지질학회지 제 57권 제 4호, p. 523-544, (2021년 8월)
J. Geol. Soc. Korea, v. 57, no. 4, p. 523-544, (August 2021)
DOI http://dx.doi.org/10.14770/jgsk.2021.57.4.523

ISSN 0435-4036 (Print)
ISSN 2288-7377 (Online)

북한지역 고생대-중생대 화성암 및 퇴적암에 대한 종합검토

Yan-Bin Zhang[1,2] · Ming-Guo Zhai[1,2,3,‡] · Fu-Yuan Wu[1,2,3] · Xiao-Hui Zhang[1,2] · Qiu-Li Li[1,2,3] · Peng Peng[1,2,3] · Lei Zhao[1,2] · Li-Gang Zhou[1,2]

[1]State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences
[2]Innovation Academy for Earth Science, Chinese Academy of Sciences
[3]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences

요 약

북한에 대한 지질학적 정보의 부족은 한반도의 지질학적 진화를 이해하는데 큰 장애가 되고 있다. 본 논문에서는 북한의 고생대-중생대 화강암류와 퇴적암에 대한 연구를 종합 검토하였다. (1) 평남분지는 하부의 고생대 초기 황주누층군(황주층군과 법동층군)과 상부의 고생대 후기 평안누층군으로 구성되어있다. 캠브리아기 황주층과 하부 법동층의 $\delta^{13}C$는 변화폭은 작으나(-4~+4‰) 자주 변화한다. (2) 고생대 중기 임진층군은 평남분지 남쪽 경계부에서만 나타나며 후기 데본기에 퇴적되었다. 한반도와 북중국판의 대표적인 고생대 퇴적층내 쇄설성 저어콘 연령분포형태가 유사한 사실은 한반도와 북중국판이 유사한 지구조 진화를 경험하였음을 지시하며 임진강대가 친링-다비-수루 충돌대의 연장이 아님을 지시한다. (3) 페름기 후기 화산-퇴적층군인 두만층군이 두만강대와 관모육괴에 퇴적되었다. (4) 중생대 퇴적층은 대부분 대륙내에 단층작용에 의해 형성된 분지내에 발달했으며 쥐라기 초기 대동계, 쥐라기 후기-백악기 초기 자성계 그리고 백악기 초-후기에 해당하는 대보계로 구성되어있다. 136-110 Ma 시기 동안 북한에서는 화산활동이 활발하게 일어났다. (5) 북한의 현생 화강암류와 그에 관련된 화성암들이 265-213 Ma, 199-163 Ma,136-83 Ma에 광역적으로 형성되었다. 남한의 현생 화성작용은 백악기 초기(136-110 Ma)에 해당하는 화성작용이 없는 것을 제외하고는 북한의 화성작용에 잘 대비된다. (6) 북한 두만강대와 관모육괴내 현생 화강암들의 연령분포형태와 지화학 특성이 중앙아시아조산대의 동부에 나타나는 현생 화강암들의 연령 패턴과 지화학 특성과 유사하다. (7) 북한의 트라이아스기 화강암류는 대륙내 열개 환경에서 형성되었으며 한반도의 북쪽과 남쪽 인근 지판들의 영향을 받았을 것으로 생각된다.

주요어: 고생대-중생대, 화강암류, 퇴적암, 북한

Yan-Bin Zhang, Ming-Guo Zhai, Fu-Yuan Wu, Xiao-Hui Zhang, Qiu-Li Li, Peng Peng, Lei Zhao and Li-Gang Zhou, 2021, Reviews on the Paleozoic-Mesozoic granitoids and sedimentary rocks in North Korea. Journal of the Geological Society of Korea. v. 57, no. 4, p. 523-544

ABSTRACT: The lack of relevant geological information and data in North Korea greatly hampers understanding of the geological evolution of the Korean Peninsula. This paper reviews the studies of the Paleozoic-Mesozoic granitoids and sedimentary rocks in North Korea. (1) Phyongnam Basin comprises lower Paleozoic Hwangju Supergroup (Hwangju and Bopdong Groups) and Upper Paleozoic Pyongan Supergroup. $\delta^{13}C$ values in the Cambrian Hwangju and lower Bopdong Groups fluctuate little (-4~+4‰), but frequently. (2) The middle Paleozoic Imjin Group only distributed in the southern margin of the Phyongnam Basin and deposited in Late Devonian. Similar detrital zircon age spectra of representative Paleozoic sequences in the Korean Peninsula and the North China Craton indicates that these two tectonic units might experience similar tectonic evolution, and the Imjingang Belt might not be the eastward extension of the Qinling- Dabie-Sulu Collisional Belt. (3) The late Permian volcano-sedimentary strata Tuman Group is well developed in the Tumangang Belt and Kwanmo Submassif. (4) The Mesozoic sedimentary strata are mostly developed in continental faulted basins, and consist of lower Jurassic Taedong, upper Jurassic-lower Cretaceous Jasong, and lower-upper Cretaceous Taebo Systems. The volcanic activity within 136-110 Ma in North Korea was significant. (5) Phanerozoic granitoids and related igneous rocks with age ranges of 265-213 Ma, 199-163 Ma to 136-83 Ma are widely distributed in North Korea. Except for the absence of early Cretaceous magmatism (136-110 Ma) in South Korea, other magmatic events can be comparable

‡ Corresponding author: +86-10-82998570, E-mail: mgzhai@mail.iggcas.ac.cn

to those in South Korea. (6) The age patterns and geochemical features of Phanerozoic granites in the Tumangang Belt and Kwanmo Submassif are similar to those of the eastern part of the Central Asian Orogenic Belt. (7) The Triassic granitoids in North Korea were most likely formed in intracontinental rift environment and were also influenced by adjacent blocks from the north and south of the Korean Peninsula.

Key words: Paleozoic-Mesozoic, granitoids, sedimentary rocks, North Korea

(Yan-Bin Zhang, Ming-Guo Zhai, Fu-Yuan Wu, Xiao-Hui Zhang, Qiu-Li Li, Peng Peng, Lei Zhao and Li-Gang Zhou, State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China; Yan-Bin Zhang, Ming-Guo Zhai, Fu-Yuan Wu, Xiao-Hui Zhang, Qiu-Li Li, Peng Peng, Lei Zhao and Li-Gang Zhou, Innovation Academy for Earth Science, Chinese Academy of Sciences, Beijing 100029, China; Ming-Guo Zhai, Fu-Yuan Wu, Qiu-Li Li and Peng Peng, College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China)

1. Introduction

The Korean Peninsula (KP) is situated at the eastern margin of the North China Craton (NCC; or Sino Korean Craton), with a complex and long geological history that extends deep into the Paleoarchean (~3600 Ma). It is generally considered that the KP can be divided into six tectonic provinces from north to south, i.e., the Tumangang Belt, Nangrim Massif (including Kwanmo and Nangrim Submassif), Imjingang Belt, Gyeonggi Massif, Okcheon Belt and Yeongnam Massif, respectively (Fig. 1a). The Paleozoic Phyongnam and Taebaeksan Basins are located within the Nangnim Massif and Okcheon Belt, respectively (Choi, 2018).

It has been long discussed for the tectonic relationship between the KP and China due to their strong affinities (e.g., Zhai, 2016; Zhai *et al.*, 2016, 2019). However, the absence of relevant geological information and data on North Korea (NK) greatly hampers our understanding of the geological history of the KP, and it's general tectonic framework in the NE Asia. In this paper, we report some new achievements and give a summary on the Paleozoic-Mesozoic magmatism and sedimentation in NK, which will shed a light on the Paleozoic-Mesozoic evolution of the KP, even of the NE Asia.

2. Paleozoic sediments

The Paleozoic sedimentary strata in NK are mainly developed in the Tumangang Belt, Hyesan-Rowon Basin and Hwaphyong-Jasong-Wiwon areas in the Nangrim Massif, and the Phyongnam Basin (Fig. 1b). Among them, the Paleozoic strata in the Phyongnam Basin have the largest outcropping area and relatively complete stratigraphic sedimentary sequence, which consist of the Lower Paleozoic (Cambrian-Middle Ordovician) and Upper Paleozoic (Late Carboniferous-Early Triassic) strata (Fig. 2). Between these two strata, an unconformity was existed, which indicates a deposition break more than 100 Myr. Rare Middle Paleozoic sediments are only distributed in the southern margin of the Phyongnam Basin and Imjingang Belt. The Tumangang Belt and Kwanmo Submassif lack the Lower Paleozoic strata, and characterized by development of the Late Paleozoic volcanic sedimentary formations.

2.1 Phyongnam Basin

The Phyongnam Basin in the Nangrim Massif is featured by Neoproterozoic to Triassic strata depositing unconformably on the Archean and Early Paleoproterozoic basement. The Lower Paleozoic sediments of the Hwangju Supergroup in the basin is exclusively of marine origin with subordinate siliciclastic rocks. The maximum thickness of this supergroup could reach 3,000 m, with an average thickness of 1,200-1,500 m. The Hwangju Supergroup was subdivided into the lower Hwangju and upper Bopdong Groups (Paek *et al.*, 1996; Park, 2012) the former one is dominated by marine terrigenous clastic deposits, while the later one is occupied by carbonate rocks.

The Hwangju Group is subdivided into conformably laid series in ascending order, namely the Pyongsan, Junghwa, Hukgyo and Rimchon Formations. The Pyongsan Formation is mainly composed of phosphate siltstones, carbonaceous slates, nodular phosphorites and Dolomites. Among them, the phosphorous and sulphide-bearing black slate at the bottom of this formation were considered as the boundary layer (Kim *et al.*, 2018). The Junghwa Formation consists of sandstone, siltstone, slate, and carbonate rock, with phosphate bearing siltstone at the bottom. The Hukgyo Formation is made up of terrigenous clastic rocks locally interlayered with carbonates. The Rimchon Formation is mainly composed of black phyllite with a limestone interlayer at the lowest part. The *hsuapis coreanicus* and *redlichia* belts occurred in the Pyongsan and Junghwa Formations, respectively, showing that these two formations should not be lower than Stage 3 and 4 of the Cambrian (Kim *et al.*, 2018). Carbon isotope study show that the $\delta^{13}C$ values in the Pyongsan Formation range from -3.1‰ to 0‰, Junghwa -4.7‰ to +2.0‰, Hukgyo -1.0‰ to +2.4‰, and Rimchon -2.6‰ to +0.4‰ (Kim *et al.*, 2016, 2018). Compared to the global carbon isotope of carbonate rocks, the Pyongsan,

