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한반도 북부의 선캠브리아기 지질에 대한 간단한 리뷰

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요 약

북중국판의 일부인 한반도 북부의 선캠브리아기 지질에 대한 이해는 북중국판의 이해와 한반도 남부와 일본이 북동아시아 선캠브리아기 암석들과 어떠한 연관성을 갖는지를 밝히는데 중요하다. 한반도 북부의 주 구성원은 낭림육괴와 관모육괴이다. 두 육괴에서는 시생대 TTG와 화강암질 편마암이 발견되었고 이들은 여러 번에 걸쳐 변성작용을 받았다. 특히 고원생대 변성작용은 한반도 북부의 모든 선캠브리아기 암석에 영향을 주었다. 한반도 북부에는 변성퇴적암으로 구성된 고원생대 마천령층군과 증산층군이 분포한다. 이들 암석은 1950-1785 Ma 시기에 변성작용과 그에 수반된 용융을 경험하였다. 증산층군내 고변성암은 북중국판 동부와 마찬가지로 시계 방향의 압력-온도 진화를 경험하였다. 그리고 한반도 북부에서는 고원생대 화성작용이 광범위하게 일어났으며 그 중 1950-1800 Ma 화강암들이 가장 많이 나타나며 I-type, S-type, 그리고 섬장암류로 분류된다. I-type과 섬장암류 화성암들은 고원생대 조산운동이 끝나는 시기에 형성되었으며 S-type 화강암은 고변성작용 시기에 일어난 부분 용융에 의해 형성되었다. 북중국판내 나타나는 창천층군과 지시안 층군을 제외한 모든 중원생대-신원생대 층군에 대비되는 퇴적암들이 한반도 북부에서 나타난다. 한반도 북부의 중원생대 황해층군은 옹진 화강암과 시기적 지리적으로 관련성이 있으며 이들은 황해 열곡작용 시기에 의해 형성되었다. 신원생대 사리원 암상은 북중국판의 남쪽과 동쪽 경계를 따라 발달되어있던 Xu-Huai-Lv-Da-평남 열곡 시스템내에서 일어난 지질작용에 의해 형성되었다. 한반도 북부 고원생대 지구조운동은 콜롬비아 초대륙의 형성과 관련이 있으며 중원생대와 신원생대 지질작용은 아직 확실치는 않지만 로디니아 초대륙의 분열과정과 관련이 있다고 알려져있다.

주요어: 한반도 북부, 선캠브라이기 지질, 낭림 육괴, 관모 육괴, 북중국판

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ABSTRACT: The northern Korean Peninsula (NKP) is a constituent part of the North China Craton (NCC). A thorough understanding of the Precambrian geology of the NKP is critical for interpreting the NCC and how the southern Korean Peninsula (SKP) and Japan were involved in the Precambrian Northeast Asia. The Rangnim and the Gwanmo massifs are two major continental blocks of the NKP. Archean TTG and granitic gneisses have been found in both massifs, with multiple metamorphic overprintings. The Paleoproterozoic metamorphism influenced almost all early Precambrian basement rocks. Two major Paleoproterozoic metasedimentary units in the NKP are the Machollyong and the Jungsan Groups. They experienced metamorphism and/or contemporaneous anatexis at ~1950-1785 Ma. High-grade rocks of the Jungsan record clockwise P-T paths, similar with eastern NCC. Paleoproterozoic magmatism is widely distributed across the NKP, with ~1950-1800 Ma granites as the most common in this region, which have been categorized into I-type, S-type and syenitic series. While the I-type group and syenites marking the end of Paleoproterozoic orogenic events, the S-type group is partial melting products of high-grade metamorphic rocks. The Meso- Neoproterozoic Changcheng and Jixian sections are absent here. However, other Meso- Neoproterozoic sequences in the NKP can all find their equivalents in the NCC. The sedimentation of the Mesoproterozoic Hwanghae Group is temporally and spatially related to the emplacement of the Ongjin granite, which collectively marks the Hwanghae rift in the NKP. The Neoproterozoic Sariwon sills are products of a Xu-Huai-Lv-Da-Pyongnam rift system along eastern NCC. The Paleoproterozoic tectonothermal events in the NKP are related to the assembly of the Columbia supercontinent, while the Meso- Neoproterozoic

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events have all been termed to reflect the dispersal processes of this supercontinent. Connections between the Sino-Korea Craton and Rodinia supercontinent are not strong.

Key words: Northern Korean Peninsula, Precambrian geology, Rangnim massif, Gwanmo massif, North China Craton

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1. Introduction

The Precambrian geology of the NKP is critical for the thorough understanding of the evolutionary history of East Asia, because it abuts (is part of, to be more accurately) one of the oldest cratons in the world (the NCC) to the northwest, and links the whole Korean Peninsula and Japanese Islands to the south and east. Several orogenic events contributed a lot to the formation of the Asian Continent, namely the Paleoproterozoic North China Jiao-Liao-Ji orogeny, the Phanerozoic Paleo-Central Asian Orogeny, the Paleo-Tethyan Orogeny and the Western Pacific Orogeny, and all seem to have influenced the NKP. This area is, therefore, of great importance in the reconstruction of a panoramic geotectonic scenario of the whole NE Asia, or even global supercontinents. The tectonic affinity of the Rimjingang or/and Okcheon belt is still hotly debated and thus the relations of the southern part of the Korean Peninsula with East Asia is not very clear (Yin and Nie, 1993; Ree *et al*., 1996; Lee and Cho, 2003; Sagong *et al*., 2003; Oh *et al*., 2004; Cho and Kim, 2005; Zhai *et al*., 2019; Zhao *et al*., 2020), but there is a consensus that the NKP is closely tied with the mainland of China, which are collectively termed as the Sino-Korea Craton (Fig. 1a; Zhao *et al*., 2006a, 2016a, 2016b, 2020; Wu *et al*., 2007a, 2016; Cho *et al*., 2008; Peng *et al*., 2011b, 2016; Lee *et al*., 2016b; Li, Q. *et al*., 2016; Zhang *et al*., 2016; Oh *et al*., 2019; Zhai *et al*., 2019). Still, such a correlation is not straightforward because of the absence of relevant geological information and new data in the NKP. Divergent opinions of whether the NKP is an early Precambrian continental terrane or belonging to a Paleoproterozoic orogenic belt along the eastern NCC have emerged (Figs. 1b-e; Zhai and Liu, 2003; Zhao *et al*., 2005, 2010, 2012; Kusky *et al*., 2007a, 2014; Zhai and Santosh, 2011, 2013; Peng *et al*., 2014, 2018; Wu *et al*., 2016).

As can be seen in Fig. 1, the Jiao-Liao-Ji belt (or Liaoji mobile belt) along the eastern NCC has long been regarded as the orogenic belt generated by the interactions of Longgang and Rangnim blocks, both of which are Archean micro-continental blocks (Zhai and Liu, 2003; Zhao *et al*., 2005, 2010, 2012; Kusky *et al*., 2007a, 2014; Zhai and Santosh, 2011, 2013). The Archean basement sequences have been widely identified from the Longgang block through zircon U-Pb age dating, like the Anshan complex with Eo- to Mesoarchean gneisses (Zhai *et al*., 1990; Liu *et al*., 1992; Song *et al*., 1996), and the Archean Liaoning - Jilin sequences (Wang *et al*., 2017; Guo *et al*., 2018; Xie *et al*., 2019). However, age information from the Rangnim block was scarce and the several geochronological results were traditional Rb-Sr, Sm-Nd model ages or isochron ages (Kim and Jon, 1996; Paek and Jon, 1996; Ri, 1996a, 1996b; Lyang *et al*., 2009) until the studies presented by Zhao *et al*. (2006a), Wu *et al*. (2007a, 2007b), Zhai *et al*. (2007b) and Peng *et al*. (2011b). Even though Neoarchean rocks have been reported to occur in the southern, eastern, western and middle part of Rangnim massif as well as in the Gwanmo massif (Zhao *et al*., 2006a, 2016b, 2020; Zhang *et al*., 2016, 2017; Zhai *et al*., 2019), dating results of detrital zircons from modern river sands and entrained zircon grains

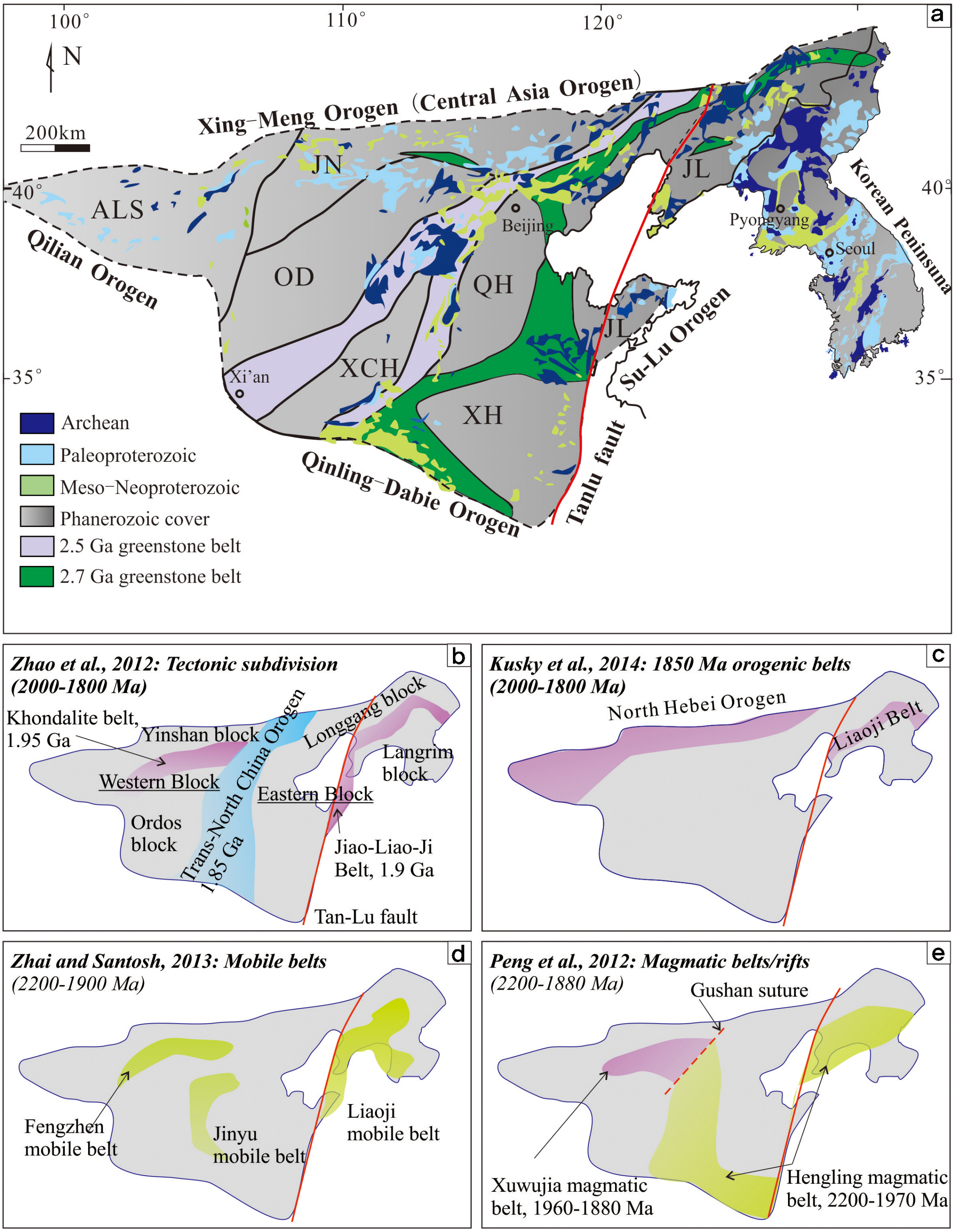

Fig. 1. Sketch of Precambrian geological map of Sino-Korean Craton, showing the Archean micro-blocks (a) and the proposed Paleoproterozoic tectonic divisions of NCC (b-e). After Zhao *et al*. (2020, 2016c), Zhai *et al*. (2021). ALS-Alashan block, JN-Jining block, OD-Ordos block, XCH-Xuchang block, XH-Xuhuai block, QH-Qianhuai block, JL-Jiaoliao block.

from Triassic kimberlites, which were thought to be able to compensate the lack of rock samples from the NKP and give a clearer picture of what Precambrian the NKP is consisted of, show prominent Paleoproterozoic rather than Archean age peaks (Wu *et al*., 2007b, 2016; Zhu *et al*., 2019). Paleoproterozoic magmatic rocks have also been identified in many parts of the NKP (Kim, J. *et al*., 2016; Peng *et al*., 2016). Rangnim massif of the NKP is therefore suggested by some researchers to be part of a huge Paleoproterozoic orogenic belt along with eastern NCC (Fig. 1e; Peng *et al*., 2014, 2016; Wu *et al*., 2016; Xu and Liu, 2019).

