE China, constituting the so-called giant granite province of NE China. The granites in the Yanji area extend across the Yalu River to the northwestern KP, featuring similar ages and geochemical characteristics. The Early Jurassic granitoids are commonly considered to result from subduction/collision/post-collision processes within the scope of CAOB. The Middle Jurassic granites are thought to relate to the CAOB or Paleo-Pacific regime (e.g., Zhao et al., 2004; Wu et al., 2011; Xu L J et al., 2013). It is remarkable that Late Jurassic magmatic rocks in Korea and NE China are rare, in contrast with their prevalence in the NCC and SCB. This implies total difference in geotectonic setting between the NCC-SCB and the KP-NE China during Jurassic.

Cretaceous magmatic rocks are well distributed in East Asia, with peaked age span from 110 to 65 Ma in the KP and a peaked span of 135–110 Ma in East China. While 110–100 Ma granitoids are widespread in the whole peninsula, ~130–120 Ma granitoids are restricted to its northwestern part, still 90–65 Ma volcanic rocks and related gra-





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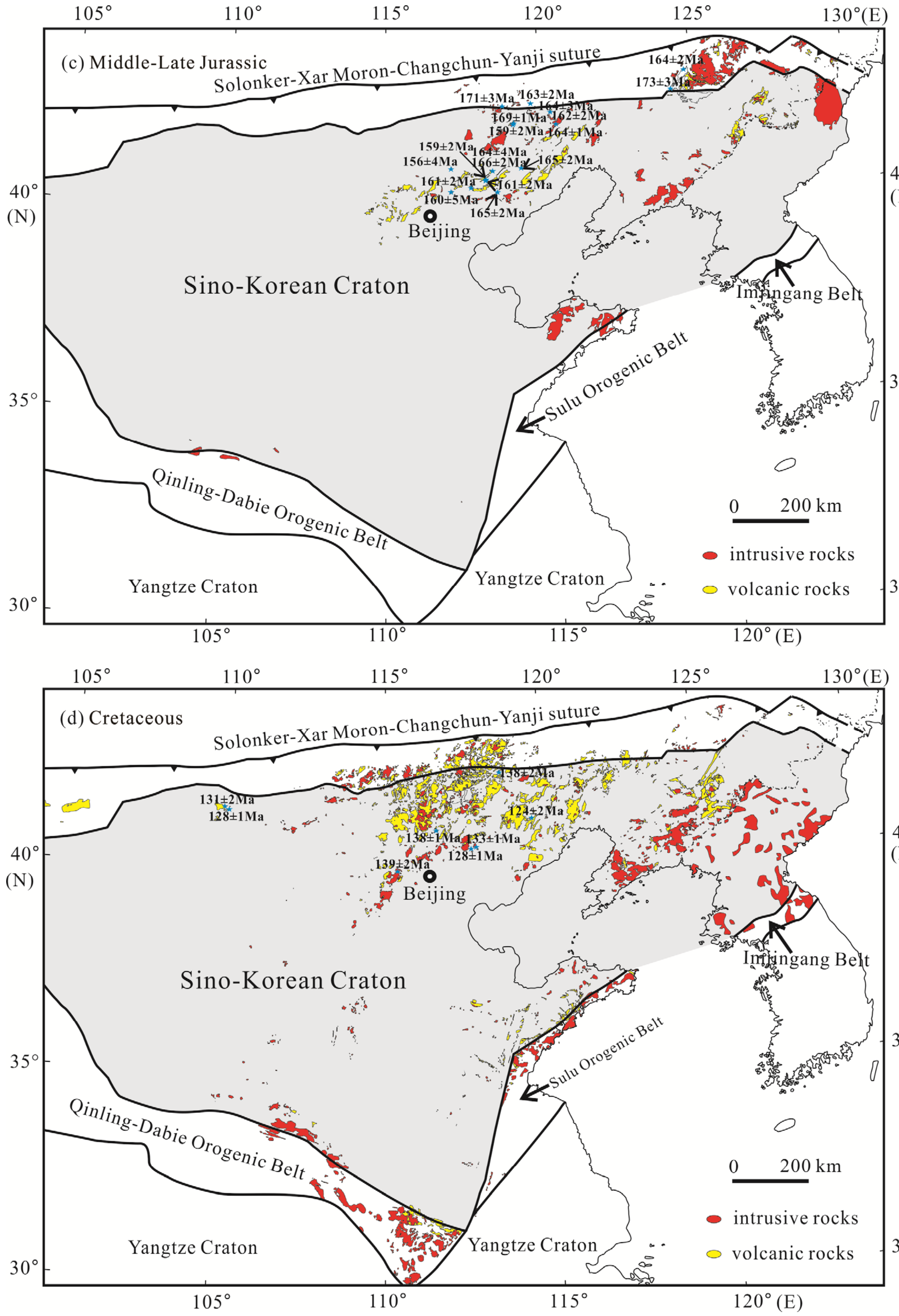

