Article

The Paleoproterozoic Evolution of Basement Rocks of the Taebaeksan Basin, Korean Peninsula, and Their Correlation to Those of the Paleoproterozoic Massifs in the Korean Peninsula

Bo Young Lee 1, Deung-Lyong Cho 1,*, Chang Whan Oh 2,*, Byung Choon Lee 3 and Seung Hwan Lee 1

1 Geology Division, Korea Institute of Geoscience and Mineral Resources, 124 Gwahak-ro, Yuseong-gu, Daejeon 34132, Republic of Korea; lby@kigam.re.kr (B.Y.L.); lsh07@kigam.re.kr (S.H.L.)

2 Department of Earth and Environmental Sciences, The Earth and Environmental System Research Center, Jeonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju 54896, Republic of Korea

3 Department of Earth and Environmental Sciences, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 61186, Republic of Korea

* Correspondence: drcho@kigam.sci.kr (D.-L.C.); ocwhan@jbnu.ac.kr (C.W.O.)

Abstract: The Korean Peninsula mainly comprises the Paleoproterozoic Gwanmo, Nangnim, Gyeonggi, and Yeongnam massifs from north to south. The Paleoproterozoic basement is rarely exposed in the Paleozoic Taebaeksan basin, which is located in the northeastern part of the Okcheon belt between the Gyeonggi and Yeongnam massifs. One of the most important issues in the tectonic interpretation of the Korean Peninsula is whether Paleoproterozoic rocks in the Taebaeksan basin have an affinity with those in the Gyeonggi or Yeongnam massifs. To solve this problem, we focused on the petrogenesis of the Imgye gabbroic diorite, Jungbongsan granite, and Jangsan quartzite in the Imgye area of the Taebaeksan basin. The Imgye gabbroic diorite shows mafic to intermediate compositions with slightly enriched LREEs compared to HREEs, slightly positive Rb, K, and Pb anomalies, and negative Ta, Nb, and P anomalies. The Imgye gabbroic diorite formed in a volcanic arc tectonic setting. The geochemical compositions of the Jungbongsan granite show enriched LREEs compared to HREEs with negative Eu anomalies, and reveal strong positive Rb, Th, K, and Pb anomalies with negative Ba, Ta, Nb, Sr, P, Eu, and Ti anomalies. This Jungbongsan granite also formed in an arc tectonic setting like the Imgye gabbroic diorite. LA-ICP-MS zircon age dating of the Imgye gabbroic diorite gives an intrusion age of 1948 ± 21 Ma, whereas SHRIMP U–Pb zircon age dating on the Jungbongsan granite yields an emplacement age of 1873 ± 14 Ma. The εHf(t) values of the Imgye gabbroic diorite are from 3.5 to 9.7, whereas those of the Jungbongsan granite are from −2.9 to 0.6. These data imply that the Imgye gabbroic diorite formed from a depleted mantle in the arc tectonic environment, whereas the Jungbongsan granite formed by reworking pre-existing crust material in the arc environment. The detrital zircons in the Jangsan quartzite show ages ranging from 3.06 to 1.85 Ga, with a peak concentration of ca. 2.5 Ga. Previous studies have suggested that the northern Gyeonggi and Nangnim massifs underwent collision-related magmatism and metamorphism at ca. 1.93–1.90 Ga, and then post-collisional magmatism and metamorphism at ca. 1.89–1.83 Ga. By contrast, subduction-related events were recognized in the northern Yeongnam massif at ca. 2.02–1.96 Ga and 1.90–1.85 Ga. This work, combined with the previous studies, suggests that the Paleoproterozoic basement in the Imgye area of the Taebaeksan basin can be correlated with the Paleoproterozoic basement of the northern Yeongnam massif rather than with those of the Nangnim and Gyeonggi massifs.

Keywords: Imgye gabbroic diorite; Jungbongsan granite; Paleoproterozoic; Taebaeksan basin; Yeongnam massif
1. Introduction

Various geological events in Northeast Asia from the Precambrian to Cenozoic provide critical information for the interpretation of the tectonic evolution of Northeast Asia, including the Korean Peninsula. In the past, the Korean Peninsula was correlated with the North China Craton [1]. However, the discovery of the Dabie–Sulu collisional belt between the North China and South China Cratons provided the possibility that the whole Korean Peninsula does not belong to the North China Craton (Figure 1a) [2–6]. Since then, several tectonic models of the Permo–Triassic collision in Northeast Asia have been proposed, and each model gives different interpretations for the extension of the Dabie–Sulu collisional belt into the Korean Peninsula [2–6]. However, it is still uncertain which tectonic model is more reasonable, and more research is needed to interpret the tectonic evolution of Northeast Asia. Understanding the Paleoproterozoic basement rocks in the Korean Peninsula is one of the essential topics to determine which model is more appropriate.