To better understand the geological evolutionary history of the NKP and its tectonic affinity, our group has carried out a long-term collaborative study with geologists from the NKP and has been organizing united field geological investigations in both the NCC and the NKP. This paper aims to present a brief review of the recent studies about the Precambrian geology of the NKP. There will be another paper within this issue dealing with the Phanerozoic geology of the NKP.

2. Geological background and Precambrian lithological units

The NKP is situated in northeastern Asia and has a geological history that can be traced back to Paleo- or even Eoarchean (~3600 Ma detrital zircons). The Rangnim massif, covering most of the NKP, is the biggest among the three Precambrian continental blocks in the Korean Peninsula (Fig. 2). The other two Precambrian blocks are the Gyeonggi massif and the Yeongnam massif with the former bounded by the Rimjingang belt with the Rangnim massif and the latter demarcated by the Okchon belt with the Gyeonggi massif (Fig. 2). Both the Rimjingang Belt and the Okcheon belt are NE-striking and have been considered as orogenic belts or intra-continental mobile belts (Cluzel *et al*., 1990; Cluzel, 1992; Chang, 1996; Paek and Jon, 1996; Ree *et al*., 1996; Oh, 2006, 2015; Lee *et al*., 2019b). As has been mentioned, there is a consensus that the Rangnim massif is a constituent part of the NCC, because rocks occurring on the two sides of their boundary river, the Yalu River, can be directly correlated. The Pyongnam basin and the Taebaeksan basin are two Paleozoic basins, covering the Rangnim and Yeongnam massifs, respectively (Fig. 2). Besides the three Precambrian massifs mentioned above, early Precambrian rock associations have also been identified from the Gwanmo massif, which was thought to be part of the Central Asia Orogenic Belt (CAOB, Figs. 1 and 2; Cao and Ju, 1999; Lyang *et al*., 2009; Zhang *et al*., 2016). The NKP is currently believed to contain two Precambrian massifs, the Rangnim and Gwanmo massifs, with resemble the gneissic high-grade terrane, like Beishan-Longgang in Eastern NCC, and the green-stone belts of NCC, respectively (like the Anshan-Qingyuan green-stone belt, Fig. 1; Zhai *et al*., 2019).

The four massifs in the Korean Peninsula all contain Precambrian lithologies, especially the Rangnim massif. The Precambrian rocks in the NKP can be divided into the Archean complex, Paleoproterozoic complex, Meso- and Neoproterozoic complex. Orthogneisses, banded iron formations (BIFs) - bearing supracrustal rocks (volcanic-sedimentary rocks) and gabbroic rocks, which experienced granulite-amphibolite facies metamorphism are the major rocks of the Archean complex. Part of the Paleoproterozoic complex exhibit high-grade granulite-amphibolite facies metamorphism while the rest showing low-grade metamorphism. The high-grade Paleoproterozoic associations consist of granulite - amphibolite facies meta-sedimentary rocks, mafic granulites and garnet-bearing or garnet-free granitic rocks, belonging mainly to the Jungsan group. The low-grade Paleoproterozoic associations, mainly belonging to the Machollyong group, consist of volcanic- sedimentary sequences, some of which contain large Pb-Zn ore deposits. The Meso- to Neoproterozoic lithologies of the

NKP show low-grade metamorphism or no metamorphic alteration at all. They consist of limestone, sandstone, phyllite, slaty schist and some magmatic rocks, like granites, mafic sills, and so on. The following are the details of these lithologies in the NKP.

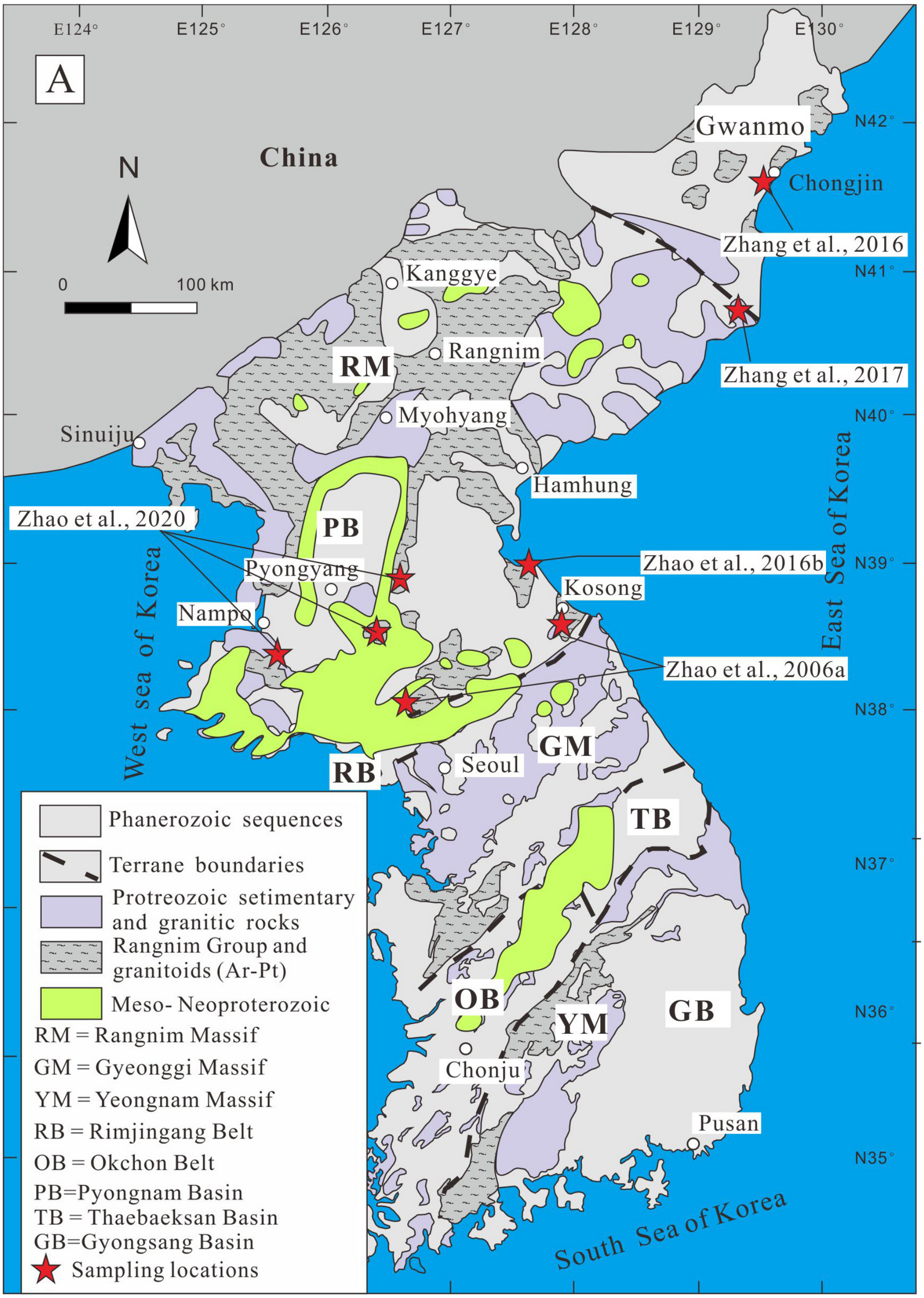

Fig. 2. Geological sketch map of the Korean Peninsula showing the distribution of Precambrian associations and the tectonic framework. Modified after Zhai *et al.* (2019) and Zhao *et al.* (2020).

3. Archean rocks

The Rangnim massif is the biggest continental block in the Korean Peninsula and hosts most Archean lithologies among the four Precambrian massifs. Early studies termed them as the Rangnim Group which dominantly consists of orthogneisses and some supracrustal rocks. However, a lot of high-grade rocks of this 'group' have been confirmed to exhibit Paleoproterozoic ages. Therefore, the name of the Rangnim complex was introduced (Zhao *et al*., 2016a, 2016b; Zhai *et al*., 2019). The supracrustal rocks of the Rangnim complex are mainly composed of mica-quartzite, cordierite-bearing gneiss and hypersthene plagioclase gneiss. Due to high-grade metamorphism during Paleoproterozoic (1.9-1.8 Ga), the protolith ages of many supracrustal rocks are not easy to testify. One reliable age result of them is the cordierite-bearing gneiss from Huichon, the central part of the Rangnim massif whose zircon U-Pb age is 2.58-2.5 Ga (Choe, 2005).

The Archean orthogneisses of the Rangnim complex are believed to contain tonalitic gneisses, granitic gneisses and gneissic granites, all exhibiting multi-phase deformation features (Zhao *et al*., 2006a, 2020; Zhai *et al*., 2019). Anatexis can also be seen in many outcrops (Zhao *et al*., 2016b). The first unequivocal Archean age results for gneisses of the Rangnim complex were reported by Zhao *et al*. (2006a), who showed that two grey gneiss samples (TTG gneisses) from the southern and southeastern Rangnim massif have magmatic ages of 2.64-2.54 Ga (Fig. 2). They also contain inherited zircons with U-Pb ages of 3.4-3.1 Ga. Based on the predominant 1800-1900 Ma age peaks yielded from detrital zircons of modern river sands sampled from Taedong, Chongchon, Songchon, Houchang and Tongno rivers flowing through the Rangnim massifs, Wu *et al*. (2016) proposed that Rangnim sub-massif is not an Archean massif, but a Paleoproterozoic equivalent to the Liaoji belt in the NCC. However, the Archean gneisses reported by Zhang *et al*. (2017) and Zhao *et al*. (2016b, 2020) from different parts of the Rangnim massif (Fig. 2) seem to show that this massif contains more Archean basement components The granitic gneisses studied by Zhao *et al*. (2016b) were collected from the eastern margin of the Pyongnam basin and have SIMS zircon U-Pb ages of 2.56-2.52 Ga and metamorphic ages of 1.89-1.87 Ga (Figs. 2 and 3). Zhao *et al*. (2020), thereafter, identified Archean granitic gneisses from the central and western Pyongnam basin (Fig. 2), using the SIMS zircon U-Pb method. These potassium-rich rocks have magmatic ages of 2.57-2.45 Ga and recorded Neoarchean (~2.45 Ga, following the definition that Archean is ended by the formation of supercratons through orogenic events during ~2.6-2.45 Ga), Paleoproterozoic (1.93-1.87 Ga) and Mesozoic (~160 Ma) metamorphic overprintings (Fig. 3; Zhao *et al*., 2020). The Machollyong complex in the northeastern Rangnim massif was originally defined as a Paleoproterozoic lithological unit (Paek and Jon, 1996). Zhang *et al*. (2017). However, it was found that this unit contains some Neoarchean TTG gneisses (Fig. 2). SIMS zircon U-Pb dating of these gneisses reveals ~2.56 Ga magmatic ages and multiple metamorphic overprintings at ~2.52 Ga and 1.85 Ga. This discovery implies that the previous lithological divisions need to be redefined.