Figure 18 Distribution of magmatic rocks in the NCC and North Korea (modified from Zhang S H et al., 2014). (a) Middle-Late Triassic; (b) Early ad early-Middle Jurassic; (c) Middle-Late Jurassic; (d) Early Cretaceous.

nitic veins/bodies sporadically occur in its southeastern corner. It is difficult to establish a genetic connection between 110–100 Ma granites and 90–65 Ma volcanic rocks in the KP. A number of ~120–110 Ma granites are present in NE Japan, whereas 90–65 Ma volcanic rocks mainly occur in the southern Japan. In the Sambagawa belt on the southern side of median tectonic line, the metamorphic complexes therein contain eclogite and high-*P*/*T* schist, with metamorphic ages of 90–70 Ma. With these volcanic and metamorphic rocks, the Sambagawa belt has been suggested

Age	Period	North China craton: West Hill	North China craton: Northern Hebei	North China craton: Eastern Shandong	Japan	Korean Peninsula: North	Korean Peninsula: South	NE China	South China Block: Along SE coast
65 Ma–100 Ma	K_3				100(110)-90 Ma volcanics 90-65 Ma / Sanbagawa metamorphic belt		Gyengsang magmatism 100-77 Ma	97-88 Ma a few volcanics	97-65 Ma volcanics
100 Ma–120 Ma	K_2			125-115Ma volcanics	125-105 Ma granites (weak)	110±5 Ma granites (strong)	110±5 Ma granites (strong)	volcanics granites	120-100 Ma volcanics/granites
120 Ma–135 Ma	K_1	Tiaojishan Formation Granites	granites volcanics	granites	125-120 Ma			volcanics granites	volcanics granites
135 Ma–157 Ma	J_3-K_1	Jiulongshan Formation Zhangjiakou Formation	volcanics granites	granites					granites
157 Ma–175 Ma	J_2	granites	granite s	granites		173-163 Ma granites		170-165 Ma granites/volcanics	volcanics granites
175 Ma–205 Ma	J_1		granite s		197 Ma Funatsu granites	granites, volcanics 197-175 Ma		granites 190-170 Ma	
205 Ma–250 Ma	T	230-210 Ma granites	230-210 Ma granites	A few granites	220 Ma Hida metamorphic belt 248-245 Ma old granites	230-210 Ma (246Ma; 264 Ma)	230-210 Ma granites	250-200 Ma granites	230-205 Ma (276 Ma)

Figure 19 Chart showing the distribution of Mesozoic granitoids and related volcanic rocks in main geological terranes in NE Asia.

to be a Late Cretaceous subduction zone (Tsujimori et al., 2006). By contrast, widespread Early Cretaceous magmatism in East China ranges in age from 140 to 110 Ma with a peak of 130–125 Ma. The granitoids in the SCB are mainly concentrated in the middle and lower reaches of the Yangtze River and the Nangling Range with polymetallic deposits. In the NCC, Early Cretaceous magmatic rocks occur in all eastern part except for Mesozoic-Cenozoic basins in the eastern NCC (Figure 18d), whereas Late Cretaceous magmatic rocks are rare. Zhai M G et al. (2007) suggested that the lower crust was thinned together with lithospheric mantle in the eastern NCC. The present lower crust has been formed through underplating and replacement within the context of lithospheric thinning. Both lower crust thinning/replacement and lithospheric thinning are controlled by the same dynamic mechanism. Zhai et al. (2002) identified the eastern boundary of the Jiaodong gold deposit cluster, coinciding with the boundary between the NCC and DSOB in the eastern Shandong. The host rocks of the gold lodes are Mesozoic granites and early Precambrian basements of the NCC. A lot of Cretaceous granitoids are developed in the eastern part of CAOB in NE China, and in the DSOB from Dabie Mountains to northern Jiangsu-eastern Shandong provinces. They may all have formed in the same tectonic regime (Wu et al., 2011; Zhang S H et al., 2014; Tang et al., 2015).