The basement of the Korean Peninsula is composed of the Paleoproterozoic Gwanmo, Nangnim, Gyeonggi, and Yeongnam massifs from north to south (Figure 1b). In the Nangnim and northern Gyeonggi massifs, continental collision-related metamorphism occurred ca. 1933–1903 Ma and 1925–1917 Ma, respectively [7–10], and was followed by post-collisional igneous activities at ca. 1854–1830 Ma and 1885–1867 Ma, respectively [7–9,11,12]. These events were caused by the collision of the Longgang block in the North China Craton with the Nangnim massif in the Korean Peninsula along the Jiao–Liao–Ji collision belt at ca. 1.93–1.90 Ga [13,14]. By contrast, the southern Gyeonggi massif underwent igneous and metamorphic activities in an arc tectonic setting at ca. 1.94–1.92 Ga, which was followed by post-collisional magmatism and metamorphism at 1.84–1.78 Ga [15–17], whereas the northern Yeongnam massif experienced different Paleoproterozoic tectonic events compared to both the Nangnim and Gyeonggi massifs. The northern Yeongnam massif underwent prolonged arc-related magmatic and metamorphic events at ca. 2.02–1.96 Ga and 1.90–1.85 Ga [18–22]. Thus, the Nangnim and northern Gyeonggi massifs, southern Gyeonggi massif, and northern Yeongnam massif may have undergone different Paleoproterozoic tectonic evolutions, and the understanding of these differences will give new insights into the geological correlation between the Korean Peninsula and China, as well as into the Paleoproterozoic tectonic evolution of Northeast Asia. Therefore, a clear understanding of the Paleoproterozoic tectonic evolution of the Korean Peninsula is essential.

The Paleoproterozoic tectonic evolution of the Okcheon belt between the Gyeonggi and Yeongnam massifs is still unclear because Neoproterozoic and Paleozoic sedimentary and volcanic rocks mainly cover the Paleoproterozoic rock. The Okcheon belt consists of the Taebaeksan basin and the Okcheon metamorphic belt. The Okcheon metamorphic belt underwent Permo–Triassic intermediate-P/T type metamorphism, but the Taebaeksan basin underwent no or very low-grade metamorphism [23,24]. The Paleoproterozoic basement is exposed in the Imgye area in the northern part of the Taebaeksan basin, the northeastern Okcheon belt. Therefore the Imgye area is important for interpreting the Paleoproterozoic tectonic evolution in the Korean Peninsula. However, few studies have been conducted in this area. Although a Paleoproterozoic intrusion age of 1837 Ma was obtained for granite using the whole-rock Rb/Sr method [25], the exact age is uncertain due to the possibility of Sr loss during later geologic events. Therefore, a detailed petrological and petrochemical study on the potential Paleoproterozoic rocks in the Imgye area is necessary to establish the Paleoproterozoic tectonic evolution of the Precambrian basement of the Taebaeksan basin.

This study presents new zircon U–Pb data on the igneous and sedimentary rocks in the Imgye area, including the emplacement ages for the Imgye gabbroic diorite and Jungbongsan granite, and the maximum depositional age for the Jangsan quartzite. Mineral chemistry, whole-rock geochemistry, and Lu–Hf isotope analysis of zircon in the Imgye gabbroic diorite and Jungbongsan granite were also carried out to investigate the petrogenesis of these rocks. The data presented herein and in previous studies allow us to determine
the tectonic evolution of the Paleoproterozoic basement in the Taebaeksan basin and its correlation with those in other Paleoproterozoic basements on the Korean Peninsula and in China.

2. Regional Geology and Petrography

The Korean Peninsula consists of four Precambrian basements: the Gwanmo, Nangnim, Gyeonggi, and Yeongnam massifs. The Imjingang and Okcheon belts are located between the Nangnim and Gyeonggi massifs and the Gyeonggi and Yeongnam massifs, respectively (Figure 1b). From west to east, the Okcheon belt is divided into the Okcheon metamorphic belt and the Taebaeksan basin.