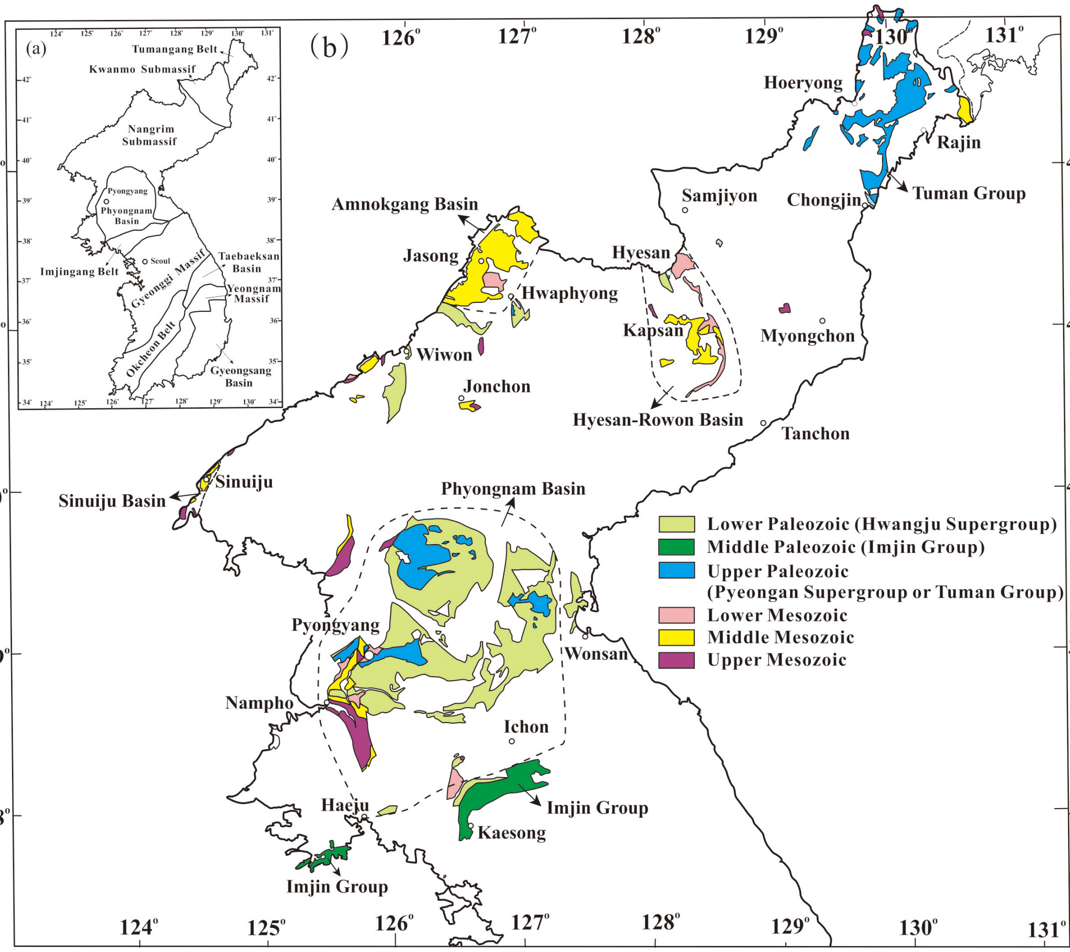

Fig. 1. (a) Tectonic units of the Korean Peninsula (revised after Paek *et al.*, 1996). (b) Distribution of Paleozoic-Mesozoic sediments in North Korea (modified after Paek *et al.*, 1996).

Junghwa and Hukgyo Formations belong to Stages 3-4 of Cambrian, and the Rimchon Formation is around the boundary of Series 2 and Miaoling Series, respectively (Kim *et al*., 2018). The positive carbon excursion in the upper Junghwa and Hukgyo Formations and negative in the lower Rimchon Formation are comparable to the global events of the mIngxinsi carbon isotopic excursion and redlichiid-olenellid extinction carbon isotopic excursion, respectively (Kim *et al*., 2018).

The Bopdong Group is subdivided into the Mujin, Kophung, Singok, Mandal, Sangsori, Koksan and Wolyang Formations, with a thickness of about 1,000 m. The first two formations are assigned to the Late Cambrian, middle three are Ordovician, and the last two are Silurian (Paek *et al*., 1996). The Mujin Formation is mainly composed of clay limestone, manganese-bearing limestone and layered limestone. The Kophung Formation is successive sequences of lower dolomite and limestone and upper dolomite and limestone. The Singok Formation consists mainly of dolomite with minor limestone. The Mandal Formation consists of lower limestone and upper dolomite. The Sangsori Formation consists of dolomite interlayered with mudstone, shale, and limestone. The Silurian Koksan and Wolyang Formations are only sporadically exposed in the Singye, Koksan and Popdong areas. The Koksan Formation is composed of siltstone, mudstone, shale and limestone, with a layer of siltstone at the bottom. The Wolyang Formation is mainly composed of limestone, with minor mudstone and dolomitic limestone (Paek *et al*., 1996). Carbon isotope study shows that the $\delta^{13}C$ values in the Mujin Formation range from -1.3‰ to 0.4‰ and the Kophung Formation displays -1.0‰ to +2.4‰ (Kim *et al*., 2018). Synthetically, the Kophung Formation belongs to the Furong Series of Cambrian, and the positive carbon excursion in the middle of the Kophung Formation is comparable to the

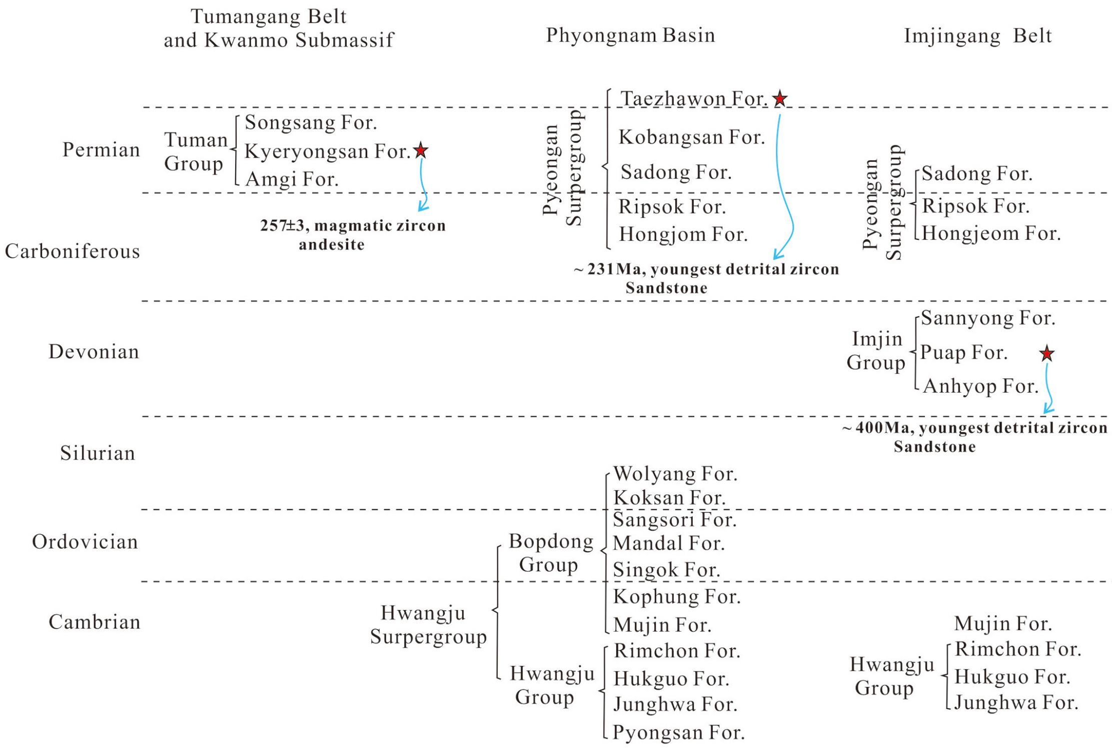

Fig. 2. The Paleozoic stratigraphic framework in North Korea.

global events of the Steptoean positive carbon isotopic excursion (Kim *et al*., 2018). Combing with biostratigraphy and regional stratigraphic correlation, the Bopdong Group was dated to be Cambrian Miaoling Series to Silurian (Kim *et al*., 2018).

The Upper Paleozoic (Late Carboniferous)-Early Triassic sediments were named the Pyeongan Supergroup, which unconformably overlies the Lower Paleozoic Hwangju Supergroup (generally Mandal Formation of the Bopdong Group), and unconformable covered by the Upper Mesozoic strata. This supergroup, approximately 1,500m thick, consists of paralic to nonmarine clastic deposits, and is characterized by high-quality coal seams and aluminous rocks. It was subdivided into the Hongjom, Ripsok, Sadong, Kobangsan and Taezhawon Formations in ascending order.

The Hongjom and Ripsok Formations were mainly composed of shale and sandstone, with thin coal measures in the upper part. The Sadong Formation (120-150 m thick) is the main coal bearing strata, and consists of shales, siltstone and sandstone with coal measures in the lower and middle parts, and aluminum rich shale and quartz sandstone in the upper part. The Kobangsan and Taezhawon Formations are mainly composed of shale and siltstone, with minor coal measures in the lower part, and silicified wood in the upper part. Above coal-bearing strata show that the paleoclimate was probably warm and arid with somewhat humid conditions.

All formations of the Pyeongan Supergroup are fossiliferous. The Hongjom Formation contains the index fusulinid fossils of the early Middle Carboniferous (*Eostaffella angusta* Kir, *Mediocris ovalis* Vissar., *Millerella kasakstanica*) in the lower part and those of the late Middle Carboniferous (*Profusulinella*, *Dagmarella* and *Aljutovella*) in the upper part. The Ripsok Formation contains the Triticites zone and plant fossils (*Neuropteris pseudovata*) and the Sadong, Kobangsan and Taezhawon Formations contain the index fossils of Lower to Upper Permian (e.g., *Callipteris conferta, Tingia carbonica, T. hamaguchii, Lobatannularia heianensis*, P. *norinii*) (Paek *et al*., 1996). On the basis of biostratigraphy, the Hongjom and Ripsok Formations were dated to be Middle and Upper Carboniferous, Sadong Formation was Lower Permian, and Kobangsan and Taezhawon Formations were dated as Upper Permian, respectively. Detrital zircons in sandstone from the Taezhawon Formation yield ages ranging from 231 Ma to 2529 Ma (Zhang, unpublished data), and the youngest group displays a weighted mean $^{206}Pb/^{238}U$ age of 231 ± 5 Ma, indicating a depositional time later than 231 Ma for the Taezhawon Formation.

2.2 Imjingang Belt

The Imjingang Belt is located between the Phyongnam Basin and the Gyeonggi Massif, separated by faults on all sides from the surrounding rocks of mainly Paleoproterozoic ages. This belt had been suggested as the eastward extension of the major Chinese suture zone (the ultra-high pressure Qinling-Dabie-Sulu Belt) (e.g., Yin and Nie, 1993; Ree *et al*., 1996; Oh and Kusky, 2007). However, Zhai *et al*. (2007) proposed that the Imjingang Belt does not exhibit any metamorphic characteristics of collisional orogenic belts. Moreover, Paek and Rim (2005) suggested the belt as a Middle Devonian to Lower Carboniferous rift zone of 15-30 km wide with tens of kilometers long in the Nangrim Massif. The belt does not extend throughout the KP with an eastern terminal in the middle peninsula.

Sedimentary strata in the Imjingang Belt were divided into the Yeoncheon Complex (or Yeoncheon Group) and Imjin System (or Imjin Group) (Cho *et al*., 1995; Paek *et al*., 1996; Ree *et al*., 1996). The Yeoncheon Complex was cropped out in the south of the 38^{th} parallel in South Korea (SK), and mainly consists of metamorphosed flysch deposits (Paek *et al*., 1996). Detrital zircon U-Pb ages of ca. 400 Ma and 420 Ma suggested a Devonian depositional time for the Yeoncheon Complex (Cho *et* *al*., 2001, 2007; Kim *et al*., 2014).

However, the Imjin Group, located in the north of the 38th parallel, is a volcano-clastic sedimentary stratum with the thickness more than 2,000 m (Paek *et al*., 1996). It is in tectonic contact with Proterozoic or even older strata, and the rocks near the margin of the Imjingang Belt have commonly suffered strong deformation and mylonitization. The metamorphic grade of this group increases from north to south, spanning from unmetamorphosed through sericite to garnet, staurolite and kyanite zones, defining a Barrovian-type facies series. This group is about 15 to 30 km in width and several hundred kilometers in length, with the eastern and western parts that divided by the Ryesonggang fault zone. The eastern part stretches as continuous volcanoclastic sedimentary strata from the estuary of the river Ryesong through Kaesong to the Cholwon area, while the western part is distributed in the Ongjin, Kangryong and Paechon districts, with outcrops at Kangryong extending into the South Yellow Sea.

The lower part of the Imjin Group mainly consists of epicontinental-shallow water terrigenous clastic sedimentary strata with thin terrigenous intercalations, while the upper part comprises volcano-sedimentary strata with terrigenous clastic rocks. It can be divided as three formations with conformable relationships, the Anhyop, Puap and Sannyong Formations, in ascending order.