6.3 Constraints on cratonic destruction in the NCC

Magmatic rock associations and their spatial-temporal distribution reflect inherent geotectonic settings and processes. This is especially true in converging plate zones, with typical magmatic and metamorphic rock associations controlled by prolonged processes of subduction, collision and post-collisional extension. Therefore, spatial-temporal distribution of magmatic suites can be effective indicators to monitor geotectonic evolution.

Cretaceous magmatic activity has a critical bearing on lithospheric thinning and cratonic destruction (Fan and Hooper, 1991; Fan and Menzies, 1992; Menzies et al., 1993; Zhai M et al., 2002, 2007; Zhang Z et al., 2012; Zhu R et al., 2012, 2015). Our previous study in the eastern NCC noticed the following features (e.g., Zhai M et al., 2001, 2002, 2004b, 2007): (1) The Mesozoic magmatism shows no zonal regularities in temporal-spatial distribution but exhibits temporal change in magmatic composition, marking the tectonic inversion from compression to extension and lithospheric thinning in the region. (2) Adakite and high-Mg andesite along the northern and southern margins of the craton attest to lower crustal delamination soon after continental collision, but there is no such evidence within the NCC. (3) Voluminous High-Sr granitoid bodies at 160–140 Ma may have derived from partial melting of lower crust. Mantle upwelling provided the heat for such lower crustal melting. (4) The present lower crust in the NCC has three layers including a thick crust-mantle transitional zone. The base of the lower crust was partly to mostly replaced by underplated magmatic rocks at 130–120 Ma. (5) The large-scale crustal partial melting led to lower crustal thinning and produced residues of eclogite or garnet-amphibolite. The high-density residues were probably recycled into the lithospheric mantle or asthenosphere. The remnant eclogite was probably small and its foundering was not the cause of extensive lithospheric thinning (80–120 km) beneath the NCC.

Most researchers considered that the peak time of destruction in the NCC is 130–120 Ma (e.g. Zhai et al., 2004b; Wu et al., 2005b; Zhu R et al., 2012). However, a controversy concerns the starting time of destruction in the NCC. For example, Yang et al. (2012) suggested that the cratonic destruction followed post-collisional and intraplate extension of the Indosinian orgeny, therefore cratonic destruction likely started in Early Jurassic or early Middle Jurassic. Dong et al. (2008) suggested that the cratonic destruction started from Late Jurassic-Early Cretaceous. According to their point of view, simultaneous opening of three major global oceans during Late Jurassic and their subduction around East Asia might form multiple compressional and convergent tectonic system, after that an extensional tectonic regime resulted in lithospheric thinning. The other prevalent view from most researchers is that the Pacific subduction presents the main dynamic factor triggering the cratonic destruction. The seismic tomography by Zhao et al. (2007) provides a model that the subducted western Pacific plate seems to extend deeply and distantly beneath the central NCC. This echoes the earlier debates on when and how the Paleo-Pacific-Kula-Inazaki plates operated (e.g., Ito, 1988, 1999; Isozaki, 1997; Maruyama et al., 1997; Sun et al., 2007).