Zircon Lu-Hf isotopic analyses were carried out on most of the above-mentioned Archean gneisses in the Rangnim massif (Fig. 4). $\varepsilon_{Hf}(t)$ values of them all show large variations, ranging from negative to highly positive, with some results plotting on the depleted mantle evolution model line. This suggests that the Neoarchean magmatism in the Rangnim massif involved both the juvenile crustal materials and ancient crustal components. Besides, most of the results can be well correlated with those of eastern NCC (Fig. 4). These new study results seem to suggest a larger scale of the Archean basement in the Rangnim massif than the several locations previously identified

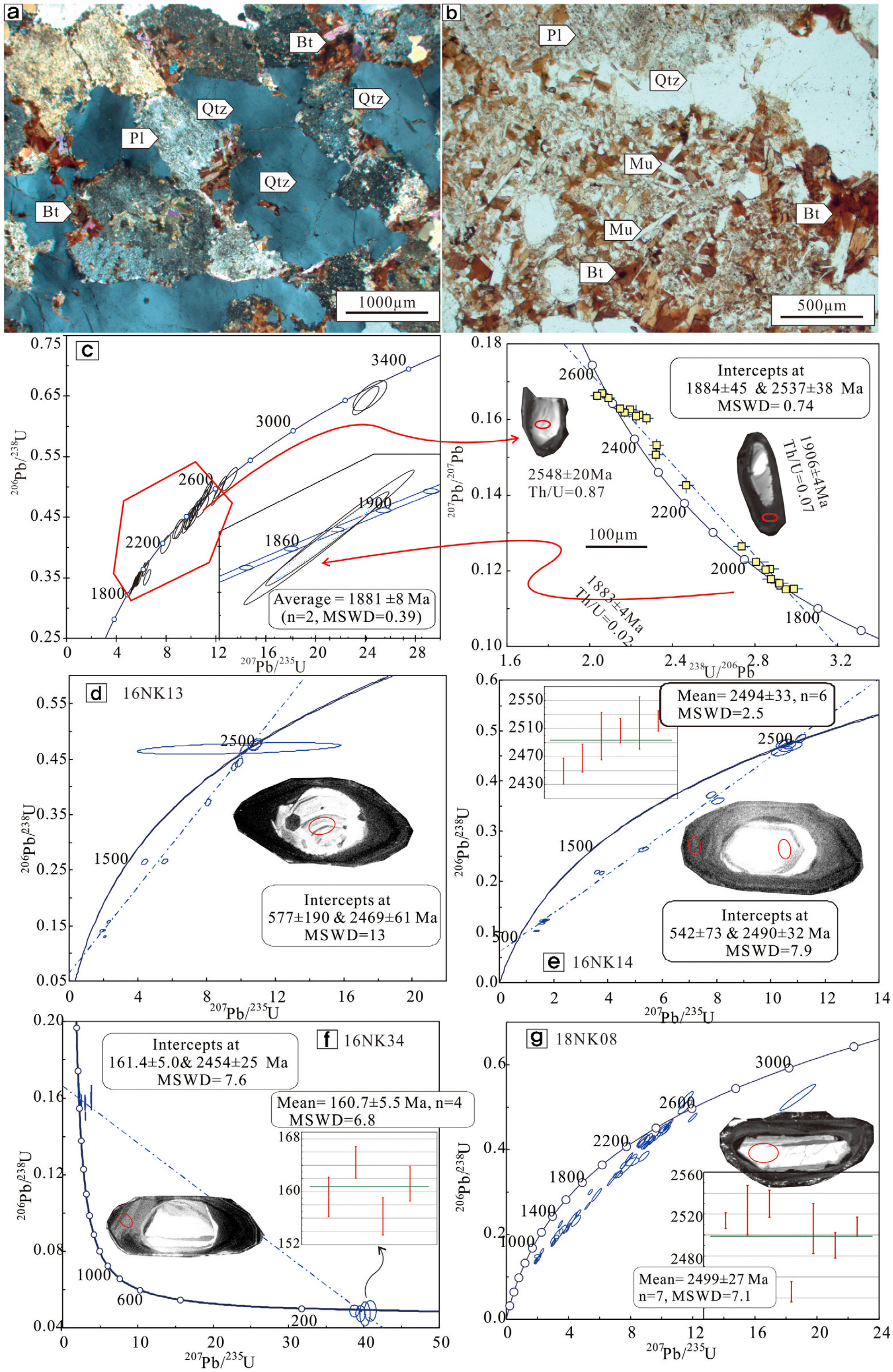

Fig. 3. Petrographic features of representative potassium-rich Archean gneisses in the Rangnim massif, their zircon CL images and SIMS U-Pb dating results. From Zhao *et al*. (2016b, 2020).

from this massif. What is more, the same metamorphic overprintings during Neoarchean and Paleoproterozoic showed by Archean lithologies in the Rangnim massif, as well as their similar zircon Lu-Hf isotopic results with those rocks in eastern NCC imply that the Rangnim massif might have amalgamated with the NCC to form a coherent continent at or before the end of Neoarchean. The occurrences of Archean high-grade gneissic rocks in the Rangnim massif also imply that this continental block is similar to other gneissic high-grade terranes in the world which were involved in the Neoarchean supercratons.

Archean rocks in the other Precambrian massif of the NKP, the Gwanmo massif, are termed as the Gwanmo complex (Kim and Jon, 1996; Zhai *et al*., 2019), which comprises BIF-bearing supracrustal sequences (the Musan Group) and orthogneisses. The supracrustal rocks are typical of volcano-sedimentary sequences, consisting of BIFs, graphite schist, felsic gneisses and amphibolites. The Ar-Ar and single zircon U-Pb ages of the metamorphosed supracrustal rocks range from 2.70 to 2.50 Ga (Kim and Jon, 1996; Zhai *et al*., 2019; Choe, 2005). Sm-Nd isochron ages of amphibolites samples interlayered with BIFs are 2.55-2.51 Ga (Zhai *et al*., 2019). Metamorphic alterations of the Archean rocks in Gwanmo massif are different from location to location, mostly ranging from greenschist to amphibolite facies, with occasional occurrences of granulite facies. The orthogneisses can be seen in almost every Archean outcrop and the BIFs-bearing supracrustal rocks occur as irregular layers, lenses, or slabs within the former (Kim and Jon, 1996; Zhai *et al*., 2019). Several episodes of magmatism can be identified, with TTG gneisses as the oldest, and then granitic and pegmatitic gneisses or veins. Precambrian granitic sills and bodies without any gneissic structures intruded into the BIF sequence and TTG gneisses can also be seen. Zhang *et al*. (2016) reported study results of a meta-intrusive complex,

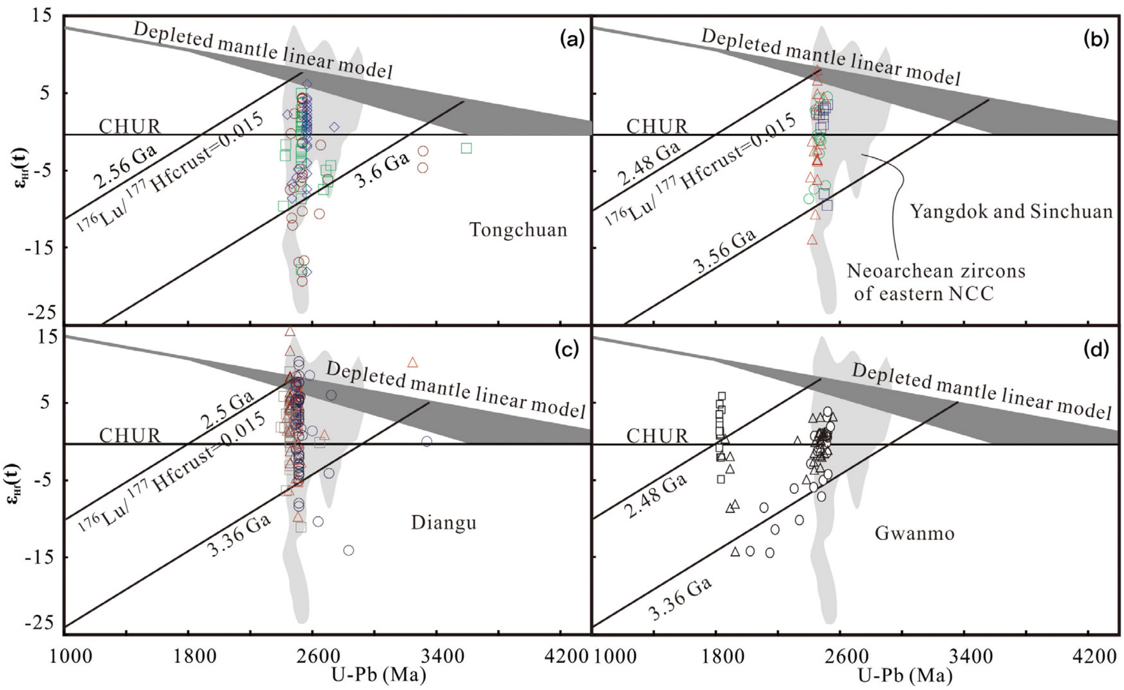

Fig. 4. Zircon Lu-Hf isotopic results of Archean gneisses from different parts of the Rangnim massif. From Zhang *et al*. (2016, 2017) and Zhao *et al*. (2020).

located near Yindedong and to the southwest of Chongjin city. This lithological unit is composed of orthogneisses with BIF lenses. The orthogneisses consist of biotite gneiss, amphibole gneiss, granitic and quartz dioritic gneiss, together with some amphibolite lenses. SIMS zircon U-Pb age of the dioritic gneiss sample is 2.53 Ga and that of the potassium-rich granitic gneiss is 2.51 Ga (Zhang *et al.*, 2016). Zircon $\varepsilon_{Hf}(t)$ values of them are -1.7 to +10.5, similar to those of the Rangnim massif described above. The Yindedong meta-intrusive complex is interpreted to be similar to products of magmatic arcs on active continental margins. They exhibit a close affinity with the Helong/Qingyuan greenstone terrains in the eastern NCC (Zhang *et al.*, 2016; Zhai *et al.*, 2019).

4. Paleoproterozoic metamorphic rocks in the NKP

Similar to the NCC, Paleoproterozoic metamorphism is pervasive in the NKP. Paleoproterozoic granulites have also been identified from several places, mainly in the northern and western Rangnim massifs (Fig. 5). Based on the differences in metamorphic grade and protolith of metamorphic rocks, the Paleoproterozoic metamorphic rocks in the NKP have been classified into two formations, which are the low-grade sequence of the Machollyong Group and the high-grade sequence of the Jungshan Group. The Machollyong Group sequences occur mainly in the Gwanmo massif and boarding regions of Gwanmo and Rangnim massifs. The Jungshan Group is more developed in the western Rangnim massif (Liao *et al.*, 2016; Zhai *et al.*, 2019). The distribution patterns of the Paleoproterozoic low- and high-grade metamorphic lithologies in the NKP are similar to those of the north and south Liaohe Groups in the Jiao-Liao-Ji belt of the eastern NCC (Zhai and Liu, 2003; Zhai, 2004a; Li *et al.*, 2006, 2011; Zhao