The Anhyop Formation covers an area of ~10 km^2 in the northern margin of the sedimentary basin, and consists of calcareous schist, chlorite schist, phyllite, psammitic conglomerate, calcareous conglomerate, quartz sandstone and limestone. On the basis of the biostratigraphy, this formation was confirmed to be Lower-Middle Devonian (Kim, 2012). The Puap Formation consists of shale, siltstone, sandstone and conglomerate with the intercalation of carbonate rocks, which contains Middle-Late Devonian standard fossils, e.g., *charophyta fossil sycidium melo var. puskowensis*, and *Cyrtospirife* (Kim, 2012). The Sannyong Formation comprises grayishgreen massive siltstone, biotite spotted and massive siltstone, aleuritic shale, dark green shale and sandstone. Zircons from the upper siltstone and sandstone of the Puap Formation yield the youngest ages at an interval of 393 ± 8 Ma and 423 ± 5 Ma (Li *et al*., 2004; Zhang *et al*., 2018), which indicate that the Puap Formation was deposited at a maximum age of ca. 400 Ma. Moreover, the Puap Formation shows similar detrital zircon age spectra features to those of representative Paleozoic sequences in the Pyongnam and Taebaeksan Basins of the KP and Paleozoic basins in the NCC, suggesting that the NCC and KP might experience similar tectonic evolution, and the Imjingang Belt might not be the eastward extension of the Qinling-Dabie-Sulu Collisional Belt (Zhang *et al*., 2018).

2.3 Tumangang Belt and Kwanmo Submassif

The Upper Paleozoic Tuman Group is well developed in the Tumangang Belt (also called the Hambuk Massif), and is also exposed sporadically in the Kwanmo Submassif (Fig. 1, 3). This group consists of the Amgi, Kyeryongsan and Songsang Formations in ascending order, with an exposure area around 1,600 km^2 (Paek *et al*., 1996; Kim, 2012).

The Amgi Formation (360-950-m-thick) is mainly distributed in the Chongjin-Najin area, unconformably overlying the Precambrian rocks. It is a suit of terrigenous and volcanic clastic rocks, which consists of shale, slate, biotite siliceous schist, metamorphic sandstone, amphibolite, siliceous limestone and crystalline limestone lens. The Kyeryongsan Formation is a 570-1200-m-thick sequence of volcanic sedimentary rocks, and almost located in the Chongjin, Hoeryong and Kyongwon areas. The lower part is dominated by the tuffite and tuffaceous rocks, with minor shale, siliceous schist and limestone, whereas the upper part consists mainly of light metamorphic mafic volcanic rocks, porphyry and tuff. At the basal part, volcanic breccia was well developed, which was considered as the boundary with the underlying Amgi Formation. Limestone lenses and tuffaceous sandstones are an occasionally observed in the upper part. The Songsang Formation consists of terrigenous clastic rock, including siltstone, mudstone, shale with minor tuffaceous sandstone and limestone. Many fossils were hosted in these Formations, including fusulinids, brachiopods, crinoids, bryozoans, and plant fossils (Paek *et al*., 1996).

Zhang *et al*. (2016) reported the SIMS U-Pb age of 257 ± 3 Ma from the basaltic andesite (13NK-1) in the Kyeryongsan Formation, and suggested that this formation was formed in the Late Permian. Moreover, basaltic andesite are characterized by positive zircon εHf(t) values (+10 to +16), and fairly young T_{DM} (262-513 Ma). Synthesizing other geochemical features, the generation of the basaltic andesite most likely involves a precursory metasomatism stage of mantle peridotites by melts from subduction-related sediments and an immediate partial melting stage (Zhang, X.H. *et al*., 2016).

3. Mesozoic sediments

The Mesozoic sedimentary strata are mostly developed in continental faulted basins, which

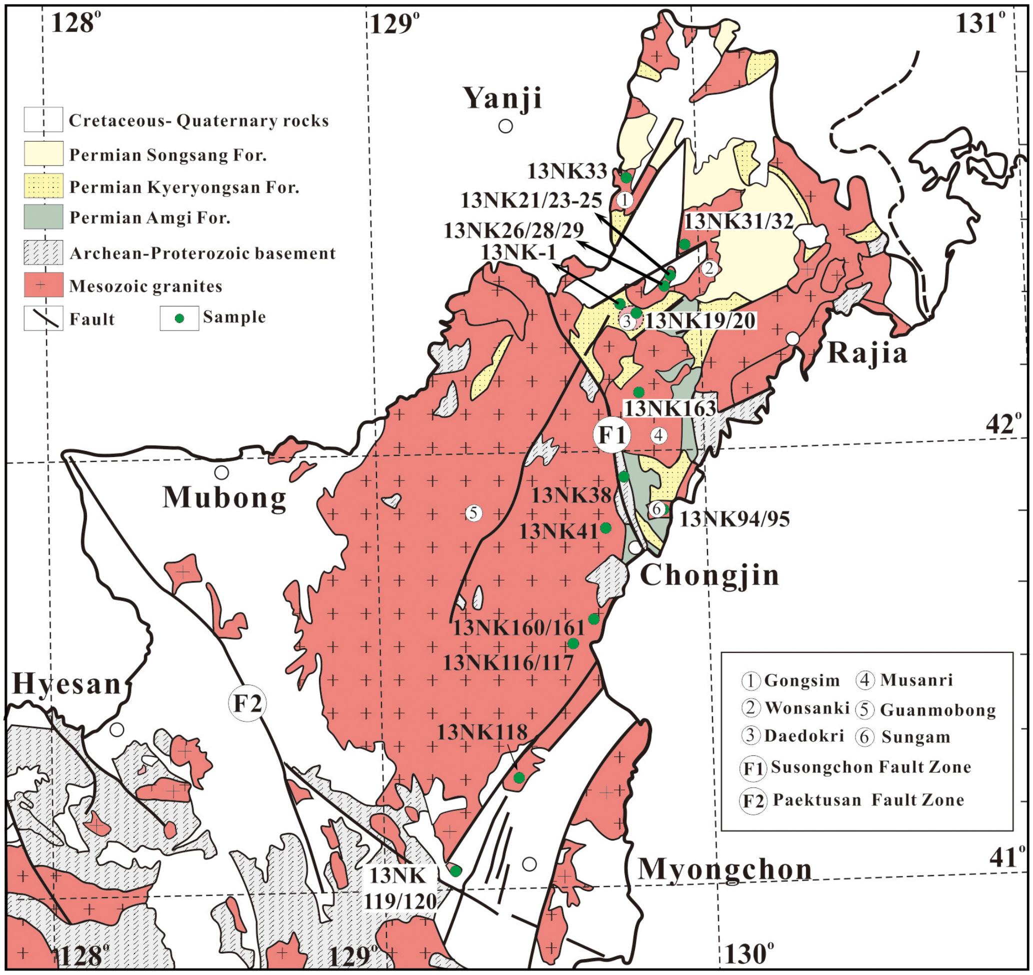

Fig. 3. Sketch geological map of the Tumangang Belt and Kwanmo Massif (modified after Paek *et al*., 1996).

caused by large faults and distributed in the long and narrow bands along the drainage areas of large rivers. Such as the Chosan, Changsong, Sinuiju Basins along the river Amnok (Yalu Jiang) were related with the Amnokgang fault zone with a NE direction, and the Anju and Pakchon Basins were related with the Jonchongang fault zone. The Mesozoic sediments consist of complex volcanic-clastic rocks, including terrigenous clastic rocks, intermediate-acid volcanic rocks, coal measures and oil shale. Usually, the Mesozoic strata consist of the Lower Jurassic Taedong, Upper Jurassic-Lower Cretaceous Jasong and Lower-Upper Cretaceous Taebo Systems. These continental strata have a variety of lithology and lithofacies, which make stratigraphic division and correlation more difficult.

The Lower Jurassic Taedong system distributed in the Jangphari, Amnokgang, Changsong, Taedonggang, Pujongang, Sinhung and Jaeronggang Basins with different names (e.g., Junggang, Songnimsan, Jangphari, Sansuri, Chongjin, Chonri, Kimpho). Similarly, the Jasong and Taebo systems are also distributed in many basins with different names.

The Amnokgang Basin, located in the Juangang-Jasong region, the west margin of the Nangnim Massif. The basin comprises the Lower Jurassic Junggang Group and Upper Jurassic-Lower Cretaceous Sinuiju Group. The Junggang Group, with an outcrop area of about 17 km^2 and subdivided into the Chilhaksan, Kobidong and Odoksan Formations. The Chilhaksan Formation is composed mainly of conglomerate, in which discontinuous sandstone is intercalated. The Kobidong Formation is composed mainly of sandstone, in which conglomerate, siltstone, silty mudstone, mudstone, coaly siltstone are often intercalated. The Odoksan Formation is also mainly composed of sandstone, in which Conglomerate and siltstone are frequently intercalated. The Sinuiju Group consists of felsic-intermediate effusive rocks, its tuffaceous rocks, clastic rock and coal measures. The Kobidong Formation host many plant fossils, and representative plant fossils include *Neocalamites carrelei* (Zeiller) Halle, *Dictyophyllum nathostii* Zeiller, *Clathropteris meniscoides* Brongn (Paek *et al*., 1996). Felsic tuff from the Kobidong Formation shows zircon U-Pb ages of 136-128 Ma, and quartz porphyry also have a zircon U-Pb age of ~110 Ma (Zhang, unpublished data), conforming the early Cretaceous depositional age, which is not the Lower Jurassic age as previously thought.

To the southwest of the Amnokgang Basin, the Sinuiju Basin is distributed along the south part within the Amnogang fault zone, with the area of over 250 km^2. The basin comprises the Upper Jurassic-Lower Cretaceous Sinuiju Group and Upper Cretaceous Sujin Group. The Sinuiju Group consists mostly of the clastic sedimentary rocks with minor intermediate effusive rocks, including grey, yellow fine sandstone, psammitic siltstone, mudstone, coal, conglomerate, pebbly tuff, agglomerate and andesitic porphyrite. The Sujin Group, outcropped about 13 km^2, is block-shaped between the Amonkgang fault zone and the Taehwari-Ryongmun fault. It consists of reddish brown psammitic conglomerate, sandstone, siltstone, andesitic porphyrite and trachyte. The tuff and dacite from the Sinuiju Formation yield 125-116 Ma zircon U-Pb ages (Zhang, unpublished data), probably indicating that the volcanic rocks of the Sinuiju Formation were erupted in the Early Cretaceous.

In addition, the volcanic rocks outcropped in the Hyesan area were previously considered to be Late Jurassic, however, the zircon U-Pb ages of ~110 Ma (Zhang, unpublished data) indicate that they were formed in the Early Cretaceous.

Above new age data show that the Early Cretaceous was a significant period of volcanic activity in NK, with an age range of 136-110 Ma. Similarly, the Cretaceous-Paleogene igneous were also well developed in SK, and mainly developed in pull-apart or extensional basins (Kim, 1996; Lee and Chough, 1999; Chough *et al*., 2000). About 70% of them are scattered in and around the Gyeongsang

Basin (Kim *et al.*, 2016). Large amounts of age data show that the Cretaceous-Paleogene magmatism occurred during 113-50 Ma, and mainly in 88-80 Ma (Kwon *et al.*, 2017 and reference therein), e.g., rhyolitic and andesitic magma in the Jinan Basin were formed at 90-89 Ma, and basaltic trachyandesite was formed at 84 Ma (Lee *et al.*, 2020). The Cheonmasan, Udongje, Seokpo and Yujeongje Tuffs of the Buan volcanics in the Kyokpo Basin were formed at 87 Ma; the Gyeongsusan and Yeongije Tuffs of the Seonunsan volcanics in the Gyehwa Basin were formed during 87-84 Ma; the Seongsan Tuff and Gyema Rhyolite of the Beopseongpo Volcanics were formed at 86-87 Ma (Kwon *et al.*, 2017). In general, the Cretaceous-Paleogene magmatism displays a younging trend from NK to SK (Kim *et al.*, 2016; Wu *et al.*, 2019).