Late Cretaceous volcanic rocks occur in three areas along the southeastern coastal zone of China (Figure 12), and they show affinities of island arc or back-arc basin. Accordingly, Mao et al. (2014a, 2014b) suggested that South China, Korea and Japan were situated at the same Pacific system. Oh (2006) suggested that the subduction of the Kula-acific ridge initiated in SE China (160 Ma in central Guangdong province) and migrated northeast, generating Cretaceous igneous activity along the southern border of the SCB. The Kula-Pacific ridge was subducted below the KP at 90 Ma, giving rise to Cretaceous granites and volcanic rocks in the Gyeongsang basin in Korea. Ridge subduction migrated to Japan by 80 Ma yielding Cretaceous granites and volcanic rocks in the inner zone of SW Japan. The migration of the Kula-Pacific ridge subduction continued until 30 Ma, when it was subducted below the Aleutian Islands. Sun et al. (2007) emphasized that the drifting direction of the subducting Pacific plate changed several times during Mesozoic. East China became an active continental margin before Jurassic. From Late Jurassic to Cretaceous (140–125 Ma), it was proposed that this margin was related to the subduction of the Pacific plate in the south, concurrent with oblique subduction of the Izanagi plate in the north. The stress field along the Tan-Lu Fault experienced several major changes in the Cretaceous. In the Early Cretaceous eastern China was dominated by roughly north-southward extension and rifting. In the NCC, Early Cretaceous magmatism was associated with extension with a peak at 125 Ma. In the late Early Cretaceous from 125 to 110 Ma, the extension was replaced by southeast-northwestward transpression. Several million years later, the stress field in eastern China switched to roughly east-westward pull-apart and extension-related magmatism resumed. The Early Cretaceous large-scale crustal reworking and gold mineralization in the NCC was closely connected that transformation of the plate subduction. Synthesizing basin analyses, metamorphic core complex, fault kinetics and dyke distribution, Zhu G et al. (2012) considered that the eastern NCC experienced NWW-SEE extension during the early-middle stage of Early Cretaceous, NW-SE stretching during the late Early Cretaceous and NS extension during the late Cretaceous-Paleogene. This clock-wise change in extensional direction coincides with the movement direction of the Pacific Plate. This suggests that the cratonic destruction in the NCC likely took place in a back- arc extensional setting in the continental margin related to the movement of the Pacific plate.

As a supplement to surface geological study, systematic in-depth observations, experiments and theoretical synthesis have been made, with an emphasis on the spatial-temporal distribution of cratonic destruction, the deep structure and shallow geological records of cratonic evolution, and the mechanism and dynamics of cratonic destruction (Zhu G et al. 2012). This led to the following conclusions: (1) significant spatial heterogeneity exists in the lithospheric thickness and crustal structure, which constrains the scope of the destruction. (2) nature of the Paleozoic, Mesozoic and Cenozoic sub-continental lithospheric mantle (CLM) underneath the NCC is distinct in detail. In terms of water content, the late Mesozoic CLM was rich in water, whereas the Cenozoic CLM was water-deficient. (3) The correlation between magmatism and surface responses confirms that the tectonic evolution is governed by cratonic destruction processes. Various models have been suggested for the lithospheric thinning and cratonic destruction in the eastern and central NCC (e.g. Xu, 2001; Zheng et al., 2003; Zhang et al., 2005; Wu et al., 2003; Li S Z et al., 2012), featuring several possible triggers (Wu et al., 2008). Some researchers prefer the dominant role of the Pacific subduction (e.g. Zhu G et al., 2012; Xu, 2014; Dai et al., 2016). However, uncertainities still persist concerning the related geochemical and geophysical evidence. For example, two high-velocity bodies have been observed below the stagnant Pacific slab in the velocity map of the mantle transition zone of the NCC (Zhu et al., 2015). They have been assumed to be remnants of the subducted paleo-West Pacific plate during the Early Cretaceous, although it is hard to confirm their age. Yu et al. (2010) and Xu (2014) documented the basalts with secular geochemical variation trends from NE China and eastern Shandong, showing different melting temperatures of the upper and lower oceanic crust and progressive thinning of the lithosphere. The more fertile basaltic crustal component is preferentially sampled during the early stage of volcanism, whereas the more depleted gabbroic lower crust and lithospheric mantle components are preferentially sampled during a late stage (Yu et al., 2010; Xu, 2014). The presence of significant recycled oceanic crustal components in the 90–40 Ma basalts could be related to Pacific subduction beneath the NCC in the late Cretaceous (Xu, 2014). This echoes previous views from other researchers (e.g. Zhang et al., 2002, 2003; Zhai M et al., 2002, 2004a, 2007; Wu et al., 2005b), who noted the magma source shift from the enriched lithosphere for the volcanic rocks of older than 130–120 Ma to the depleted one for Late Cretaceous to Cenozoic volcanic rocks. Most recently, Dai et al. (2016) pointed out that this dramatic demarcation between ancient SCLM to juvenile SCLM stands at ~121 Ma, and the absence of mafic magmatism in the period from ~200 to ~135