The Taebaeksan basin consists of Paleozoic sedimentary units, which are divided into the Joseon and Pyeongan supergroups [1,26]. The Joseon supergroup was deposited during the Cambrian–Ordovician and the Pyeongan supergroup was deposited unconformably during the Carboniferous–Permian. The Joseon supergroup comprises the Taebaek, Yeongweol, Pyeongchang, Yongtan, and Mungyeong groups. The Taebaek group consists of ten formations: the Jangsan, Myobong, Daegi, Hwajeol, Sesong, Dongjeom, Dumugol, Maggol, Jigunsan, and Duwibong formations. The Jangsan formation is considered the lowermost part of the Taebaek group and mainly consists of quartzite [1,26–29].

The Imgye area is located in the northern part of the Taebaeksan basin (Figure 1c). The Precambrian Taebaeksan gneiss complex in the Imgye area mainly comprises gneiss, schist, and quartzite. In the northern part of the Taebaeksan gneiss complex, granitic rocks are abundant and classified into Jungbongsan granite, leucocratic granite, Imgye granite, and Samhwa granite. However, it is difficult to distinguish each granite due to gradual mineral assemblage changes [30]. From the Jungbongsan granite and leucocratic granite, ca. 1837 Ma and ca. 2108–2088 Ma were obtained using Rb/Sr whole-rock age dating, respectively [25]. The Imgye gabbroic diorite is exposed along the western part of the Jungbongsan granite with the Jangsan quartzite. However, the contact among them is still uncertain. Chang et al. [31] suggested that the Imgye gabbroic diorite formed in a subduction-related environment based on whole-rock geochemical data. The Jangsan quartzite occurs between the Precambrian basement and the Cambrian Myobong formation. The Jungbongsan granite lies below the Jangsan quartzite [32]. Recently, the Jangsan quartzite has been interpreted as a Precambrian formation rather than a Cambrian formation due to the youngest Precambrian detrital zircon ages ranging from 2.0 to 1.8 Ga, with a peak at 2.5 Ga and no Paleozoic detrital zircon [33–36]. However, this issue is still under debate [37]. The Cambrian sedimentary rocks of the Taebaek group are distributed in the west and consist of the Myobong, Daegi, and Hwajeol formations from bottom to top. The Myobong formation was deposited unconformably on the Jangsan quartzite and consists of fine-grained slate. The Daegi formation mainly consists of limestone, and the Hwajeol formation mainly consists of shale and limestone. The Ordovician sedimentary rocks unconformably overlie the Cambrian sedimentary rocks and consist of the Dongjeom formation, the Dumugo formation, and the Maggol formation from bottom to top with conformable relationships. In the Imgye area, several deformations occurred from the Paleozoic to the early Tertiary period [30]. Firstly, mylonitization occurred along the boundary of the Cambrian–Precambrian formation [31,38]. Then, the thrust and fold were formed in the middle of the Triassic [32,39,40]. After that, the Jurassic Daebi Orogeny caused another thrust fault and folding [41]. Lastly, this area was folded with east–west-trending axial traces because of the Bulgusga Orogeny from the late Cretaceous to early Tertiary [42]. The deformation degree increases as the region approaches the faults and mylonite zones.
Figure 1. (a) Tectonic map of the China Craton and Korean Peninsula (modified after [43]). (b) Simplified tectonic map of the Korean Peninsula (modified after [44]). (c) Geological map of the study area and sample locations [45]. Abbreviations: LB, Longgang block; GwM, Gwanmo massif; MB, Macheonllyeong belt; NM, Nangnim massif; PB, Pyeongnam basin; IB, Imjingang belt; NGM, northern Gyeonggi massif; SGM, southern Gyeonggi massif; OMB, Okcheon metamorphic belt; TB, Taebaeksan basin; YM, Yeongnam massif; GB, Gyeongsang basin; JVT, Jeju volcanic terrain.