4. Late Paleozoic-Mesozoic magmatic rocks

Phanerozoic granitoids and related igneous rocks are widely distributed in NK (Fig. 4), which is a part of the NE-SW-trending Mesozoic tectono-magmatic belt that extends from southeastern China to Far East Russia along the eastern margin of the Asian continent (Kinoshita, 1995; Kim, 1996; Cheong *et al.*, 2002; Sagong *et al.*, 2005; Wu *et al.*, 2007; Zhai *et al.*, 2016a). It was traditionally thought these granitic magmatism took place in

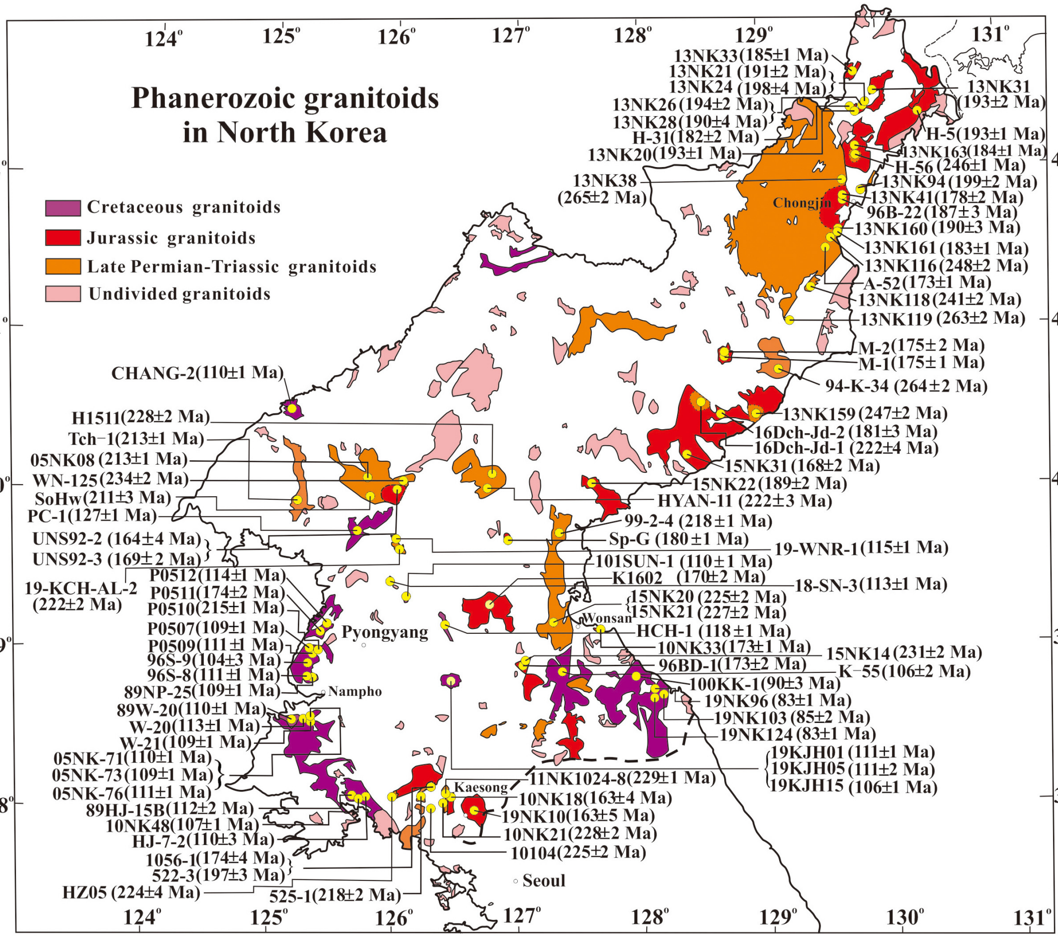

Fig. 4. Distribution of Phanerozoic granitoids in North Korea.

several distinct pulses, and are classified into Permian (Phyonggang and Tumangang), Triassic (Hyesan), Jurassic (Tanchon), and Cretaceous (Amnokgang) pulses (Paek *et al*., 1996). Among them, the Permian Tumangang complex are thought to be concentrated in the Tumangang Belt, and the Phyonggang alkaline intrusions occurred in the south margin of the Phyongnam Basin and Imjingang Belt (Paek *et al*., 1996).

After more than 20 years of geological investigation and geochronological research, we have obtained 91 zircon U-Pb ages of these granitoids (Table. 1). The data show the Phanerozoic granitic magmatism in NK occurred during 265-83 Ma, and they can be temporally subdivided into 3 dominant stages: Late Permian-Triassic (265-213 Ma), Jurassic (199-163 Ma) and Cretaceous (133-83 Ma), respectively (Fig. 5).

4.1 Late Permian-Triassic rocks

Twenty five Late Permian-Triassic ages was obtained. Among them, three Late Permian ages (265-263 Ma) were obtained from the Rimmyongdong biotite granite and Guanmobong foliated granite and biotite granite, other ages are Triassic, ranging from 248 Ma to 211 Ma. These granites are mainly distributed in the Kwanmo Submassif, Nangrim Submassif and south margin of the Phyongnam Basin, and divided into calc-alkaline igneous rocks and alkaline rocks. The calc-alkaline igneous rocks include diorite, quartz diorite, tonalite, granodiorite, and monzogranite. Representative plutons are the Guanmobong batholith in the Kwanmo Submassif, the Pukjin-Unsan, Komsanyong, and Jongphyong batholithes in the Nangrim Massif.

The Guanmobong batholith in the Kwanmo Submassif is exposed area over 3,000 km^2, and it extends northward into China, where it is called the Bailiping-Gaoling batholith. This batholith shows a wide range of lithological types, including gabbro, through diorite, biotite granite, granodiorite and monzogranite. Among the eight dated samples, one foliated granite and one biotite granite yielded Paleozoic U-Pb zircon ages of 265 ± 2 Ma and 263 ± 2 Ma, and two monzogranites revealed Early Triassic ages of 248 ± 2 Ma and 241 ± 2 Ma, and the remaining 4 samples (diorite, biotite granite, granodiorite and monzogranite) yielded Jurassic ages, ranging from 190 ± 3 Ma to 173 ± 1 Ma. Above age data show that the Guanmobong batholith was a composite one which formed from Late Paleozoic to Jurassic. Similarity, four magmatic stages are distinguished from the Bailiping-Gaoling batholith: Permian (285 ± 6 Ma), Triassic (248 ± 2~245 ± 6 Ma), Jurassic (192 ± 2~170 ± 3) and Cretaceous (119-116 Ma) (Zhang *et al*., 2004). The main part of the batholith was formed during Triassic to Jurassic. In addition, Jurassic diorite, biotite granite and granodiorite from the Guanmobong batholith are characterized by positive ε_{Hf} (t) values (4.9 ~ 10.6), fairly young T_{DM2} (Hf) (500-784 Ma) and uniform O isotopic composition ($\delta^{18}O$: 5.7 ~ 6.9‰) (Fig. 6). Nevertheless, most of the Permian and Jurassic biotite granite and monzogranite present lower $\varepsilon_{Hf}(t)$ values (-10.9 ~ 3.8), older T_{DM2} (Hf) (889-1651 Ma) and large variation of O isotopic composition ($\delta^{18}O$: 5.6 ~ 9.2‰) (Zhang, Y.B. *et al*., 2016).

Late Triassic alkaline (syenite) plutons in NK are known as the Phyonggang Complex, which previously thought as formed in Permian, with the K-Ar ages ranged from 300 Ma to 190 Ma (Paek *et al*., 1996). These plutons mainly distributed in the south margin of the Phyongnam Basin, with minor sporadic exposed in the Nangrim Massif. In the Phyongnam Basin, the Phyonggang Complex are mostly distributed along major faults, and consist of more than ten syenite plutons and some small satellite bodies (e.g., Tokdal, Yonan, Ryeui, Kangbuk, Solhwasan, Sokthandong, Jodoksan), with the total area of about 530 km^2. The syenite plutons composed of Na-pyroxene syenite, quartz syenite, nepheline syenite, alkali amphibolite, gab-

Table 1. Zircon U-Pb ages of Phanerozoic granitoids in North Korea.

Sample No.	Pluton	Rock type	Age (Ma)	Method	References
13NK38	Guanmobong	Foliated granite	265±2	SIMS	Zhang *et al*., 2016
94-K-34	Rimmyongdong	Granite	264±2	LA-ICP-MS	
13NK119	Guanmobong	Bi-granite	263±2	SIMS	Zhang *et al*., 2016
13NK116	Guanmobong	Monzogranite	248±2	SIMS	Zhang *et al*., 2016
13NK159	Tanchon	Bi-granite	247±2	SIMS	Zhang *et al*., 2021
H-56	Tumangang	Granodiorite	246±1	LA-ICP-MS	Wu *et al*., 2007
13NK118	Guanmobong	Monzogranite	241±2	SIMS	Zhang *et al*., 2016
WN-125	Pukjin-Unsan	Syenite	234±2	LA-ICP-MS	Wu *et al*., 2007
15NK14	Kosan	Bi-granite	231±2	SIMS	
11NK1024-8	Kangbuk	Syenite	229±1	SIMS	Peng *et al*., 2016
10NK21	Kangbuk	Syenite	228±2	SIMS	
H1511	Komsangryong	granite	228±2	SIMS	
15NK21	Jongphyong	Mafic dyke	227±2	SIMS	
10104	Ryeui	Granite	225±2	LA-ICP-MS	
15NK20	Jongphyong	Granite	225±2	SIMS	
HZ05	Tokdal	Syenite	224±4	SIMS	Peng *et al*., 2008
16DCH-JD-1	Tanchon	Bi-granite	222±4	SIMS	Zhang *et al*., 2021
19-KCH-AL-2	Joang	biotite granite	222±2	LA-ICP-MS	
HYAN-11	Komsangryong	Granite	222±3	LA-ICP-MS	
525-1	Ryeui	Syenite	218±2	SIMS	
99-2-4	Jongphyong	Granite	218±1	LA-ICP-MS	
P0510	Nampho	Deformed Monzogranite	215±1	LA-ICP-MS	Wu *et al*., 2007
05NK08	Pukjin-Unsan	Bi-granite	213±1	LA-ICP-MS	Wu *et al*., 2007
Tch-1	Kusong	Granite	213±2	LA-ICP-MS	
Sohw	Pukjin-Unsan	Granite	211±3	LA-ICP-MS	
13NK94	Sungam	Bi-granite	199±2	SIMS	Zhang *et al*., 2016
13NK24	Wonsanki	Granodiorite	198±4	SIMS	Zhang *et al*., 2016
522-3	Mulkilri	Leucogranite	197±3	LA-ICP-MS	Zhang *et al*., 2021
13NK26	Wonsanki	Granodiorite	195±2	SIMS	Zhang *et al*., 2016
13NK20	Daedokri	Quartz diorite	193±1	SIMS	Zhang *et al*., 2016
H-5	Tumangang	Granodiorite	193±1	LA-ICP-MS	Wu *et al*., 2007
13NK28	Wonsanki	Granodiorite	192±2	SIMS	Zhang *et al*., 2016
13NK31	Wonsanki	Diorite enclave	192±2	SIMS	Zhang *et al*., 2016
13NK21	Wonsanki	Granodiorite	191±2	SIMS	
SP-G	Sampyong-ri	Bi-granite	191±3	LA-ICP-MS	Zhang *et al*., 2021
13NK160	Guanmobong	Granodiorite	190±3	SIMS	Zhang *et al*., 2016
15NK22	Ragwon	Porphyritic granite	190±2	SIMS	Zhang *et al*., 2021
96B-22	Guanmobong	Granite	187±3	LA-ICP-MS	
13NK33	Gongsim	Bi-granite	185±2	SIMS	Zhang *et al*., 2016
13NK163	Musanri	Bi-granite	184±1	SIMS	Zhang *et al*., 2016
13NK161	Guanmobong	Diorite	183±1	SIMS	Zhang *et al*., 2016
H-31	Tumangang	Granodiorite	182±2	LA-ICP-MS	Wu *et al*., 2007
16DCH-JD-2	Tanchon	Bi-granite	181±3	SIMS	Zhang *et al*., 2021
13NK41	Guanmobong	Bi-granite	178±2	SIMS	Zhang *et al*., 2016
M-1	Manthapsan	Granodiorite	175±1	LA-ICP-MS	Zhang *et al*., 2021

Table 1. continued.