Ma records a duration of cratonic thinning due to the westward flat subduction of the Paleo-Pacific slab beneath the NCC. The analyses on sedimentary basins and regional structures also indicated that a tectonic transition from contractional to extensional deformation occurred in 130–120 Ma, possibly in response to an inverse of geotectonic mechanism (Lin et al., 2007; Zhu G et al., 2012). Noting a broad scope of Early Cretaceous extentional deformation spanning from the eastern NCC and NE China via Inner Mongolia to central Mongolia, Meng (2003) suggested that the stretching and breakoff of the subducted Mongol-Okhotsk oceanic slab, in conjunction with gravitational collapse and spreading, might serve as the driver for the late Mesozoic extensional tectonism in this tract.

Abundant data on the granitiods and related rocks from the KP could facilitate the comparative study with other areas of NE Asia and provide refined constraints on the cratonic destruction.

(1) As shown in Figure 19, the records of Triassic magmatism and metamorphism in all terranes indicate that the formation of a united NE Asia continent similar to the present can be attributed to the Indosinian orogeny during late Triassic.

(2) During Early Jurassic to early Middle Jurassic, magmatic rocks occurred in the KP and NE China but rarely in Japan. Middle Jurassic volcanic and granitoid rocks occurred in most terranes except Japan. Numerous studies (e.g., Kinoshita, 1995; Oh et al., 2006; Nishiro and Yoshida, 2014; Mao et al., 2014a) resorted to the subduction of the Farallon-Izanagi ridge beneath the SCB to explain Jurassic igneous activity within the SCB. The same subduction event might produce the Daebo granites in the KP and the Funatsu granite in the Hida belt of Japan.

(3) Magmatic activity in the KP was weak during Middle Jurassic (~173–163 Ma) and muted from Late Jurassic to Middle Cretaceous (~110 Ma). By contrast, Middle-Late Jurassic volcanic rocks and granitoids are well developed in the NCC, SCB and NE China, representing the episode A in the Yanshanian Movement.

(4) Early Cretaceous magmatism is strongest in the NCC, SCB and NE China, associated with large-scale gold-metallogeny. The magmatism has been interpreted as crustal reworking, representing the episode B of the Yanshanian Movement and the peaked period of lithospheric thinning. It is noteworthy that Early Cretaceous magmatic rocks are rare in the KP and sporadically occur in Japan.

(5) Late Middle Cretaceous granites present as diagnostic occurrence in the KP, in contrast with their rarity in the SCB, NE China and Japan. Moreover, Late Middle and Late Cretaceous magmatic rocks are absent in the NCC.

(6) Late Cretaceous volcanic rocks and granites occur in the Gyengsang basin in the southeastern corner of the KP. The lower (~94–80 Ma) and upper (~70–55 Ma) parts of the volcanic-sedimentary rocks show tectonic affinities of island arc and back-arc-basin, respectively. The corresponding rhyolites and related granites in SW Japan have ages of 86–84 Ma and 74–62 Ma (Sonehara and Harayama, 2007; Mao et al., 2014b), while the Sabagawa metamorphic belt features metamorphic ages of 90–70 Ma. The Inner belt of southwestern Japan tends to show a younging trend of volcanic rocks from west to east. The magmatic rock associations from Japan to Korea argue for Pacific plate subduction during Late Cretaceous.

In summary, this study demonstrates that the magmatic/metamorphic rock associations and their spatial-temporal distribution in East China, Korea and Japan are inconsistent with the subduction of the Paleo-Pacific Plate.