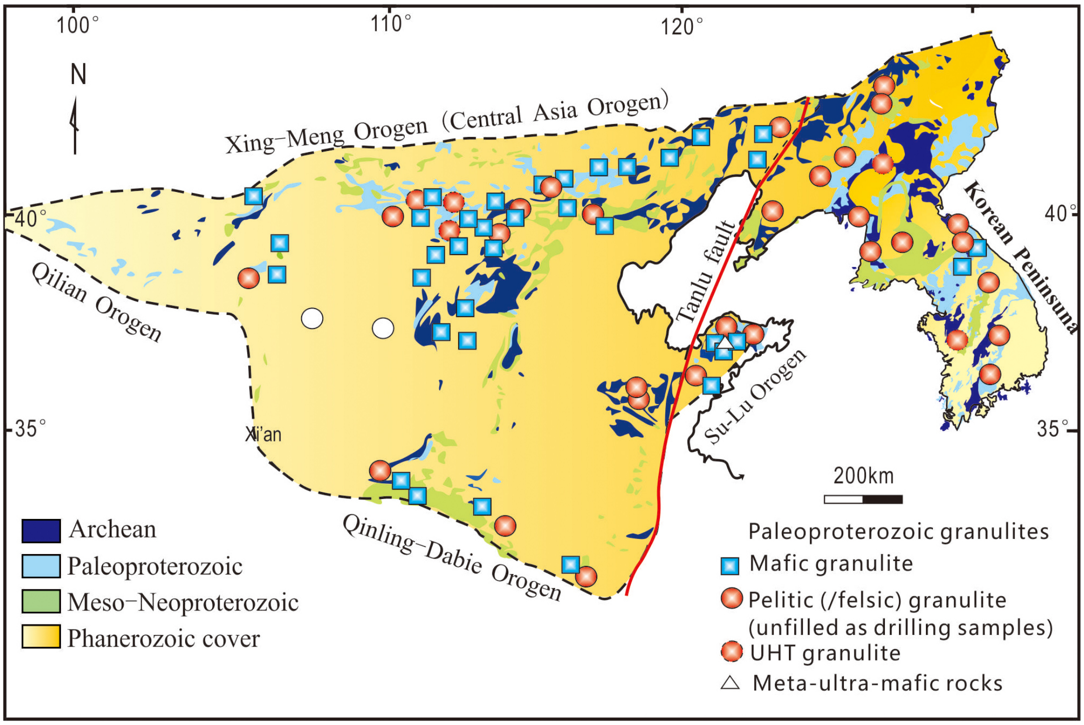

Fig. 5. Simplified geological map of the Sino-Korean Craton and spatial distribution of identified Paleoproterozoic granulites in this area. After Zhao *et al.* (2016c) and Zhou *et al.* (2017).

et al., 2012; Liu, F.L. *et al*., 2015; Liu *et al*., 2017). Besides these two lithological units, rocks of the Rangnim complex often exhibit Paleoproterozoic high-grade metamorphism as well, like the Nampo granulite-facies migmatites (Zhao *et al*., 2016a).

4.1 The Jungsan Group

The Jungsan Group is typical of a khondalite series, consisting of high-alumina pelites, graphite-bearing gneisses, quartzite, marble, amphibolites and mafic granulites. These rocks mainly occur in the southern and western Rangnim massif, closely associated with Paleoproterozoic granites and migmatites. High-alumina pelites are composed of granulite facies mineral assemblages of garnet + sillimanite and/or kyanite + plagioclase + K-feldspar + quartz + biotite ± cordierite, or amphibolite facies mineral assemblage of garnet + staurolite + kyanite + biotite + plagioclase + quartz (Fig. 6). Graphite is also widely developed in pelitic rocks. The estimated peak metamorphic temperature and pressure conditions for sillimanite-bearing granulite-facies pelitic rocks are ~750-850℃/7-9 Kbar and ~700-800℃/10-12 Kbar for kyanite-bearing granulite-facies pelitic rocks (Zhai *et al*., 2019). Mineral assemblages, as well as metamorphic reaction textures, roughly indicate a clockwise P-T path for the Paleoproterozoic metamorphism in the NKP, similar to those occurring in the NCC (Fig. 5; Zhao *et al*., 2016a). Detrital zircons in the Jungsan Group meta-pelitic rocks are relatively scarce. The several detrital grains previously reported have U-Pb ages of 2.16-1.95 Ga and metamorphic zircons show metamorphic ages of 1.90-1.85 Ga (Paek and Jon, 1996; Choe, 2005; Li *et al*., 2016; Zhai *et al*., 2019).

A case study on metamorphism of the Jungsan Group was recently carried out by Li *et al*. (2016), who presented detailed petrographic and zircon, rutile and titanite U-Pb age results of meta-pelites and amphibolites (Figs. 6a-d). Mineral assemblages of the meta-pelite and amphibolite samples are garnet + biotite + kyanite + staurolite + plagioclase + quartz, and garnet + amphibole + plagioclase + quartz, respectively. These assemblages are indicative of amphibolite facies metamorphism and a clockwise P-T path. Zircons from the pelitic sample do not contain any detrital cores and all the grains belong to metamorphic zircons. SIMS zircon U-Pb dating gives an intercept age of 1846 ± 3 Ma and a weighted mean age of 1850 ± 5 Ma (Figs. 6c and 6d). Titanite grains from the garnet amphibolite not only recorded the Paleoproterozoic metamorphic age of 1831 ± 5 Ma but also recorded the overprinted Mesozoic metamorphism at 155 ± 3 Ma. Rutile grains from the two different rocks preserved little Paleoproterozoic geochronological information while most of their U-Pb systems were reset at ~155 Ma. Granulite facies meta-pelites, with the mineral assemblage of garnet + sillimanite + K-feldspar + plagioclase + biotite + quartz, as well as granulite facies meta-mafic rocks, with the mineral assemblage of garnet + orthopyroxene ± clinopyroxene + plagioclase + quartz, have also been identified from the Jungsan Group. However, their metamorphic evolution and geochronology are still awaiting further studies.

Accompanying the Paleoproterozoic high-grade metamorphism, many early Precambrian rocks of the Jungsan Group experienced strong anatexis. One typical locality for such anatectic rocks lies in the western Rangnim massif, near Nampo (Figs. 2 and 6). Leucosomes, melanosomes and mesosomes are well preserved in the field. Big anatectic garnet grains are pervasive and they usually occur in leucosomes or boundaries between leucosomes and melanosomes. Microscopic evidence like thin-film structures between mineral boundaries can also be easily seen (Zhao *et al*., 2016a). The occurrence of orthopyroxene indicates that the anatexis took place at granulite-facies pressure and temperature conditions (Fig. 6f). The replacement reaction textures of ortho-

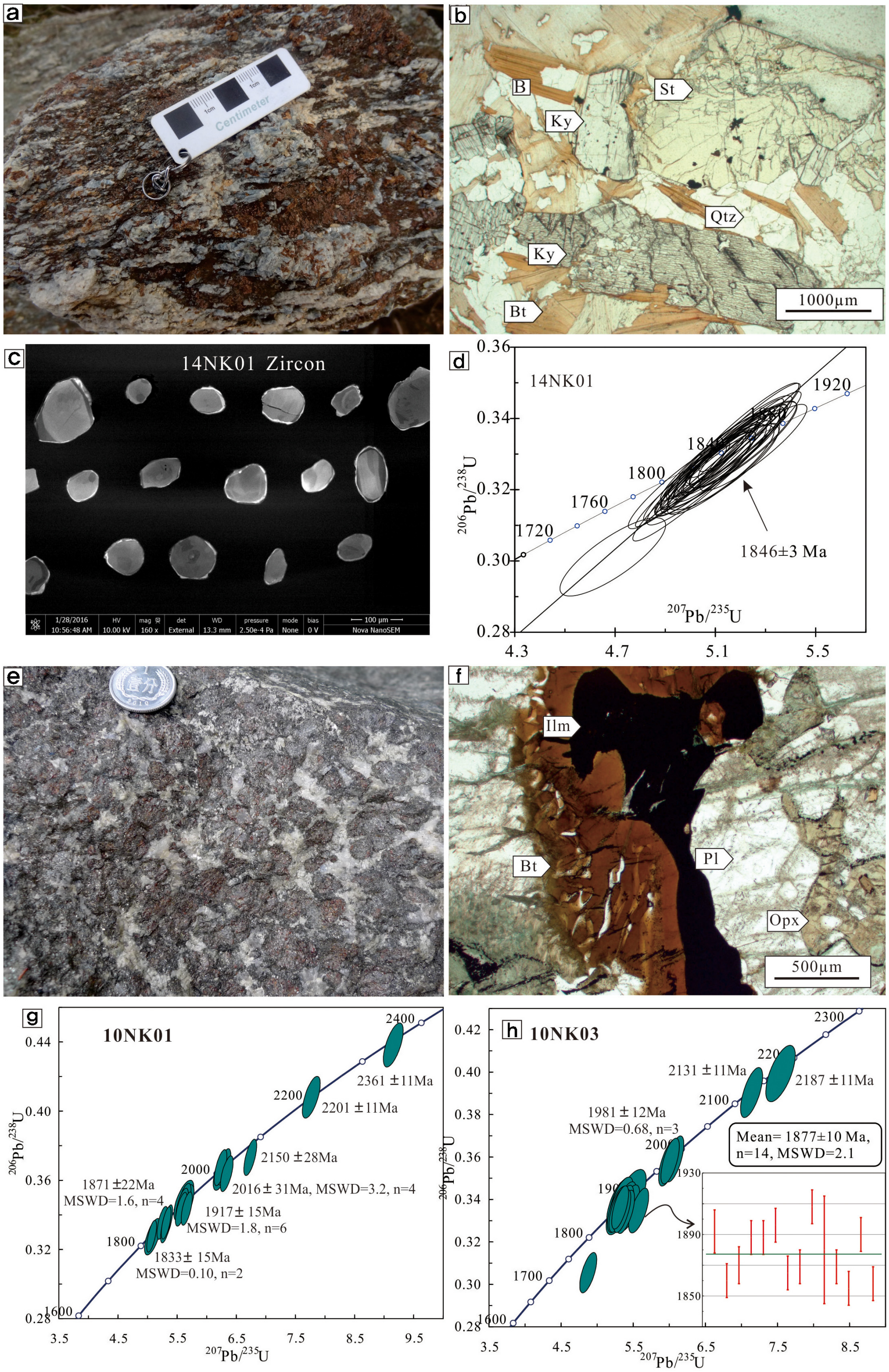

Fig. 6. Typical field occurrences, petrographic, zircon CL images and U-Pb dating results of representative metamorphic rocks from the Jungsan (A-D) and Nampo Groups (E-H) in western Rangnim massif of the NKP. Modified from Li, Q. *et al*. (2016), Zhao *et al*. (2016a).

pyroxene grains by later amphiboles tend to suggest back-reaction during the later cooling and melt crystallization stage. Zircons from these migmatites often exhibit complex internal structures and U-Pb dating results show episodic metamorphism at 1.92 Ga and 1.88-1.86 Ga, as well as later melt cooling and crystallization age at 1.84 Ga (Figs. 6g and 6h). Some samples constrain the time of anatexis and garnet growth at 1.84-1.83 Ga and melt cooling and crystallization at 1.79 Ga (Zhao *et al*., 2016a). The high-grade metamorphism and synchronous anatexis of the Jungsan Group in the Rangnim massif show great similarities with those occurring in the NCC, suggesting that the two terranes have evolved into a uniform continent before Paleoproterozoic. These metamorphic lithologies later became the sedimentary provenance, as well as the underlying basement of the Meso- Neoproterozoic strata.

4.2 The Machollyong Group

As has been previously described, the metamorphic grade of the Machollyong Group is relatively low, at greenschist to low amphibolite facies. But they all display strong deformation features (Fig. 7b). This lithological unit was proposed to have been deposited in the Machollyong Ocean between the Rangnim and Gwanmo massifs (Kim and Jon, 1996; Zhai *et al*., 2019). It has also been suggested that this ocean once extended from the NKP to Liaoning and Jilin Provinces of the NCC which collectively formed the Paleoproterozoic Jiao-Liao-Ji belt. Rocks of the Machollyong Group have been categorized into three formations, which are (from bottom to top) the Songjin Formation, Puktaechon Formation, and Namdaechon Formation (Fig. 7a). The lithologies of the Songjin Formation are marble, quartz schist, and amphibolites while that of the Puktaechon Formation and the Namdaechon Formation are dolomite, pyroclastic rock and siliceous dolomite, and marble, thick and thin quartz schist, quartzite and conglomerate, respectively (Fig. 7). Sulfide Pb-Zn ore bodies and lodes are well-developed in the Puktaechon and Namdaechon formations. In terms of sedimentary, metamorphism and ore-bearing potential, the Songjin, Puktaechon and Namdaechon formations roughly correspond to the Lieryu and Gaojiayu, Dashiqiao and Gaixian formations in the NE China (Paek and Jon, 1996; Zhai *et al*., 2019).