Sample No.	Pluton	Rock type	Age (Ma)	Method	References
M-2	Manthapsan	Granodiorite	175±2	LA-ICP-MS	Zhang *et al*., 2021
1056-1	Mulkilri	Two-mica granite	174±4	LA-ICP-MS	Zhang *et al*., 2021
P0511	Nampho	Deformed Two-mica granite	174±2	LA-ICP-MS	Wu *et al*., 2007
10NK33	Kosan	Diorite	173±2	SIMS	Zhang *et al*., 2021
96BD-1	Kosan	Granite	173±2	LA-ICP-MS	
A-52	Gommo	Porphyritic granite	173±1	LA-ICP-MS	Wu *et al*., 2007
13NK136	Komdok	Bi-granite	171±1	SIMS	
16NK03	Yangdok	Bi-granite	170±2	SIMS	Zhang *et al*., 2021
UNS92-3	Pukjin-Unsan	Two-mica granite	169±2	LA-ICP-MS	Zhang *et al*., 2021
15NK31	Tanchon	Bi-granite	168±2	SIMS	Zhang *et al*., 2021
19NK90	Kaesong	Bi-granite	166±2	SIMS	Zhang *et al*., 2021
10NK18	Kyejong	Bi-granite	163±4	SIMS	Zhang *et al*., 2021
UNS92-2	Pukjin-Unsan	Two-mica granite	164±4	LA-ICP-MS	Zhang *et al*., 2021
PC-1	Pukjin-Unsan	Granite	127±2	LA-ICP-MS	
HCH-1	Hoechang	Porphyritic granite	118±1	LA-ICP-MS	
19-WNR-1	Wonri	granite	115±1	LA-ICP-MS	
P0512	Nampho	Porphyritic granite	114±1	LA-ICP-MS	Wu *et al*., 2007
18-SN-3	Sunchon	granite	113±1	LA-ICP-MS	
W-20	Kuwolsan	Porphyritic granite	113±1	LA-ICP-MS	Wu *et al*., 2007
89HJ-15B	Haeju	Bi-granite	112±2	LA-ICP-MS	Wu *et al*., 2007
05NK-76	Kuwolsan	Diorite enclave	111±1	LA-ICP-MS	Wu *et al*., 2007
19-KJH-1	Onjinsan	porphyritic granite	111±1	LA-ICP-MS	
19-KJH-5	Onjinsan	granite	111±2	LA-ICP-MS	
96S-8	Nampho	Granite	111±1	LA-ICP-MS	
M-1-M	Mukbang	granodiorite	111±2	LA-ICP-MS	
P0509	Nampho	Deformed syenogranite	111±1	LA-ICP-MS	Wu *et al*., 2007
05NK-71	Kuwolsan	Porphyritic granite	110±1	LA-ICP-MS	Wu *et al*., 2007
101SUN-1	Sung-asan	Granite	110±1	LA-ICP-MS	
89W-20	Nampho	Granite	110±1	LA-ICP-MS	
Chang-2	Changsong	Leucogranite	110±1	LA-ICP-MS	
HJ-7-2	Kuwolsan	Bi-granite	110±3	LA-ICP-MS	Wu *et al*., 2007
05NK-73	Kuwolsan	Bi-granite	109±1	LA-ICP-MS	Wu *et al*., 2007
89NP-25	Nampho	Porphyritic granite	109±1	LA-ICP-MS	Wu *et al*., 2007
P0507	Nampho	Deformed tonalite	109±1	LA-ICP-MS	Wu *et al*., 2007
W-21	Kuwolsan	Foliated Bi-granite	109±2	LA-ICP-MS	Wu *et al*., 2007
10NK48	Haeju	Bi-granite	107±1	SIMS	
19-KJH-15	Daegwan	Biotite granite	106±1	LA-ICP-MS	
K-55	Kosan	Two-mica granite	106±2	LA-ICP-MS	Wu *et al*., 2007
19-SAK-1	Sakju	granodiorite	104±1	LA-ICP-MS	
96S-9	Nampho	Granite	104±3	LA-ICP-MS	
100KK	Kumgangsan	Granite	90±3	LA-ICP-MS	
19NK103	Kumgangsan	Bi-granite	85±2	SIMS	
19NK102	Kumgangsan	Bi-granite	84±1	SIMS	
19NK124	Kumgangsan	Bi-granite	83±1	SIMS	
19NK96	Kumgangsan	Quartz syenite	83±1	SIMS	

bro, pyroxenite, and kimberlite, with composition changed from sodic to potassic from west to east (Paek *et al*., 1996). Peng *et al*. (2016) divided these

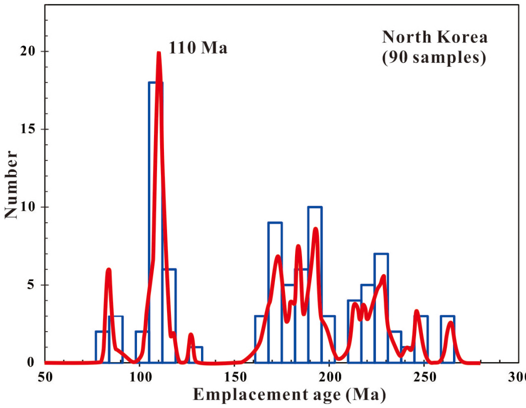

Fig. 5. Age histogram and probability diagrams for Phanerozoic granitoids in North Korea (n = 90).

plutons into the northern (in the Nangrim Massif) and southern (in the Phyongnam Basin) syenite belts. The Pukjin pluton, belonging to the northern syenite belt, shows a U-Pb zircon age of 234 ± 2 Ma (Wu *et al*., 2007). The Tokdal and Kangbuk Complexes crop out in the Hwanghae province, belonging to the southern syenite belt. The former having an exposed area about 30 km^2, is consist of alkali pyroxenite, gabbro, alkali amphibole, clinopyroxene, biotite and/or nepheline syenite. A SHRIMP U-Pb zircon age of 224 ± 4 Ma was obtained from a biotite syenite sample (Peng *et al*., 2008). The latter having an exposed area about 50 km^2, is mostly composed of biotite syenite, with minor quartz syenite and pyroxene syenite. Peng *et al*. (2016) reported the Triassic age (229 ± 1 Ma, SIMS U-Pb) of the biotite syenite.

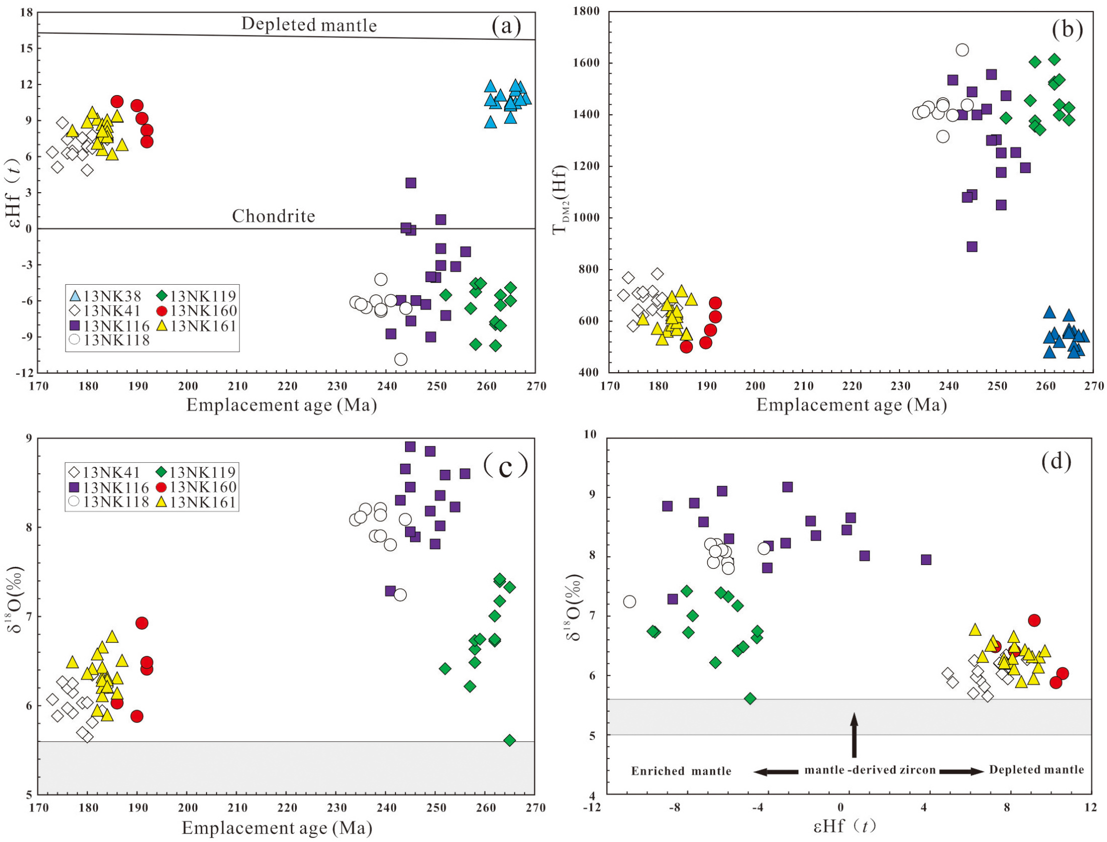

Fig. 6. Hf-O isotopes of the zircons for Phanerozoic granitoids in the Kwanmo Massif, Korean Peninsula (after Zhang, Y.B. *et al*., 2016).

In generally, these syenite plutons formed at ca. 234-220 Ma.

4.2 Jurassic rocks

The Jurassic granites are well developed in NK, with the ages ranged from 199 Ma to 163 Ma (Table 1). Early Jurassic granites are mostly exposed in the Tumangang Belt and Kwanmo Submassif, and Middle Jurassic granites are mainly distributed in the central KP (Fig. 3).

The Tumangang Belt and Kwanmo Submassif were characterized by large volumes of granitoids, which are known as the Tumangang Complex (Paek *et al*., 1996). New age data indicate that these granites were mostly emplaced during the Early Jurassic (199-183 Ma), which differs greatly from the previous view that most of them were in the Late Permian and Early Triassic age (Paek *et al*., 1996). Representative plutons are the Daedokri, Wonsanki, Gongsim, Sungam, and Musanri plutons. The rock types include diorite, quartz diorite, granodiorite, and biotite granites. These granites are I- and highly fractionated I-types, and most rocks belong to high-K calc-alkaline (Zhang, Y.B. *et al*., 2016). Zircons from these Jurassic granites are characterized by positive $\varepsilon_{Hf}(t)$ values (+4.7 to +13.5), relatively young T_{DM2}(Hf) model ages (784-367 Ma), and uniform O isotopic compositions ($\delta^{18}O$ = 5.7‰-7.4‰) (Zhang, Y.B. *et al*., 2016) (Fig. 7). Such Hf-O isotopic characteristics are likely indicative of a high proportion of juvenile material in their petrogenesis.