We would like to emphasize two points. First, the NCC has been located at a specific junction among multi-continental or oceanic plates during Late Triassic to early Middle Jurassic. The accumulated effects from multi-directed compression-convergence or extension-drifting could operate. Second, complicated interactions from changing ocean-continent patterns and independent continental dynamics could be a contributing factor when the adjacent plates move relative to each other. Figure 20 shows a probable stress scenario during the latest Jurassic to Early Cretaceous (Zhai et al., 2004a). The tectonic influence from the subduction-collision processes in the Paleo-Mongol-Okhotsk Ocean regime could last up to the present. Following Late Permian- Early Triassic collision, Jurassic and Tertiary subduction from the Paleo-Mongol-Okhotsk Ocean are important (Worrall et al., 1996). In the Yanshan area of central-northern NCC, the pre-Late Jurassic basins belong to compressive-flexure associated with NEE-trending thrust zones. The Late Jurassic NNE-trending rift basins coexisted with the uplifted zones. The post-Late Jurassic basins trending NE-NNE coexisted with active uplift zones and controlled by NEE-trending thrust zones. The southern and northern Dabieshan units have different exhumation histories with the thrusting in Middle Jurassic-Early Cretaceous (Lin W, private communication). Ding and Lai (2003) noted that the crustal shortening and fast uplifting happened during Late Jurassic in the southern margin of Asia and proposed that the northward subduction of the Tethys Ocean started at least before Late Jurassic. Concurrent effects could come from the Jurassic-Early Cretaceous Paleo-Pacific oceanic regime. Compressional stress could be principal in Middle-Early Late Jurassic, while extensional stress tend to dominate in Late Jurassic to Early Cretaceous.

Standing among the surrounding plates during the Cretaceous, the NCC was firstly in a joint compressional stress field and then in an extensional stress field, with a mantle upwelling acted on the NCC (Zhai et al. 2004a, 2004b; Dong et al., 2008; He et al., 2015). The resultant strong crust/mantle interaction led to magmatic underplating, significant lower crustal fusion, delamination and fluid infusion into lithospheric mantle. Asthenospheric upwelling provided the heat for such lower crustal melting, although the lithosperic thinning process is still unclear. Fluid addi-

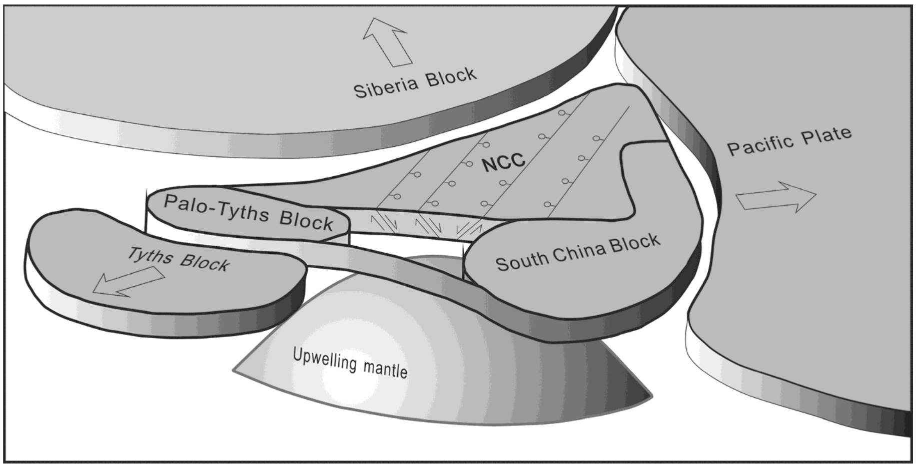

Figure 20 Tectonic model for Lithospheric thinning of the eastern NCC (after Zhai et al., 2004a).

tions to the ancient cratonic mantle may be an important function. Zhang et al. (2009) suggested that such episodic magma underplating resulted in the compositional modification of the ancient lower crust, markedly similar to the compositional transformation from the refractory lithospheric mantle to a fertile one through the refractory peridotite-melt reaction. A part of cratonic lithosphere mantle transferred to fertile asthenosphere is a manifestation pattern of lithospheric thinning. The present lower crust in the NCC has three layers including a thick crust-mantle transitional zone. The base of the lower crust was partly to mostly replaced by underplated magmatic rocks at 140–120 Ma (Xu, 2001; Zhai and Fan, 2002). The adakite-like granites in eastern Shandong can derive from mafic lower crust and need no orogenic process and thickened crust (Ma et al., 2015). However, the amount of remnant eclogite was probably small, and foundering of this material was not the cause of extensive lithospheric thinning (80–120 km) beneath the NCC. This study raised another possibility that the cratonic destruction of the NCC might not only be due to the subduction of Paleo-Pacific Plate, but also owe much to the intraplate geodynamic forces triggered by other adjacent continental plates like the Eurasian and Indian plates.