Liao *et al*. (2016) collected samples from Puktaechon and Namdaechon formations of the Machollyong Group and carried out SIMS U-Pb analyses on detrital zircons from them. Zircon U-Pb results of the Puktaechon Formation sample exhibit a dominant age peak of ~2.53 Ga and the youngest age peak of ~2.19 Ga. Ages of detrital zircons from the Namdaechon Formation show a dominant age peak at 2.18-2.02 Ga, a subordinate peak at ~2.46 Ga, and some older ages ranging from 3.30 Ga to 2.78 Ga (Fig. 7). These age results reflect dual provenances of the Paleoproterozoic plutons and the Neoarchean crustal components in the source regions of the Machollyong Group metasedimentary rocks. The several older ages also suggest the potential occurrences of Mesoarchean crusts in this area. Considering other geological information and age data, the Songjin Formation deposition time is not older than 2.2 Ga, and the Puktaechon formation is younger than 2.02 Ga. The youngest detrital age constrains the maximum deposition time of the Namdaechon formation is ca. 1.96 Ga (Zhai *et al*., 2019). Rock assemblages, geochronology and metamorphic features of the Machollyong Group are all similar to those of the Liaohe Group in eastern NCC (Li *et al*., 2001, 2019; Liu, F.L. *et al*., 2015; Wang *et al*., 2018a; Xu and Liu, 2019). Such consistency indicates their synchronization in deposition and similarity in provenance. These coeval and consanguineous litho-stratigraphic sequences can provide an important reference for calibrating the tectonic affinity in the Liao-Ji and Korea mobile belt during the Paleoproterozoic (Liu, F.L. *et al*., 2015;

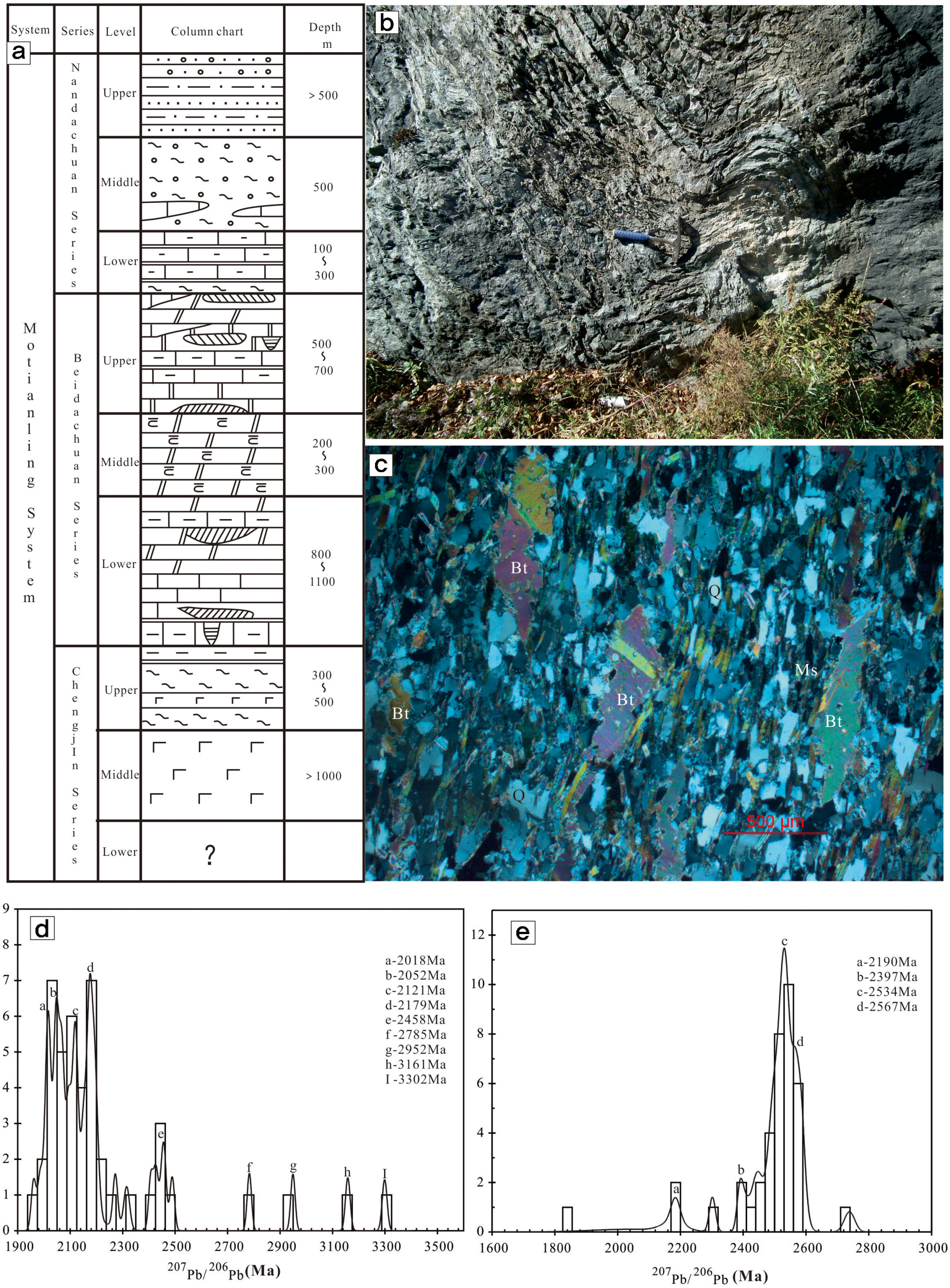

Fig. 7. Lithostratigraphic units, field and petrographic features, and detrital zircon U-Pb age results of the Machollyong Group in the NKP (Liao *et al*., 2016).

Liao *et al*., 2016; Zhai *et al*., 2019).

5. Paleoproterozoic Magmatic rocks in the NKP

Paleoproterozoic magmatic rocks are widely developed in the NKP, in both the Rangnim massif and the Gwanmo massif. Study results on modern river sands, as mentioned above, suggest that Paleoproterozoic magmatic rocks dominate the source regions of modern sediments along these rivers (Wu *et al*., 2007b, 2016). Although the Paleoproterozoic sedimentary rocks in the NKP show great similarities with those of the Liaohe Group in NCC, fewer ~2.1 Ga A-type granites have been identified from the NKP compared to the Liaoji Belt (Lu *et al*., 2004, 2006; Wu *et al*., 2007a; Li *et al*., 2011; Liu *et al*., 2017). The several samples with zircon U-Pb ages of ~2.1 Ga occur near Sinuiju and are biotite granite and garnet granite samples (Wu *et al*., 2007a). Zircon U-Pb ages of other reported Paleoproterozoic granites in the NKP mostly range from 1.95-1.80 Ga (Kim, J. *et al*., 2016; Peng *et al*., 2016). These magmatic rocks, dominantly of granitic composition, intruded into the Archean and Paleoproterozoic country rocks. Gabbroic intrusions sporadically occur as well. A previous synthesis study on Paleoproterozoic granites (~2.0-1.8 Ga) in the NKP has divided them into three series including porphyritic granites (I-type granites), S-type granites and syenites (Peng *et al*., 2016).

The porphyritic granite series (I-type granite, Figs. 8a and 8c) in the NKP seems to be associated with the volcanic-bearing supracrustal rocks of the Jungsan Group. They are typical of anorogenic magmatic associations, including rapakivi granites and several leucogabbroic / anorthositic / gabbroic stocks. One of the rapakivi batholiths was reported by (Zhai *et al*., 2007b), which occurs in the Myohyang Mountains with an outcropping area of 300 km^2 and shows intrusive relations with Archean and Paleoproterozoic metamorphic rocks. The Myohyang rapakivi granites exhibit typical porphyritic and mega- porphyritic granitic textures, with evenly distributed ovoidal porphyritic alkali feldspars (dominant mineral of the rock, occupying 45-55 vol.%) ranging in diameter from 1-4 cm to 6 cm (Zhai *et al*., 2007b). SiO_2 and Al_2O_3 contents of analyzed rapakivi granite samples are 67.93-72.44 wt.% and 12.44-16.41 wt.%, respectively, with high K_2O/Na_2O ratios of 1.71-3.99 (Fig. 9). The analyzed zircons from the rapakivi granite gave a weighted mean SHRIMP U-Pb $^{207}Pb/^{206}Pb$ age of 1861 ± 7 Ma, similar to the ca. 1839 Ma Yangyang Rapakivi granite in the Gyeonggi massif (Zhai *et al*., 2005b). The Paleoproterozoic rapakivi granites in the Korean Peninsula share great similarities with those in the NCC, although zircon U-Pb ages of them are older than those in the NCC where the rapakivi granites and anorthosites spanned in age from 1.72 to 1.68 Ga (Zhai *et al*., 2004b, 2015; Zhao *et al*., 2004, 2009; Yang *et al*., 2005; Zhang *et al*., 2007). Notably, rapakivi granites often show a close association with gabbro, leucogabbro and anorthosite, which collectively indicates extensional setting after orogenic events. The age differences between rapakivi granites in the NKP and NCC are therefore interpreted to imply that the Paleoproterozoic orogeny in the NKP finished a little earlier than the NCC (Zhai and Liu, 2003; Zhai *et al*., 2019).

Another type locality for Paleoproterozoic porphyraceous granites is northwestern Rangnim massif, near Cholsan (Kim, J. *et al*., 2016). Other Paleoproterozoic magmatic rocks closely associated with the porphyraceous granites in this region are coarse-grained syenite and aegirine-augite syenite. They show intrusive relations with rocks of the Archean Rangnim complex. Lengths of alkaline feldspar grains in porphyraceous granites are up to 6-8 cm (Figs. 8a). Alkaline feldspar is the dominant mineral of syenite in this area and they occupy up to 90 vol.% of the rock (Fig. 8). Some of the syenites occur as dykes in the field and contain aegirine, augite and fluorite grains (Figs. 8b and 8d). SIMS zircon U-Pb dating gave magmatic ages of 1865 ± 6 Ma for the weathered (coarse-grained) syenite, 1868 ± 8Ma for the aegirine-augite syenite and 1866-1873 Ma for porphyraceous granites (Figs. 8e and 8f; Kim, J. *et al*., 2016). According to Peng *et al*. (2016), these plutons are largely coeval with the metamorphism time of the amphibolite-granulite facies country rocks. They have also been interpreted to originate from the high-pressure