In the central KP, the Jurassic granites are also well developed, with the emplacement ages ranged

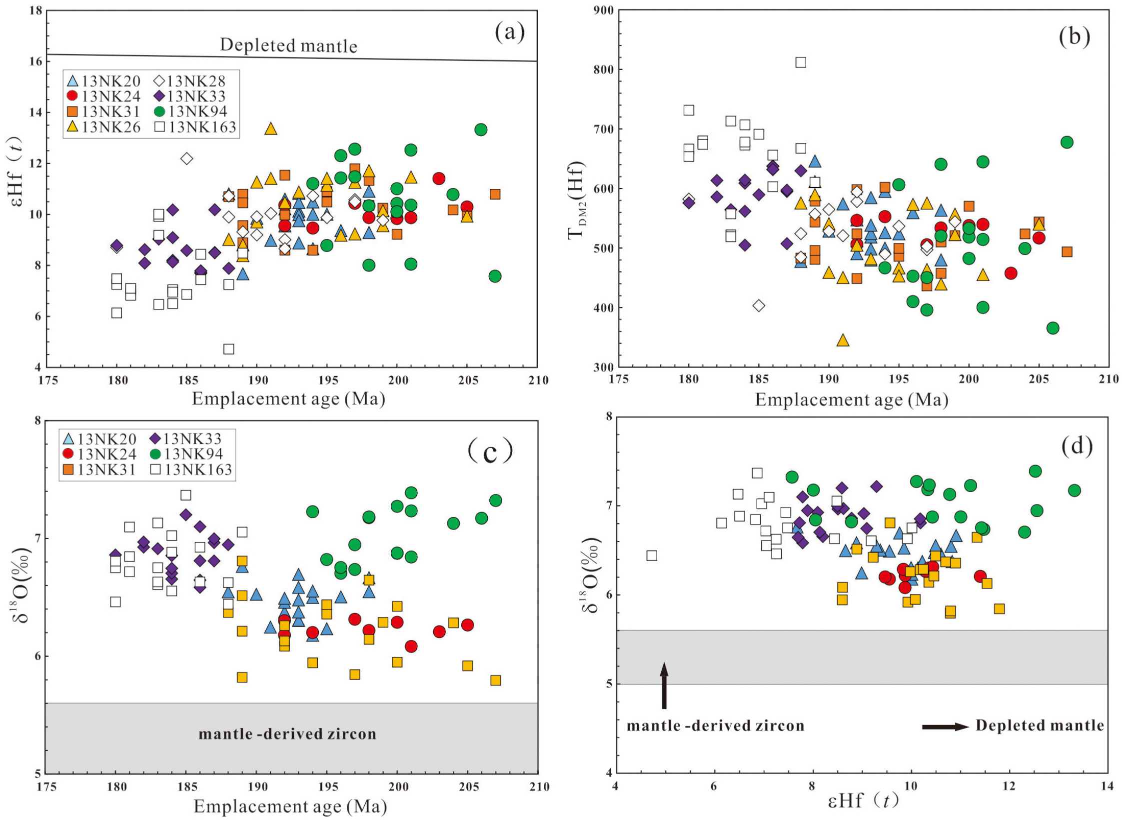

Fig. 7. Hf-O isotopes of the zircons for Phanerozoic granitoids in the Tumangang Belt, Korean Peninsula (after Zhang, Y.B. *et al*., 2016).

from 191 Ma to 163 Ma. The representative plutons include the Manthapsan, Tanchon, Ragwon, Sampyong-ri, Yangdok, Kosan, and Pukjin-Unsan plutons in the Nangrim Massif and Phyongnam Basin, and the Mulkilri, Kyejong-ri, Kaesong plutons in the Imjingang Belt.

The large Tanchon batholith is considered to be representative of the Jurassic granites, and the "Tanchon Complex-J_2" is the terminology used for all the Jurassic granites in the KP (Paek *et al*., 1996). However, a zircon age of 250 ± 5 Ma was obtained within this granitic pluton, and therefore it has been classified as the Triassic magmatism (Paek *et al*., 1996). The batholith consists of diorite, fine-grained biotite granite, medium- to coarse-grained biotite granite, and porphyritic biotite granite. New zircon U-Pb ages from 4 samples indicate the Tanchon batholith was a composite one, and mainly formed during Triassic (247-222 Ma) and Jurassic (181-168 Ma).

Most of other plutons also have complex rock types. For instance, the Yangdok pluton consists mainly of biotite granite, two-mica granite, and leucogranite; the Pukjin-Unsan batholith contains abundant rock types, including the diorite, biotite granite, two-mica granite, monzogranite, and syenite. Geochemically, biotite monzogranites from the Kyejong-ri pluton and porphyritic granite from the Yangdok pluton have tetrad REE patterns with large negative Eu anomalies, suggestive of extensive magmatic differentiation (Zhang *et al*., 2021). Some samples (e.g., the Kosan diorite and Tanchon and Yangdok biotite granites) are characterized by high Ba-Sr and low Y and heavy REE contents, high Sr/Y ratios, and strong light and heavy REE fractionation, which suggest that they are high Ba-Sr granites (Zhang *et al*., 2021).

In general, the Jurassic granites in the central KP are I-type or highly fractionated I-type ones, with small plutonic shapes or a part of composite batholiths, such as the Tanchon batholith.

4.3 Cretaceous rocks

The Cretaceous granites are distributed mainly in the eastern and western parts of the Nangrim Massif (Fig. 4), with the ages ranging from 127 Ma (granite sample PC-1 from the Pukjin-Unsan pluton) to 83 Ma (Table 1), represented by the Nampho and Kuwolsan batholithes in the west, and the Kosan and Kumgangsan ones in the east.

The Nampho and Kuwolsan batholithes were traditionally thought to be Triassic or Triassic-Jurassic age (Paek *et al*., 1996). However, recent study reveals that the rock types of the Nampo batholith include diorite, tonalite, monzogranite and syenogranite. Three magmatic stages were distinguished as Triassic (234-215 Ma), Jurassic (174 Ma) and Cretaceous (114-109). Seven samples (dioritic enclave, biotite granite, and porphyritic granite) from the Kuwolsan batholith yield uniform Early Cretaceous ages between 113 ± 2 and 109 ± 2 Ma (Wu *et al*., 2007), which suggests this batholith were formed in the Early Cretaceous.

The huge Kosan and Kumgangsan batholithes located in the east of NK, and were considered as Jurassic age (Paek *et al*., 1996). Nevertheless, medium-grained two-mica granite from the Kosan batholith yields zircon U-Pb age of 106±2 Ma, and Quartz diorite and biotite granites from the Kumgangsan batholith yield emplacement ages ranging from 100 Ma to 83 Ma. The ages of the Kumgangsan batholith show that the Late Cretaceous magmatism also occurred in the NK.

Combined with ages of volcanic rocks, the Cretaceous magmatism in NK mainly occurred from 136 to 83 Ma, with an age peak of ~110 Ma.

5. Discussion

5.1 Tectono-stratigraphic correlation between the Phyongnam Basin, Taebaeksan Basin and some Paleozoic Basins in the NCC

It is an important geological issue that the relationship between the Paleozoic strata in the

Phyongnam Basin and those in it's neighboring tectonic blocks, e.g., the NCC. The Paleozoic sedimentary strata are mainly developed in the Hyesan-Rowon and Phyongnam basins in the northern KP, and the Taebaeksan Basin in the southern KP.

The Lower Paleozoic sediments, named the Hwangju and Joseon Supergroups in the Phyongnam and Taebaeksan basins, respectively, are exclusively of marine origin. Their general stratigraphic successions are very similar with each other (e.g., Lee and Lee, 2003; Li *et al.*, 2016; Zhai, 2016; Zhai *et al.*, 2019; Peng *et al.*, 2020), with inner continental shelf carbonate depositional features. The Upper Paleozoic littoral coal-bearing sediments were named the Pyeongan Supergroup in both basins, and the paleoclimate was probably warm and arid with somewhat humid conditions when they were deposited. As a result, many large coalfields were formed, e.g., the Samcheok and Yeongweol ones in the Taebaegsan region, the Ripsok one in the Phyongnam Basin.

The NCC was stable during the Paleozoic. The well-developed Cambrian and Ordovician sedimentary rocks consist predominately of marine carbonate with minor fine clastic rocks (Chen and Qin, 1989). Late Ordovician strata are locally developed, and volcanic rocks from the constituent formations (the Zhaolaoyu, Pingliang, and Jinsushan Formations) yielded the eruption ages ranging from 449 Ma to 466 Ma (Chen *et al.*, 2012; Wu *et al.*, 2014; Wang *et al.*, 2015). After a depositional hiatus in the Early Carboniferous, the NCC subsided again and then transgressional marine sediments with coal-bearing clastics and continental clastics deposited during the Late Carboniferous and Permian, respectively. The Late Paleozoic strata are the Benxi and Taiyuan Formations with Late Carboniferous age, whereas the Shanxi and Xiashihezi Formations are Early Permian strata, and the Shangshihezi and Shiqianfeng Formations are Late Permian strata (Chen and Qin, 1989).

Detail comparative studies show that the NCC (the Western Hill and Dalian basins in Beijing and Liaodong Peninsula, respectively) and the KP (the Taebaeksan and Pyongnam basins) have similar Paleozoic stratigraphic sequences (Zhai *et al.*, 2007 and references therein). Furthermore, detrital zircon age spectra for representative Paleozoic sequences in the Pyongnam Basin, Taebaeksan Basin, Imjingang Belt, and the NCC show similar features, suggesting that the KP and NCC may share congruous provenances evolutional history during the Paleozoic (Zhang *et al.*, 2018).

5.2 Tumangang Belt: a part of the Central Asian Orogenic Belt

The Tumangang (Domangang) Belt, situated in the northeastern part of the KP, was regarded as the southeastern extension of the eastern Central Asian Orogenic Belt (CAOB) (Paek *et al.*, 1996; Kim, 2012; Zhang, X.H. *et al.*, 2016; Zhang, Y.B. *et al.*, 2016), or called the Hambuk Block comparable with the Jiamusi Block in the NE China (Lyang *et al.*, 2009; Kim *et al.*, 2012). This belt is characterized by the Late Paleozoic low-grade metamorphic volcano-sedimentary strata (Tumen Group) and granites. The mafic-ultramafic Chongjin Complex in this belt was considered as the ophiolite (Paek *et al.*, 1996), and consists of a rock assemblage of peridotite, clinopyroxenite, gabbro, gabbroic diorite, hornblendite and doleritic dykes. Moreover, zircon SIMS U-Pb dating on distinct rock units document a prolonged emplacement ages from ca. 250 to ca. 170 Ma (Zhang *et al.*, 2019). In addition, they exhibit a compact elliptical geometry, with linear array of stock clusters and crude lithological zonation from cores of peridotites to margins of hornblendites and gabbroic rocks. Furthermore, their geochemical characteristics are very similar to those of the classic Phanerozoic Alaskan-type complexes, e.g., SiO_2 ranged from 39.4% to 57.4%, enrichment in light rare earth elements (LREE), depletion in high field strength elements (HFSE), whole- rock ($I_{Sr}(t)$ = 0.703062 to 0.705507,

ε_{Nd}(t) = +3.80 to +12.2) and ε_{Hf}(t) values from + 12.5 to + 24.8, and zircon ε_{Hf}(t) values from -17.3 to +12.8 and $\delta^{18}O$ from 4.92 to 10.4 ‰ (Zhang *et al.*, 2019). Above features indicate the Chongjin Complex belongs to the Alaskan-type complexes, and their petrogenesis most likely involved precursory metasomatism of mantle peridotites by melts from subduction-related sediments with subsequent partial melting.

Large volumes of granitoids distributed in the Tumangang Belt, and the plutons extend into the Kwanmo Massif. The Jihei (Jilin-Heilongjiang) Orogenic Belt, part of the CAOB, which is connected with the Tumangang Belt, also distinguished by extensive distribution of Phanerozoic granites and volcanic rocks. Our age data show that the Phanerozoic magmatism in the Tumangang Belt can be divided into three stages, i.e., Late Permian (265-263 Ma), Early Triassic (248-240 Ma) and Early-Middle Jurassic (199-173 Ma). From the presently available data, the granites in the Jihei Orogenic Belt show a broadly similar chronological sequence at 285-230 Ma, 228-150 Ma and 130-110 Ma, and the Triassic and Jurassic granites distributed all over the area, occupying about 95% of the exposed granites. Consequently, we may infer that the Triassic and Jurassic magmatism took place synchronously across these tectonic units. Furthermore, these granites have the similar mineralogical and geochemical features; e.g., i) most of granites are I- and high fractionated I-types and belong to high calc-alkaline series, ii) although granites located in the north margin of the NCC (or the Nangnim Massif) yield relatively lower ε_{Hf}(t) values and older T_{DM2} ages, most others display positive ε_{Hf}(t) values and fairly young T_{DM2} ages. Such Hf isotopic characteristics of these granitoids are likely indicative of a high proportion of juvenile material in their petrogenesis. Overall, above similarity between granites in the Jihei Orogenic Belt and those in the Tumangang Belt suggested that the Tumangang Belt is a part of the CAOB.