7. Conclusions

1) The KP hosts massive Mesozoic igneous rocks. They can be classified into three age groups, i.e., Triassic granites with a peak age of ~220 Ma, Jurassic ones of ~190–170 Ma and Cretaceous ones including ~110 Ma granites, bimodal calc-alkaline volcanic rocks of 94–55 Ma and granitic-hypabyssal intrusive bodies of 72–70 Ma.

2) Triassic igneous rocks include syenite, calc-alkaline and alkaline granites, as well as minor kimberlite in the Pyeongnam Basin of North Korea. They have been considered to form in post-orogenic setting related to the CAOB in the northern-central KP and the DSOB in the central-southern KP.

3) Jurassic granitoids are well-developed in the KP, designated as the Daebo-period magmatism. They are comparative to coeval counterparts in NE China, the northeastern corner of the NCC and eastern end of the CAOB. However, Early Jurassic to early Middle Jurassic magmatic rocks turned out to be rare occurrence in most parts of the NCC, so did Middle-Late Jurassic granites and volcanic rocks in the KP.

4) Abundant Cretaceous granites show a great contrast in formation time between NCC and KP, with the peak ages of ~130–120 Ma in the former and ~110–105 Ma in the latter. A few granites of ca. 130–125 Ma occur in the northwestern margin of KP. Early-Middle Cretaceous granitoids and volcanic rocks are not developed in Japan.

5) Late Cretaceous volcanic rocks are only documented in the Gyeongsang basin in the southeastern corner of KP. Together with the Sambagawa metamorphic belt, the Jurassic Chichibu accretionary complex containing Cretaceous strike-slip basin sediments, and the Cretaceous Shimanto mélange zone in SW Japan, they tend to trace a continuous island arc system in SE Korea extending from SW Japan during ~94–80 Ma. The Gyeongsang basin changed in affinity from island arc to back-arc with bimodal volcanic rocks of ~70–55 Ma.

6) Most Triassic granitoids and Jurassic-Cretaceous magmatic rocks in the KP usually contain numerous inherited zircons with ages of ~1.8–1.9 or ~2.5 Ga. Most magmatic zircons have $\varepsilon_{Hf}(t)$ values from −25 to −15, indicating that their derivation from re-melting a similar old basement to the NCC.

7) Synthesizing the present abundant data on the Mesozoic granitoids and related rocks from the KP, East China and Japan, it is possible to compare Mesozoic magmatism and its tectonic setting in NE Asia. In summary, (1) all geological terranes in NE Asia were situated in the same setting in Triassic and Indosinian orogeny led to the formation of the Mesozoic NE Asia continent; (2) Jurassic-middle Late

Cretaceous magmatic rock associations provide no evidence for the subdution of the Paleo-Pacific Plate in Japan-Korea-North China; (3) Late Cretaceous volcanic rocks from Japan and the Gyeongsang Basin in the KP might attest to the subdution of the Paleo-Pacific Ocean, whereas the NCC might be exempt from this subduction.

8) This study raises another possibility that the cratonic destruction in NCC might not only be due to the subduction of Paleo-Pacific Plate, but also owe much to the intraplate geodynamic forces triggered by other adjacent continental plates like the Eurasian and Indian plates. Compressional stress could be principal in Middle-Early Late Jurassic, whereas extensional stress could dominate from Late Jurassic to Early Cretaceous. Strong crust/mantle interaction gave rise to magmatic underplating, significant lower crustal fusion, delamination and fluid additions to lithospheric mantle. The significant thinning tends to happen not only in mantle but also in crust. The cratonic lithosphere mantle has been transferred to fertile asthenosphere mantle with fluid replacement and large-scale melting of the lower crust associated magma underplating.

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