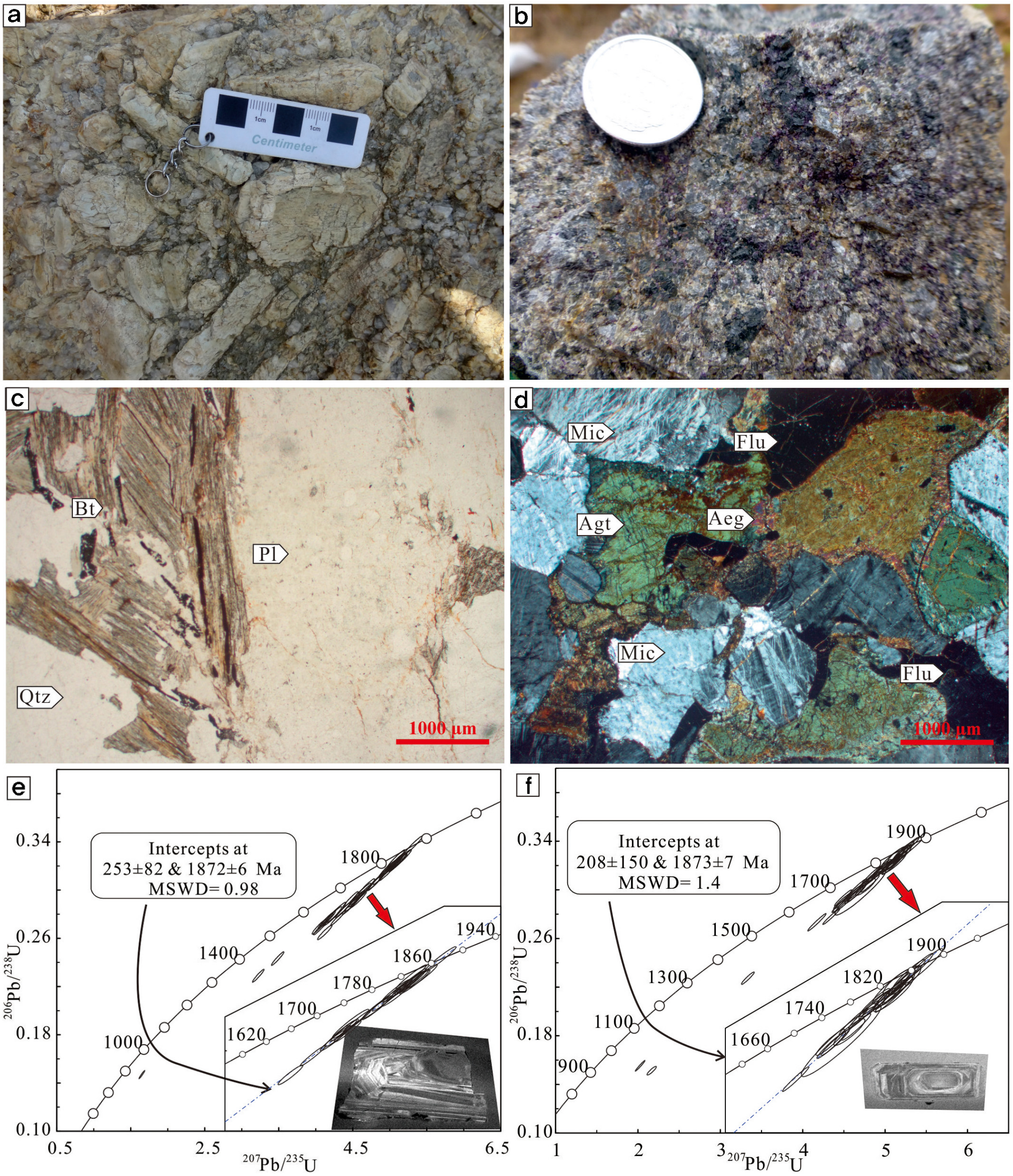

Fig. 8. Field photos, microphotographs and SIMS zircon U-Pb dating results of porphyraceous granites (a, c, d) and syenites granites (b, d, f) in the NKP (Kim, J. *et al*., 2016).

melting of crustal materials (Peng *et al*., 2016).

S-type granite series in the NKP are widely distributed in the Rangnim massif and they normally intruded into the high-grade Jungsan Group, low-grade Machollyong Group and Rangnim complex. These rocks have been termed the Paleoproterozoic Ryonhwasan Complex (Ri, 1996b; Peng *et al*., 2016). Major lithologies of this complex are garnet and/or cordierite/biotite bearing granites, gneissic granites, monzonite, granodiorite, leucogranite, etc. The several analyzed S-type granite samples show large variations in major and trace element compositions (Fig. 9). Zircon U-Pb results of them suggest that they were emplaced during 1844-1862 Ma (Peng *et al*., 2016). Chemical compositions, geochronology as well as isotopic features of S-type granites show that they are closely linked to the Paleoproterozoic high-grade meta-sedimentary rocks.

6. Meso- and Neoproterozoic sedimentary rocks

The Meso-Neoproterozoic strata in the NKP show some differences from those in the NCC. For example, the Changcheng System (Mesoproterozoic according to the Chinese stratigraphic chart or Paleoproterozoic to International stratigraphic chart) and the Jixian System, which are widely developed in NCC, are absent in the NKP (Fig. 10; Hu *et al*., 2012; Zhai, 2016; Zhai *et al*., 2019). These Meso-Neoproterozoic sedimentary rocks mainly occur in the Pyongnam Basin and sporadically occur in the northern part of the NKP (Fig. 2). Early studies suggested the Sangwon and Kuhyon

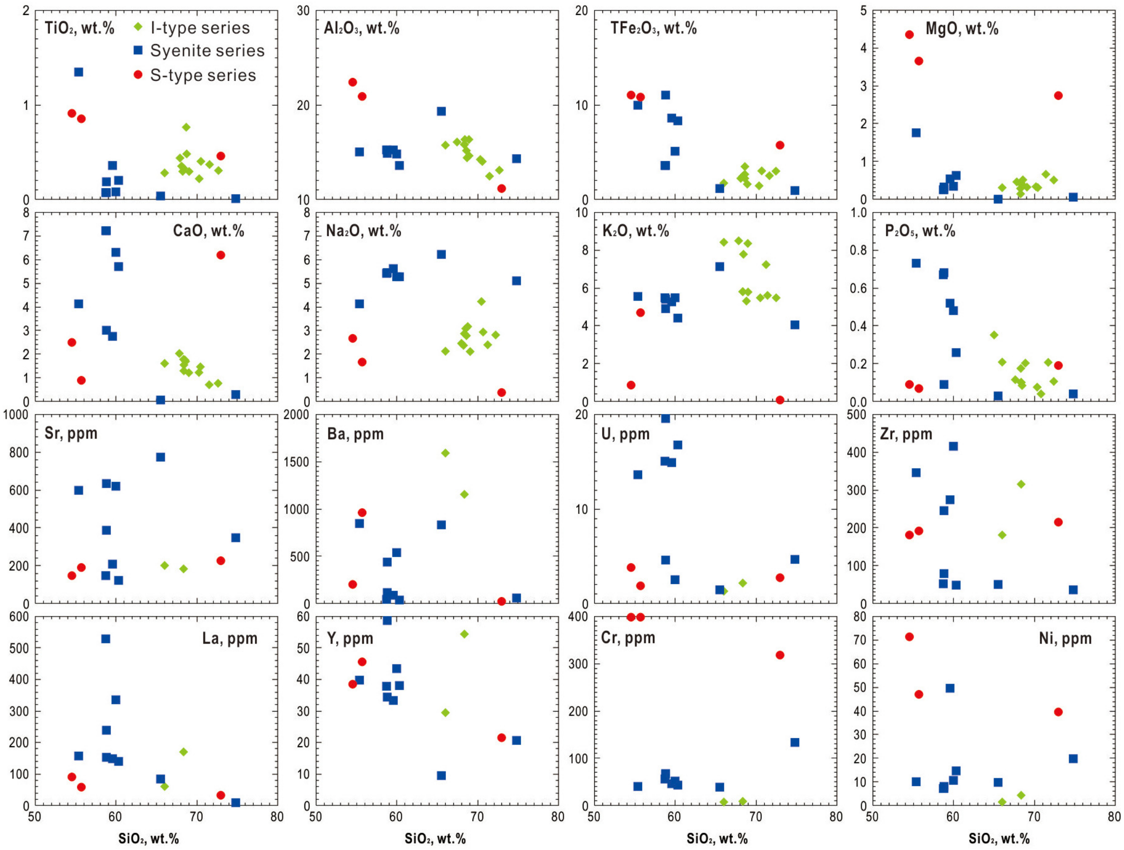

Fig. 9. Major and trace element plots of Paleoproterozoic magmatic rocks in the NKP. After Zhai *et al*. (2007b) and Peng *et al*. (2016).

systems as the major Meso- and Neoproterozoic sedimentary lithological units, which unconformably overlie the Paleoproterozoic Hwanghae Group and are unconformably overlain by the Cambrian Hwangju Group (Ri and Om, 1996). Yang *et al.* (2016) found that the Hwanghae Group rocks contain detrital zircon grains with U-Pb age peaks of ~1250 Ma (Fig. 10), and therefore, a new division of the Meso-Neoproterozoic stratigraphic strata was brought up to include the Hwanghae Group as Mesoproterozoic, the Sangwon Supergroup as Neoproterozoic, and the Yontan Group as Late Neoproterozoic (Fig. 10; Yang *et al.*, 2016). The Hwanghae Group rocks mainly occur in the southern part of the Pyongnam Basin and consist of three lithological sections which are: 1) the lower section dominated by pelitic schist, 2) the middle section dominated by quartz schist, and 3) upper

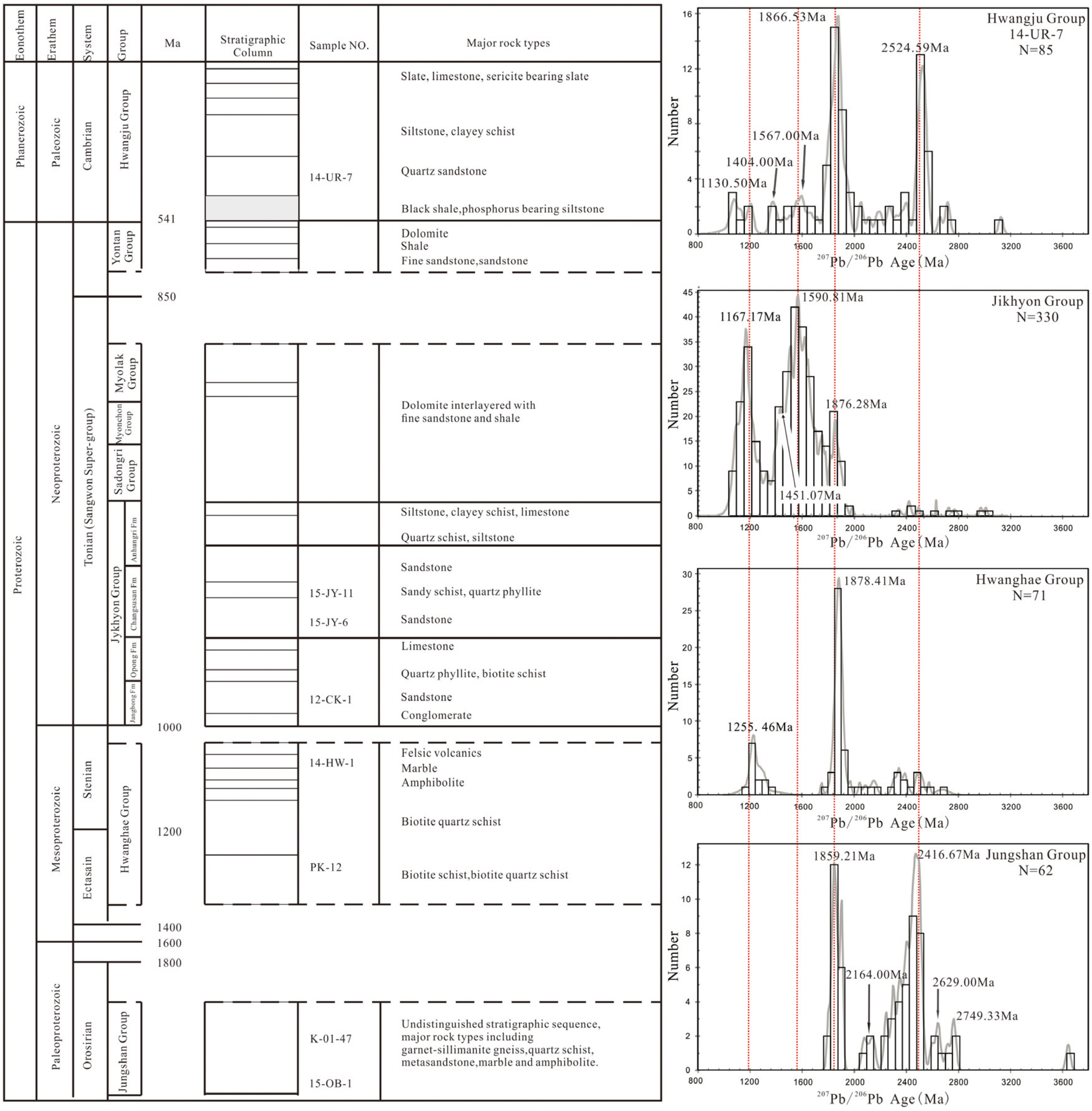

Fig. 10. Stratigraphic column and detrital zircon U-Pb age results of different Paleo- to Neoproterozoic lithological units in the NKP (Yang *et al.*, 2016; Zhai *et al.*, 2019).

section dominated by meta-felsic and basic volcanic rocks and marble. Rocks of the Sangwon Supergroup are widely distributed across the Pyongnam basin and this lithological unit was further be divided into (from bottom-up) the Jykhyon, Sandangu, Myonchon and Myoraksan groups (Fig. 10). The Jykhyon Group is one of the most common lithological units in the Pyongnam basin and it is composed of interlayered and multicycle of conglomerate, sandstone, pelitic siltstone and carbonatic schist. The Sandangu Group mainly consists of versicolor banded or massive dolomite and limestone. The Myonchon and Myoraksan groups consist of different proportions of limestone, dolomite, phyllite, calcareous conglomerate and quartz schist or quartz sandstone. The Yontan Group can diverge into a lower part of the Pirangdong Formation and an upper part of the Rumgri Formation. The former is characterized by well-developed lower conglomerate layers of basal or tillite origin. And the latter mainly consists of grayish phyllite and siltstone. Although the Changcheng and Jixian sections are absent in the NKP, rocks of the Hwanghae Group are believed to well-correlate with the Daijian System and the Sangwon Supergroup to the Qingbaikou System in the NCC (Hu *et al*., 2012; Li, Z. *et al*., 2016; Zhai *et al*., 2019). The Yontan Group of Ediacaran sequence probably corresponds to the Luoquan Group in the southern NCC and the Jinxian Group in the Lv-Da Basin in NE China (Zhai, 2014, 2016).