5.3 Tectonic implications of Triassic granitoids in North Korea

The Triassic granitoids in NK can be divided into two groups: east-west-trending alkaline rocks (234-220 Ma) at the south margin of the Phyongnam Basin, and calc-alkaline igneous rocks (248-211 Ma) in the Nangrim Massif. These Triassic granitoids, especially alkaline rocks, have been considered to be formed in Syn- to post-collisional tectonic setting after collision between the North and South China blocks by some studies (e.g., Chough *et al.*, 2000; Peng *et al.*, 2008, 2016; Seo *et al.*, 2010). However, Triassic granitoids are mainly distributed in the south part of the Dabieshan-Sulu Orogenic Belt, and the alkaline and gabbroic intrusive bodies (the Jiazishan complex) only outcropped in east margin of the Sulu Orogenic Belt and yield little younger isotopic ages of ~211-205 Ma (Guo *et al.*, 2005). Furthermore, the basement of different massifs (the Nangrim, Gyeonggi and Yeongnam Massifs) are closely correlated to the NCC, and the Paleozoic basins in the KP have a similar Paleozoic tectono-stratigraphy to those in the NCC. These geological observations indicate that the NCC and KP might share congruous tectonic history in the Paleozoic (Zhai, 2016; Zhai *et al.*, 2019), and further inferences that the Hongseong Complex might be an allochthonous tectonic slab and not the tectonic zone cut cross the KP (Zhai *et al.*, 2007, 2016, 2019). Therefore, the influence of the continental collision between the North and South China blocks on the KP may be a local and not be as intensive as previously thought.

It should be noted that the Triassic granitoids are widespread in the NCC (Fig. 8). In addition, the Triassic alkaline rocks are distributed in east-west-trending belts along the north margin of the NCC, while calc-alkaline igneous rocks are mainly in the eastern NCC (Zhai, 2016; Zhai *et al.*, 2016, 2019; Wu *et al.*, 2019). By comparison in petrological observations, chronology and geochemical features, the Triassic granitoids and igneous rocks in the KP and NCC indicate that they were most likely formed in the same tectonic setting. Previous studies on the Triassic granitoids in the NCC proposed different models. While two main models ascribed them to post-orogenic extension related to the CAOB or the Sulu Belt, a third one resorted to intracontinental rifting within the NCC (e.g., Zhang *et al.*, 2009; Yang *et al.*, 2012; Wu *et al.*, 2018; Zhu *et al.*, 2020). The first model advocated the continuation of the CAOB orogeny until the Late Triassic. However, some geological and chronological data indicate that the CAOB orogenic event might have ended before the Permian, with the granite-alkaline-gabbro belt in the northern margin of the NCC representing a rift type. Other studies suggested that the Triassic magmatic rocks are related to the Dabie-Sulu orogeny (Oh and Kusky, 2007; Peng *et al.*, 2016). However, since the 250-230 Ma granite-alkaline granite-gabbro rocks are widely distributed from the north through the middle to the south of the KP, and are older than the Jiazishan complex in the eastern Sulu belt, this makes them incompatible with the Sulu orogenic belt (Zhai *et al.*, 2016b, 2019). Therefore, this favored the intracontinental rifting model. In a word, the same tectonic regime may serve as one of the mechanisms for forming the Triassic granitoids in both NK and the NCC. Given the tectonic position of NK in the Triassic, the formation of Triassic igneous rocks in the KP should be influenced by surrounding blocks including the South and North China blocks as well as the Pacific plate.

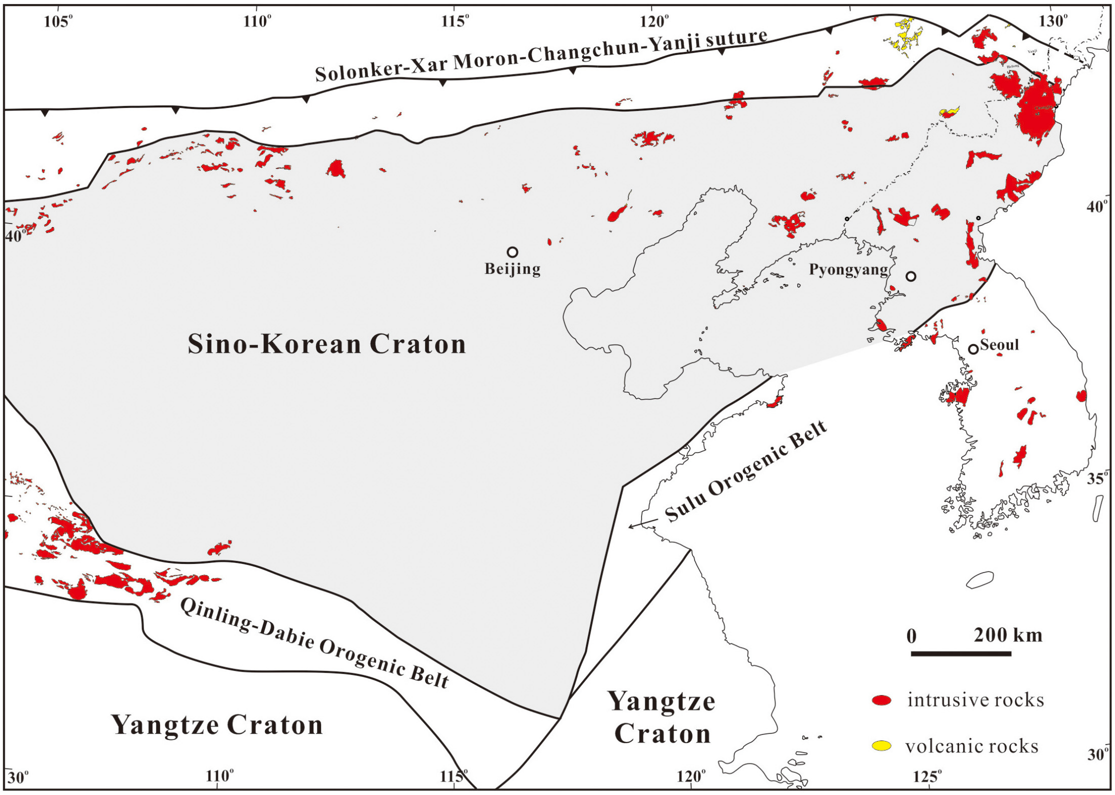

Fig. 8. Distribution of Triassic magmatic rocks in the NCC and KP (modified from Peng *et al.*, 2016; Zhai *et al.*, 2016).

6. Summary

1) The Phyongnam Basin comprises the Lower Paleozoic Hwangju Supergroup (Hwangju and Bopdong Groups/bottom up: ca. 521-467 Ma) and Upper Paleozoic Pyongan Supergroup (ca. 331-242 Ma). $\delta^{13}C$ values in the Cambrian Hwangju and lower Bopdong Groups fluctuated relatively little (-4.7~+2.4), but frequently. The three carbon excursions in the upper Junghua-Hukgyo Formations (positive), lower Rimchon Formation (negative) and the middle Kophung Formation (positive) are comparable to the global events of the mIngxinsi carbon isotopic excursion, redlichiid-olenellid extinction and Steptoean positive carbon isotopic excursion, respectively.

2) The Imjin Group tectonically deposited on the Late Mesoproterozoic to Ordovician sequences on the southern margin of the basin and the Imjingang Belt. The group consists of the Anhyop, Puap and Sannyong Formations, in ascending order. The youngest detrital zircon ages (~400 Ma) and Upper Devonian Famennian standard fossil assemblage in the Puap Formation, indicating it's deposition during the Late Devonian period. The Puap Formation has similar detrital zircon age spectra to those of representative Paleozoic sequences in the Pyongnam and Taebaeksan Basins of the KP and Paleozoic basins in the NCC, indicating that the NCC and KP might experience similar tectonic evolution, and the Imjingang Belt might not be the eastward extension of the Qinling-Dabie-Sulu Collisional Belt.

3) The Upper Paleozoic Tuman Group is well developed in the Tumangang Belt and Kwanmo Massif. It is a Late Paleozoic volcano-sedimentary strata, with SIMS mafic zircon U-Pb age of 257 Ma.

4) The Mesozoic sedimentary strata are mostly developed in continental faulted basins, and consist of the Lower Jurassic Taedong, Upper Jurassic-Lower Cretaceous Jasong, and Lower-Upper Cretaceous Taebo Systems. New age data show that the volcanic activity was significant in NK during the Early Cretaceous in the interval of 136-110 Ma.

5) The Phanerozoic magmatism in NK can be divided into three geochronological stages, i.e., 265-213 Ma, 199-163 Ma and 136-83 Ma, respectively. Among them, the former two are comparable to those in SK. Whereas, the Cretaceous magmatism has a southward younging trend from NK to SK, and Early Cretaceous magmatism (136-110 Ma) are absent in SK.

6) The age patterns and geochemical features of the Phanerozoic granites in the Tumangang Belt are similar to those of the Jihei Orogenic Belt. And therefore, the Tumangang Belt has been suggested as a part of the CAOB.

7) The Triassic granitoids in NK can be divided into two groups: east-west-trending alkaline rocks (234-220 Ma) at the south margin of the Phyongnam Basin, and calc-alkaline igneous rocks (248-211 Ma) in the Nangrim Massif. These granitoids show similar characteristics in petrology, chronology and geochemistry to those in the NCC, indicating that they may share the same tectonic setting.

Acknowledgements

We are grateful to our cooperators from Democratic People's Republic of Korea, Prof. Hyo Nuk Park, Jong Hyok Yang and Jong Nam Kim for their organization of the field excursion and assistance in sample collection. The final version of the paper has benefited from the perceptive comments of two anonymous reviewers and the Editor. This research was supported by the National Science Foundation of China (Grant Nos 41573048, 41890834 and 41530208).

REFERENCES

Chen, C., Shi, X.Y., Pei, Y.P. and Wang, X.Q., 2012, K-Bentonites from the Jinsushan Formation of Late Ordovician, Southern Ordos Basin: SHRIMP Dating and Tectonic Environment. Geoscience, 26, 205-219 (in Chinese with English abstract).

Chen, H. and Qin, D., 1989, Unstable cratonic and Paleozoic basins of China. In: Zhu, X.(ed), Chinese sedimentary basins. Elsevier, Amsterdam, 7-16.

Cheong, C.S., Kwon, S.T. and Sagong, H., 2002, Geochemical and Sr-Nd-Pb isotopic investigation of Triassic granitoids and basement rocks in the northern Gyeongsang Basin, Korea: implications for the young basement in the East Asian continental margin. The Island Arc, 11, 25-44.

Cho, D.L., Kwon, S.T., Jeon, E.Y. and Armstrong, R., 2001, SHRIMP U-Pb zircon geochronology of an amphibolite and a paragneiss from the Samgot unit, Yeoncheon Complex in the Imjingang belt, Korea: tectonic implication. Annual Conference of the Geological Society of Korea, (Abstract), Daegu, October 26-27, 89 p.

Cho, M., Kim, Y. and Ahn, J., 2007, Metamorphic evolution of the Imjingang Belt, Korea: Implications for Permo-Triassic collisional orogeny. International Geology Review, 49, 30-51.

Cho, M., Kwon, S.T., Ree, J.H. and Nakamura, E., 1995, High-P amphibolite of the Imjingang belt in the Yeoncheon-Cheongok area. Journal of the Petrological Society of Korea, 4, 1-19 (in Korean with English abstract).

Choi, D.K., 2018, Evolution of the Taebaeksan Basin, Korea: I, early Paleozoic sedimentation in an epeiric sea and break-up of the Sino-Korean Craton from Gondwana. Island Arc, 28, https://doi.org/10.1111/iar.12275.