Zircon U-Pb age dating of the different lithological units in the NKP has been carried out to constrain their geochronology and provenances (Hu *et al*., 2012; Li, Z. *et al*., 2016; Park *et al*., 2016; Yang *et al*., 2016). Yang *et al*. (2016) reported detrital zircon ages of sandstone samples collected from the Hwanghae Group, the Jykhyon Group and Hwangju Group and compared them with those from meta-sandstones of the Jungsan Group (Fig. 10). The age results of the Jungsan Group samples display two prominent peaks at ~2,500 Ma and ~1850 Ma. The former was interpreted to represent the basement age of the Rangnim massif while the latter was suggested to represent the time of Paleoproterozoic high-grade metamorphism (Fig. 10; Yang *et al*., 2016). Samples of the Hwanghae Group display two prominent age peaks of ~1,850 Ma and ~1,250 Ma, and some ~2,500 Ma ages, which are all interpreted to represent provenance ages (either metamorphism or magmatism). Detrital zircons from sandstone samples of the Jykhyon Group display dominant age peaks at 1,100-1,200 Ma and 1,400-1,600 Ma and a subordinate age peak at ~1,850 Ma (Fig. 10). The 1,000 Ma detrital zircons and ~900 Ma dolerite sills inside the Jykhyon Group constrain the deposition of the Jykhyon Group to ca. 1,000 -900 Ma. The Hwangju Group samples show prominent age peaks ~1850 Ma and ~2500 Ma, as well as some ages spanning from 1,000-1,200 Ma to 1,400-1,600 Ma. The Cambrian Hwangju Group has a similar detrital zircon age spectrum with those of the Hwanghae and Jykhyon Group combined, which was interpreted to indicate that the Hwangju Group might have been sourced from the latter two lithological units (Fig. 10; Yang *et al*., 2016).

Other researches on Myonchon and Jykhyon groups yielded prominent age peaks of 1,000-1,800 Ma (Li, Z. *et al*., 2016) and reached conclusions that the age peaks are compatible with the episodic Meso- Neoproterozoic magmatic events in the NCC at 1,800-1,780 Ma, 1,720-1,620 Ma, 1,400-1,200 Ma and 1,000-880 Ma (Peng, 2015a, 2015b; Su *et al*., 2018), corresponding to multi-stage rifting during the Earth's Middle age period (Zhai *et al*., 2014, 2015, 2019; Zhai, 2016). Both detrital zircon age spectrum and fossils have been used to constrain the deposition time of the Yontan Group. The detrital zircons from the Pirangdong Formation have ages ranging from 850 Ma to 2,700 Ma, similar to the Myonchon Group and the Jykhyon

Group. However, the deposition age of the Yontan Group is Ediacaran according to stratigraphic correlation and fossil evidence (Jon *et al*., 2009; Zhai *et al*., 2019). As mentioned above, several previous studies correlate the Yontan Group in the NKP with the Luoquan Group in the NCC, which has been widely acknowledged to contain tillites and corresponds to the Nantuo Group or the Dengying Group in South China based on microfossil plants (Zhai *et al*., 2019). However, except the various pebbles include sandstone, pelite, limestone, granite and gneiss ranging in grain size from dozens cm to several mm in the Yontan Group rocks, the carbon isotope results of them seem to argue against the notion of glaciation sediments (Kim, M. *et al*., 2016).

7. Meso- and Neoproterozoic granites and mafic sills and dykes

Previous studies reported Mesoproterozoic granites in two places in the NKP ; one in the northern Rangnim massif (Zhao *et al*., 2006a) and the other in southwestern Rangnim massif (Ongjin area; Wu *et al*., 2007a; Park *et al*., 2016). The southwestern Rangnim massif is currently believed to be the major place where Mesoproterozoic granites in the NKP occur, showing intrusive relations with the Hwanghae Group. The granites were collectively designated as the Ongjin granite batholith, and comprises several stocks of biotite granites and dioritic intrusive bodies (Park *et al*., 2016). The granites exhibit obvious features of deformation and their deformation is consistent with those of the hosting Hwanghae Group. According to Zhai *et al*. (2019), early studies attributed the Ongjin granites to A-type granites in terms of petrology and petrochemistry and represent the felsic component of a bimodal magmatic suite within the Mesoproterozoic Hwanghae rift. Accompanying the granites, there are some felsic volcanics, termed as part of the Hwanghae Group.

Zircon U-Pb ages of felsic volcanics in the Hwanghae Group are 1,235-1,203 Ma, while those of the granites are 1,199-1,250 Ma (Figs. 11a and 11b; Wu *et al*., 2007a; Park *et al*., 2016). Together with ~1,200 Ma hornblende-granite body in the northern Rangnim massif (Zhao *et al*., 2006a), it can be seen that the Mesoproterozoic magmatism in the NKP is quite widespread and that the deposition of the Hwanghae Group should be between 1,400 and 1,200 Ma.

The most noteworthy Neoproterozoic magmatic event in the NKP is the dolerite sills identified around the city of Sariwon, in the Pyongnam basin (Peng *et al*., 2011b). These sills have been described to be up to 150 m in thickness and up to more than 10 km in length. The weighted SIMS ^{206}Pb-^{207}Pb age of baddeleyite grains separated from them is 899±7 Ma (MSWD = 0.34, n = 14), representing the crystallization age of the sill (Figs. 11e and 11f). Zircon grains were also separated from the same sill whose lower intercept U-Pb age is ~400 Ma, which has been interpreted to represent a close estimation of the greenschist facies metamorphism of the sills. The Sariwon sills are dolerites and have tholeiitic compositions. They show enrichment of light rare earth element concentrations (La/Yb_N=1.4-2.8) and are slightly depleted in high field strength elements (e.g. Nb, Zr, and Ti), in comparison to neighboring elements on the primitive-mantle normalized spider diagram. The whole rock $\varepsilon_{Nd}(t)$ (t=900 Ma) values are around −2, whereas in-situ $\varepsilon_{Hf}(t)$ (t=900 Ma) values of zircon grains vary from −25 to +8. They are similar to the coeval sills or dykes in other parts of the NCC, e.g., the Chulan sills (Xu-Huai basin, Shandong peninsula) and the Dalian sills (Lv-Da basin, Liaodong peninsula), whose magmatic ages have been constrained to be ~925-900 Ma (Peng *et al*., 2011a). According to geochemical and isotopic compositions, these sills and dykes possibly were interpreted to have been originated from a depleted mantle source (e.g., asthenosphere),

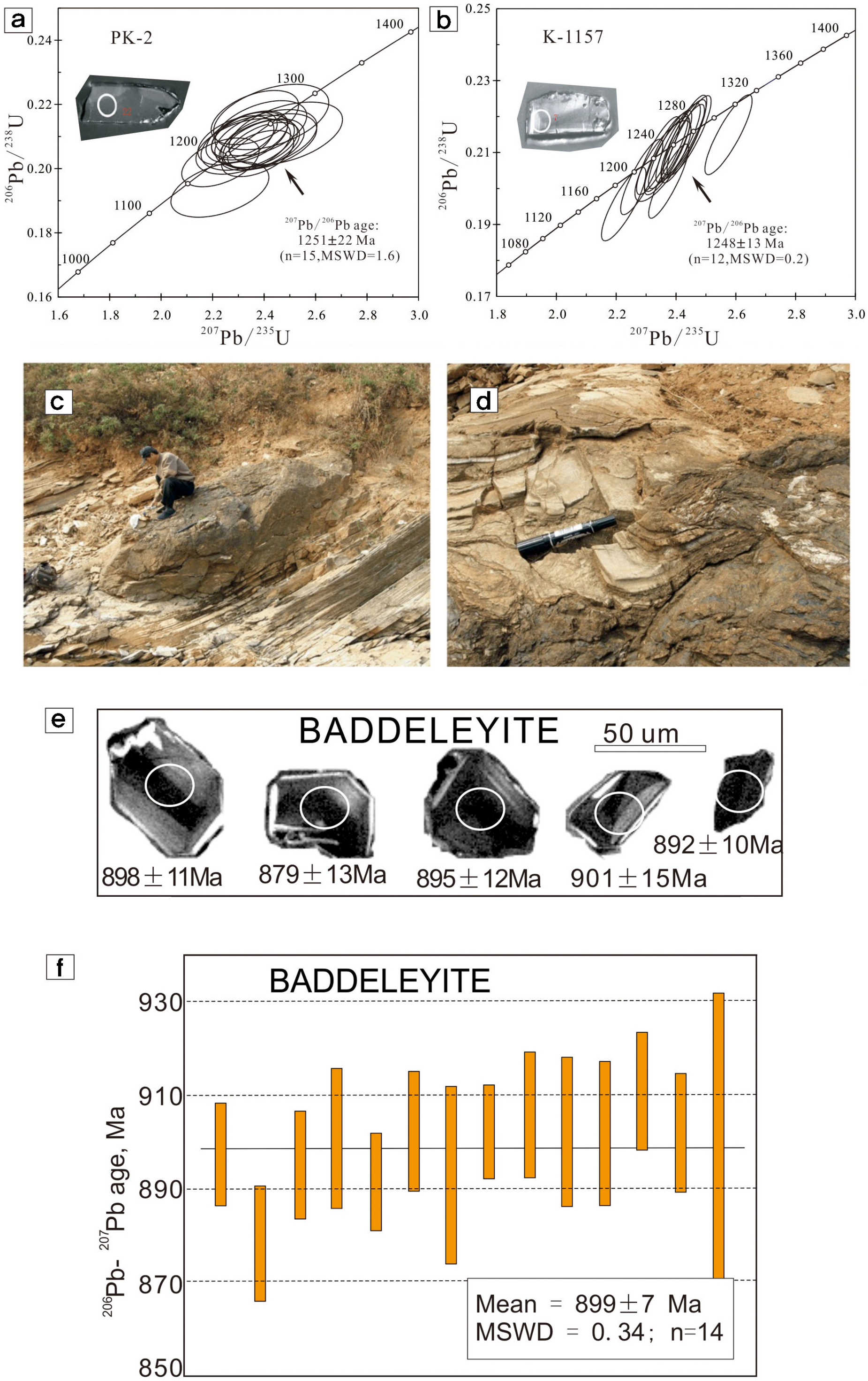

Fig. 11. Zircon and baddeleyite Cathodoluminescence images, and SIMS dating results of Mesoproterozoic granites (A and B) and Neoproterozoic sills (E and F) in the NKP. Representative field photos of Sariwon sills and formations nearby are also shown (C and D) (Peng *et al*., 2011b; Park *et al*., 2016).

rather than from the ancient lithospheric mantle of the NCC, and negative isotopic values have been accounted for by significant assimilations of lithospheric materials. Considering that the strata and sills in the Xu-Huai, Lv-Da and Pyongnam basins are comparable, and the three basins are geographically correlated based on Neoproterozoic geographical reconstructions, Peng *et al*. (2011a, 2011b) proposed that there once existed a Xu-Huai-Lv-Da-Pyongnam rift system along the southeastern edge of the NCC during Neoproterozoic (~900 Ma), with its closure at ~400 Ma as a result of continent-margin processes.

8. Discussion and concluding remarks

The Rangnim massif, which occupies most of the NKP, was originally thought to be an ancient micro-continent. This was challenged by the proposal that it should be part of a huge Paleoproterozoic orogenic belt in eastern NCC (Wu *et al*., 2007b, 2016; Peng *et al*., 2016a). However, abundant Archean basement components have been identified from different parts of the NKP (Fig. 2; Zhao *et al*., 2006a, 2016b, 2020; Zhang *et al*., 2016, 2017), inconsistent with the orogenic belt model. These Archean gneisses have zircon U-Pb ages of ~2.64-2.45 Ma and their Lu-Hf isotopic compositions show large variations, with $\varepsilon_{Hf}(t)$ values ranging from -20 to +10 and plotting on and below the depleted mantle linear model line (Fig. 4; Zhao *et al*., 2016a, 2020; Zhang *et al*., 2017). These Neoarchean TTG gneisses and granitic gneisses in the NKP can all find their equivalents in the NCC and besides, in the SKP (Cho *et al*., 2008; Kim *et al*., 2009). Considering the occurrences of these Archean gneisses in different parts of the NKP and the thick coverage by Mesoproterozoic to Phanerozoic sedimentary rocks in the pervasive basins, it is quite likely that Archean basement rocks are more widespread than presently identified. They should be important constituent components of the NKP.

Neoarchean granitic and grey gneisses in almost every identified localities exhibit ~2.50 Ga and 1.80-1.90 Ga metamorphic overprintings. The Neoarchean metamorphism occurs in the southern (Zhao *et al*., 2006a), northeastern (Zhang *et al*., 2017), and also middle Pyongnam basin (Zhao *et al*., 2020). This episode of metamorphism also widely influenced early Precambrian basement rocks of the NCC, as delineated by the granulites of that age in the Jiaobei Terrane (Fig. 5; Xie *et al*., 2014; Liu, S. *et al*., 2015), eastern Hebei (Duan *et al*., 2017; Lu *et al*., 2017; Wang *et al*., 2018b), northern Beijing (Zhang *et al*., 2019), and western NCC (Dong *et al*., 2014). The similar Neoarchean metamorphic ages of the NKP suggest that it was involved in the NCC since at least the end of Neoarchean, representing the first cratonization of this continental block (Fig. 1).

The late Paleoproterozoic (~1.95-1.80 Ga) metamorphism is developed in many ancient cratons around the world, related to the amalgamation of the Columbia Supercontinent (Rogers and Santosh, 2006; Zhao *et al*., 2006b, 2011). Paleoproterozoic metamorphic grade of rocks in the Gyeonggi massif, the Yeongnam massif and the NCC all reached granulite facies (Fig. 5; Kim and Cho, 2003; Kwon *et al*., 2003; Zhai *et al*., 2005a; Zhao *et al*., 2005, 2015, 2016c; Kusky *et al*., 2007b; Santosh and Kusky, 2010; Peng *et al*., 2014; Lee *et al*., 2016a; Zhou *et al*., 2017; Zou *et al*., 2017; Oh *et al*., 2019). The occurrences of Paleoproterozoic orthopyroxene-bearing migmatites and staurolite kyanite garnet gneisses in the NKP (Li, Q. *et al*., 2016; Zhao *et al*., 2016a), as well as the Paleoproterozoic metamorphic records as shown by Neoarchean gneisses across the NKP, suggest that this continental block experienced a range of high-grade metamorphism from amphibolite facies to granulite facies during late Paleoproterozoic, similar with the Gyeonggi Massif, the Yeongnam Massif, and the NCC. It seems that the widespread Paleoproterozoic metamorphism in the NKP and eastern NCC can be explained by the previously proposed huge orogenic belt (continental margin) model (Peng *et al*., 2016; Wu *et al*., 2016), if the Archean basement rocks are not considered. Moreover, these high-grade metamorphic rocks are far from enough to represent an orogenic belt, because it is still unclear if these high-grade metamorphic rocks are directly related to Paleoproterozoic orogenic events, or representing uplifted lower continental crust (Zhai and Liu, 2001; Zhai, 2009; Zhai and Peng, 2020). There are indeed some Paleoproterozoic high-grade rocks in the Sino-Korea Craton which are linearly distributed, consistent with the occurrences of orogenic belts along continental margins (Zhai *et al*., 2005a; Zhao *et al*., 2005; Zhai, 2009, 2011; Peng *et al*., 2014). The overall distributions of the Paleoproterozoic high-grade metamorphism in the NCC, however, don't follow the linear distribution pattern. Many of them occur outside of the three Paleoproterozoic orogenic belts previously defined (Fig. 5), which implies that some of the high-grade Paleoproterozoic metamorphic rocks might represent the uplifted lower continental crust, rather than orogenic products formed at continental margins (Figs. 1 and 5). More studies will be needed in the future to fully understand the geological significance of the Paleoproterozoic high-grade rocks in the NKP.

As mentioned above, the Rimjingang belt and the Okchon belt have been regarded as the geological boundaries between the Rangnim and Gyeonggi massifs, and the Gyeonggi and Yeongnam massifs, respectively. Oh (2006, 2010), Oh and Kusky (2007) and Oh *et al*. (2015) have also suggested the Hongseong-Odesan belt in the Gyeonggi Massif. However, we propose that none of these two belts penetrate the peninsula, but rather occur mainly in the west and start to shrink in the middle and then disappear in the east (Yin and Nie, 1993; Oh *et al*., 2004; Cho *et al*., 2007; Zhai *et al*., 2007a; Kwon *et al*., 2009; Zhang *et al*., 2018). These belts, therefore, might not be able to represent the true terrane boundaries. On the other hand, the early Precambrian basements of Gyeonggi and Yeongnam Massifs have been confirmed by many different studies, and they seemingly exhibit great similarities with those of the Rangnim massif, albeit the fact that the 2017-1960 Ma subduction related magmatism occurring in the Yeongnam Massif (Lee *et al*., 2019a; Cho *et al*., 2020) are unique among these regions. Multiple Paleoproterozoic (2017-1800 Ma) magmatism and metamorphism can be detected in both massifs (Lee and Cho, 2003; Lee *et al*., 2003, 2017; Zhai *et al*., 2005b; Oh *et al*., 2019; Cho *et al*., 2020). Archean lithologies (2600-2500 Ma) have been reported from the western and southeastern parts of the Gyeonggi Massif, as well as Neoarchean and Paleoproterozoic metamorphism (Cho *et al*., 2008; Lee and Cho, 2013; Lee *et al*., 2016b). The broad similarities as shown by the three Precambrian massifs in the Korean Peninsula seem to suggest that they might share a similar basement and evolutionary history, at least before the end of the late Paleoproterozoic.

During Meso- and Neoproterozoic, the NCC is believed to have experienced multiple rifting events related to the dispersal of the Columbia supercontinent during a long-lasting period of ~1.8-0.7 Ga (Zhai *et al*., 2015; Xiang *et al*., 2020). Sedimentary and igneous rocks formed during this period have all been correlated with the rifting systems. Even though the counterpart of the Mesoproterozoic Ongjin granite has yet to be identified from the NCC, contemporaneous mafic sills and dykes have been reported from different parts of the eastern NCC (Xiang *et al*., 2020). Besides, Mesoproterozoic detrital zircons are abundant in sedimentary rocks of the NCC (Luo *et al*., 2006; Zhai *et al*., 2015). Rocks of such ages (~1.2 Ga, Grenville) in other continents have widely been regarded to be related to the assembly of the Rodinia supercontinent (Li *et al*., 2008). However, rocks of this age occurring in the Sino-Korea Craton have all been regarded as indicating extension or even rifting settings (Zhai *et al*., 2015; Xiang *et al*., 2020), inconsistent with the convergent affinities shown by rocks in other continents. Neoproterozoic magmatism occurs in both eastern NCC and the Rangnim massif. They have been regarded as products of the Xu-Huai-Lv-Da-Pyongnam rift system along the south-eastern edge of the NCC during Neoproterozoic (~900 Ma; Peng *et al*., 2011a, 2011b). Based on the occurrences of these Meso- and Neoproterozoic rocks in both eastern NCC and the Rangnim massif, researchers have suggested that this area must have been located in the peripheral regions of the Rodinia supercontinent (Zhai *et al*., 2015; Xiang *et al*., 2020).

Based on the above reviews, summaries, and comparisons, the following concluding remarks can be reached.

1) The NKP contains the biggest Precambrian continental block within the Korean Peninsula, namely the Rangnim massif, which occupies most of the NKP. The Precambrian Gwanmo massif is situated in northeastern the NKP and the Precambrian lithologies of this massif show some differences from those of the Rangnim massif.

2) Both the Rangnim massif and the Gwanmo massif in the NKP contains Archean TTG and granitic gneisses, with zircon U-Pb ages of 2.64-2.45 Ga. Multiple metamorphic overprintings were identified from these Neoarchean rocks, at ~2.52-2.45 Ga, ~1.95-1.83 Ga and ~160 Ma. The Paleoproterozoic (~1.83-1.95 Ga) metamorphic alteration is the strongest and influenced almost all early Precambrian basement rocks. Considering the pervasive covers within the Phanerozoic Pyongnam basin, it is suggested that Archean rocks should be more widespread in the NKP than the several places identified. Rock assemblages, geochronological and isotopic features of Archean components in the NKP resemble those in the eastern NCC.

3) Similar to those within the Jiao-Liao-Ji belt of the NCC, Paleoproterozoic metasedimentary rocks in the NKP can also be categorized into the low- and high-grade lithological units, namely the low-grade Machollyong Group and the high-grade (granulite facies) Jungsan Group. The low-grade Machollyong Group occurs mainly in the eastern and northeastern NKP while the high-grade Jungsan Group occurs mainly in western NKP. Zircon U-Pb dating constrains the Neoarchean and Paleoproterozoic magmatic rocks as the major provenances for both the Machollyong and Jungsan Groups, and that the high-grade metamorphism and contemporaneous anatexis to have taken place at ~1.95-1.79 Ga. Mineral assemblages, as well as reaction textures in high-grade rocks, imply clockwise P-T paths, similar to those in the eastern NCC.

4) Paleoproterozoic magmatism is widely distributed across the NKP with zircon U-Pb ages ranging from ~2.10 to ~1.80 Ga. The ~1.95-1.80 Ga granites are the most common Paleoproterozoic magmatic rocks in the NKP, which have been categorized into porphyritic (I-type) series, S-type granites and syenites. While the porphyritic rocks (rapakivi granite) and syenites have been interpreted to mark the end of Paleoproterozoic orogenic events, the S-type granites in the NKP have been suggested to be partial melting products of high-grade metamorphic rocks.

5) Meso- Neoproterozoic sedimentary rocks in the NKP are different from those of the NCC in that the Changcheng and Jixian sections are absent. However, the Mesoproterozoic Hwanghae Group, the Neoproterozoic Sangwon Supergroup and the late Neoproterozoic Yontan Group in the NKP can all find their equivalents in the NCC. Whether or not the diamictites of the Yontan Group can represent glaciation depositions is still a matter of debate.

6) The deposition of the Mesoproteroozic Hwanghae Group is temporally and spatially related to the emplacement of the 1250-1200 Ma Ongjin granite. They have been suggested to be products of the Hwanghae rift in the NKP. The Neoproterozoic Sariwon sills in the NKP led the geologists to define a Xu-Huai-Lv-Da-Pyongnam rift system along the south-eastern edge of the NCC at ~900 Ma, which closed at ~400 Ma. Eastern NCC as well as the Rangnim massif are believed to have been located in the peripheral regions of the Rodinia supercontinent.

7) The NKP Precambrian massifs share similar evolutionary histories with the NCC, since at least Neoarchean. Because of its critical geological position and the preservation of some unique geological records, more detailed studies on the NKP geology are needed in the future to address some debatable issues of Northeast Asia

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