Chough, S.K., Kwon, S.T., Ree, J.H. and Choi, D.K., 2000, Tectonic and sedimentary evolution of the Korean peninsula: a review and new view. Earth Science Reviews, 52, 175-235.

Guo, J.H., Chen, F.-K., Zhang, X.M., Siebel, W. and Zhai, M.G., 2005, Evolution of syno- to post-collisional magmatism from north Sulu UHP belt, eastern China: zircon U-Pb geochronology. Acta Petrologica Sinica, 21, 1281-1301 (in Chinese with English abstract).

Kim, B.S., 2012, Characteristics of Paleozoic sedimentary from East China-Korean peninsula and its tectonic evolution. Jilin University Doctoral Thesis, 1-124.

Kim, B.S., Liu, Y.J., Han, G.Q. and Jin, C.Y., 2012, Late Paleozoic sedimentary characteristics in Yanji-Jilin-Hambuk area, Korea and its significance to tectonic evolution. Journal of Jilin University (Earth Science Edition), 42, 296-305 (in Chinese with English abstract).

Kim, J.H., 1996, Mesozoic tectonics in Korea. Journal of Southeast Asian Earth Sciences, 13, 251-265.

Kim, M.C., Yang, J.H., Peng, P., Zhai, M.G., Pak, H.U., Feng, L.J., Ri, C.I. and Ju, S.H., 2016, Characteristics of carbon isotope of the Ediacaran and Lower Cambrian strata in the Pyongnam basin, DPR Korea. Acta Petrologica Sinica, 32, 3180-3186.

Kim, M.C., Yang, J.H., Peng, P., Zhang, Z.Y., Park, H.U., Byon, C.N., Park, U., Jong, C.S. and Zhai, M.G., 2018, Carbon isotope excursions of Cambrian Hwangju and Bopdong groups in Pyongnam Basin, Korean Peninsula. Earth science, 43, 4096-4108.

Kim, S.W., Kwon, S., Park, S.I., Lee, C., Cho, D.L., Lee, H.J., Ko, T. and Kim, S.J., 2016, SHRIMP U-Pb dating and geochemistry of the Cretaceous plutionic rocks in the Korean Peninsula: a new tectonic model of the Cretaceous Korean Peninsula. Lithos, 262, 88-106.

Kim, S.W., Kwon, S., Santosh, M., Cho, D.L. and Rhy, I.C., 2014, Detrital zircon U-Pb geochronology and tectonic implications of the Paleozoic sequences in western South Korea. Journal of Asian Earth Sciences, 95, 217-227.

Kinoshita, O., 1995, Migration of igneous activity related to ridge subduction in southwest Japan and the East Asian continental margin from the Mesozoic to the Paleogene. Tectonophysics, 245, 25-35.

Kwon, C.W., Ko, K., Gihm, Y.S., Koh, H.J. and Kim, H., 2017, Late cretaceous volcanic arc system in southwest Korea: distribution, lithology, age, and tectonic implications. Cretaceous research, 75, 125-140.

Lee, S.H. and Chough, S.K., 1999, Progressive changes in sedimentary facies and stratal patterns along the strike-slip margin, northeastern Jinan Basin (Cretaceous), southwest Korea: implications for differential subsidence. Sedimentary Geology, 123, 81-102.

Lee, S.H., Oh, C.W. and Park, J.W., 2020, The age and geochemistry of the mid-Cretaceous volcanic rocks in the Jinan Basin: Implications for the mid-Cretaceous tectonic environments of the Korean Peninsula and Northeast Asia. Lithos, 358-359, 105383

Lee, Y.I. and Lee, J.I., 2003, Paleozoic sedimentation and tectonics in Korea: A review. The Island Arc, 12, 162-179.

Li, Z., Chen, D.Z. and Zhai, M.G., 2004, Paleozoic sedimentary records correction between Korea and North China: Implication on the united Sino-Korea Block. In: Gondwana to Asia of 2004, Abstract Volume. Chonju: Chonbuk University, 31-32.

Li, Z., Ni, L.M. and Xu, J.Q., 2016, The Paleozoic records of sedimentary sequences and detrital zircon geochronology in Korean Peninsula and North China: Implications for tectonic attributes and division. Acta Petrologica Sinica, 32, 3139-3154 (in Chinese with English abstract)

Lyang, T.J., Liu, Y.J., Li, J.J., Bai, J.Z. and Liu, C.X., 2009, Structural framework of Korea Peninsula in Middle Paleozoic-Early Mesozoic. World Geology, 28, 157-165 (in Chinese with English abstract).

Oh, C.W. and Kusky, T., 2007, The late Permian to Triassic Hongseong- Odesan collision belt in South Korea, and its tectonic correlation with China and Japan. International Geology Review, 49, 636-657.

Paek, R.J., Kang, H.G. and Jon, G.P., 1996, Geology of Korea. Foreign Languages Books Publishing House, Pyongyang, 1-631.

Paek, R.J. and Rim, D.S., 2005, On the Rimjinang Belt. Gondwana to Asia Symposium of 2005, Abstract Volume. Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, p. B-1-5.

Park, M.H., 2012, Geological Series of Korea. vol. 2. Industrial Publishing House, 309-363 (in Korean).

Peng, P., Hu, B., Zhang, Z.Y., Zhang, Y.B., Guo, J.H. and Zhai, M.G., 2020, Review on geological evolution of the Pyongnam basin in Korean Peninsula. Acta Petrologica Sinica, 37, 129-142.

Peng, P., Yang, S.Y. and Wang, X.P., 2016, A preliminary study on the distribution, magma series and petrogenesis of the Triassic igneous rocks in middle-southern Korean Peninsula. Acta Petrologica Sinica, 32, 3083-3097 (in Chinese with English abstract).

Peng, P., Zhai, M.G., Guo, J.H., Zhang, H.F. and Zhang, Y.B., 2008, Petrogenesis of Triassic post-collisional syenite plutonsin the Sino-Korean craton: an example from North Korea. Geological Magazine, 145, 637-647.

Ree, J.H., Cho, M., Kwon, S.T. and Nakamura, E., 1996, Possible eastward extension of Chinese collision belt in South Korea: the Imjingang belt. Geology, 24, 1071-1074.

Sagong, H., Kwon, S.T. and Ree, J.H., 2005, Mesozoic episodic magmatism in South Korea and its tectonic implication. Tectonics, 24, http://dx.doi.org/10.1029/2004TC001720.

Seo, J., Choi, S.G. and Oh, C.W., 2010, Petrology, geochemistry, and geochronology of the post-collisional Triassic mangerite and syenite in the Gwangcheon area, Hongseong Belt, South Korea. Gondwana Research, 18, 479-496.

Wang, Z.T., Zhou, H.R., Wang, X.L., Jing, X.C. and Zhang, Y.S., 2015, Volcanic event records at the southwestern Ordos Basin: The message from geochemical and zircon U-Pb geochronology of K-bentonites from Pingliang Formation, Shaanxi and Gansu region. Acta Petrologica sinica, 31, 2633-2654 (in Chinese with English abstract).

Wu, F.Y., Han, R.H., Yang, J.H., Wilde, S.A., Zhai, M.G. and Park, S.C., 2007, Initial constraints on the timing of granitic magmatism in North Korea using U-Pb zircon geochronology. Chemical Geology, 238, 232-248.

Wu, F.Y., Yang, J.H., Xu, Y.G., Wilde, S.A. and Walker, R.J., 2019, Destruction of the North China Craton in the Mesozoic. Annual Review of Earth and Planetary Sciences, 47, 173-195.

Wu, S.J., Li, Z.H., Hu, J.M. and Gong, W.B., 2014, Confirmation of Ordovician Sediments in South Margin of Ordos Basin by SHRIMP U-Pb Zircon Dating of Volcanic Tuff Interlayers and Its Significance. Geological Review, 60, 903-912 (in Chinese with English abstract).

Yang, J.H., Sun, J.F., Zhang, M., Wu, F.Y. and Wilde, S.A., 2012, Petrogenesis of silica-saturated and silica-undersaturated syenites in the northern North China Craton related to post-collisional and intraplate extension. Chemical Geology, 328, 149-167.

Yin, A. and Nie, S., 1993, An indentation model for the north and south China collision and the development of the TanLu and Honam fault systems, eastern Asia. Tectonics, 12, 801-813.

Zhai, M.G., 2016, Comparative study of geology in North China and Korean Peninsula: Research advances and key issues. Acta Petrologica Sinica, 32, 2915-2932 (in Chinese with English abstract).

Zhai, M.G., Guo, J.H., Li, Z., Chen, D.Z., Peng, P., Li, T.S., Hou, Q.L. and Fan, Q.C., 2007, Linking the Sulu UHP belt to the Korean Peninsula: Evidence from eclogite, Precambrian basement, and Paleozoic sedimentary basins. Gondwana Research, 12, 388-403.

Zhai, M.G., Zhang, X.H., Zhang, Y.B., Wu, F.Y., Peng, P., Li, Q.L., Li, Z., Guo, J.H., Li, T.S., Zhao, L., Zhou, L.G. and Zhu, X.Y., 2019, The geology of North Korea: An overview. Earth-Science Reviews, 194, 57-96.

Zhai, M.G., Zhang, Y.B., Zhang, X.H., Wu, F.Y., Peng, P., Li, Q.L., Hou, Q.L., Li, T.S. and Zhao, L., 2016, Renewed profile of the Mesozoic magmatism in Korean Peninsula: Regional correlation and broader implication for cratonic destruction in the North China Craton. Science China Earth Sciences, 59, 2355-2388.

Zhang, S.H., Zhao, Y., Song, B., Hu, J.M., Liu, S.W., Yang, Y.H., Chen, F.K., Liu, X.M. and Liu, J., 2009, Contrasting late Carboniferous and late Permian-Middle Triassic intrusive suites from the northern margin of the North China craton: Geochronology, petrogenesis, and tectonic implications. Geological Society of America Bulletin, 121, 181-200.

Zhang, X.H., Zhang, Y.B., Yuan, L.L., Li, Y.S., Choi, W.J. and Kim, H., 2016, Late Permian mafic volcanic rocks in the Hambuk massif, Korean Peninsula: Geochemistry, origin and tectonic implications. Acta Petrologica Sinica, 32, 3070-3082 (in Chinese with English abstract).

Zhang, X.H., Zhang, Y.B., Zhai, M.G., Wu, F.Y. and Hou, Q.L., 2019, Tracing Paleo-Pacific plate subduction through the Alaskan-type Chongjin ultramafic-mafic complexes in the Korean Peninsula. In: The 74th Annual Meeting of the Geological Society of Korea and 2019 Fall joint conference of the Geological Sciences, (Abstracts), Jeju, October 23-26, 29 p.

Zhang, Y.B., Hu, B., Zhai, M.G., Wu, F.Y., Hou, Q.L., Peng, P., Zhang, X.H. and Li, Q.L., 2018, In situ U-Pb zircon dating of Devonian sandstones and Paleoproterozoic gneissic granites in the Imjingang Belt: Tectonic implications for the Korean Peninsula and North China. Lithos, 316, 232-242.

Zhang, Y.B., Wu, F.Y., Yang, J.H., Kim, J.N. and Han, R.H., 2016, Petrogenesis and geological implications of Phanerozoic granitiods at northern Korean Peninsula. Acta Petrologica Sinica, 32, 3098-3122 (in Chinese with English abstract).

Zhang, Y.B., Zhai, M.G., Wu, F.Y., Zhang, X.H., Li, Q.L., Peng, P., Zhao, L. and Zhou, L.G., 2021, In situ zircon U-Pb dating of Jurassic granitoids in North Korea and its tectonic implications. Lithos, 398-399, 106346.

Zhu, Y.S., Yang, J.H., Wang, H., Xu, L., Li, R. and Wu, Y.B., 2020, Geochemical and Sr-Nd-Hf-O isotopic constraints on the source and petrogenesis of the Xiangshuigou silicic alkaline igneous complex from the northern margin of the North China Craton. Lithos, 378-379, 105866.

Received	:	March	10,	2021
Revised	:	May	4,	2021
Accepted	:	July	29,	2021