In this study, the Imgye gabbroic diorite, Jungbongsan granite, and Jangsan quartzite were studied to determine their intrusion or maximum depositional ages, petrogenesis, and tectonic evolution. These rocks did not experience metamorphism. The Imgye gabbroic diorite far from the fault and mylonite zones shows weak foliation due to the deformation, with well-developed joints in the outcrop (Figure 2a). The Imgye gabbroic diorite comprises...
medium-grained amphibole, plagioclase, biotite, quartz with minor fine-grained epidote, and titanite. The color of the amphibole becomes darker from the core to the rim. The feldspar and quartz usually show an irregular shape, and fine-grained amphibole and biotite are included within the feldspar (Figure 2b). The Jungbongsan granite comprises medium-grained K-feldspar, plagioclase, biotite, and muscovite with coarse-grained K-feldspar phenocrysts. The length of the feldspar phenocrysts is about 2–3 cm (Figure 2c). Closer to the mylonitization zone, the feldspar phenocrysts were deformed into an augen shape. The biotite generally shows a well-developed orientation (Figure 2d). The feldspar phenocrysts include fine-grained muscovite and show twining. The Jangsan quartzite shows bedding and comprises more than 80% quartz (Figure 2e), which was cemented by fine-grained quartz and mica (Figure 2f). Quartz of the Jangsan quartzite occurs as single grains or aggregates, and some quartz grains show undulose extinction. However, the whole rock does not show a deformed texture, indicating that some quartz was deformed before sedimentation.

Figure 2. Outcrop photographs and photomicrographs showing textures and mineral assemblages of the studied igneous rocks and sedimentary units in the Imgye area: (a,b) Imgye gabbroic diorite, (c,d) Jungbongsan granite, and (e,f) Jangsan quartzite. Abbreviations: Amp, amphibole; Bt, biotite; Ep, epidote; Kfs, K-feldspar; Mus, muscovite; Pl, plagioclase; Qtz, quartz; PPL, plane-polarized light; XPL, cross-polarized light.
3. Analytical Methods

3.1. Whole-Rock Geochemistry

Representative samples of the Imgye gabbroic diorite \((n = 13)\) and Jungbongsan granite \((n = 4)\) in the study area were analyzed for major, trace, and rare-earth elements. These samples were crushed so 95\% could pass through a 200-mesh sieve to provide homogenous and representative samples for analysis. In the induction furnace, a flux of lithium metaborate and lithium tetraborate blended together was used to fuse the powder samples. When the materials were melted, 5\% nitric acid (in-house standard) was added and blended until the samples dissolved. The major elements of all samples were analyzed by inductively coupled plasma atomic emission spectrometry (ICP-AEC) (Thermo Jarrel-Ash ENVIRO II), and trace and rare-earth elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) (Perkin Elmer Sciex ELAN 9000) at Activation Laboratories Ltd., Ancaster, ON, Canada. The detailed analyses are described on their website [46]. The representative whole-rock compositions of the Imgye gabbroic diorite and Jungbongsan granite are given in Tables S1 and S2, respectively.

3.2. Mineral Chemistry

Amphibole, plagioclase, and biotite in the Imgye gabbroic diorite were analyzed using a Field-Emission Electron Probe Micro-Analyzer (FE-EPMA) JEOL JXA-8100 instrument at the Center of Research Facilities, Gyeongsang National University, Jinju, Republic of Korea. The instrument has an accelerating voltage of 15 kV, a probe current of 10 nA, and a probe diameter of 5 \(\mu\)m. The wavelength-dispersive X-ray spectroscopy (WDS) detection limit is about 10–100 ppm. The ZAF correction program was calculated for matrix correction. The natural and synthetic mineral standards used in the analysis were albite (Na), kyanite (Si, Al), Fe (Fe), orthoclase (K), wollastonite (Ca), rhodonite (Mn), Mgo (Mg), and TiO (Ti). The results are shown in Tables S3–S5.

3.3. Zircon U–Pb Isotope Analysis

For U–Pb age dating, zircons from the Imgye gabbroic diorite (IG-9), Jungbongsan granite (IG-15), and Jangsan quartzite (TB-7) were separated by crushing, magnetic separation, and heavy-liquid techniques, and then handpicked. The handpicked zircon grains from the Imgye gabbroic diorite were mounted onto an epoxy disk. After the mount was polished to obtain cross-sectional views, cathodoluminescence (CL) images were obtained using a Jeol JXA-8800R scanning electron microscope. The reference materials GJ-1, Plesovice, and silicate glass NIST 610 were used as the primary standards for optimizing the machine. The Imgye gabbroic diorite was analyzed for zircon U–Pb dating using Agilent 7900 laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Wuhan Sample Solution Analytical Technology Company, Wuhan, China. The ICP-MS is equipped with approximately 80 mJ laser energy, a 32 \(\mu\)m diameter, and a 5 Hz repetition rate. The zircon standards GJ-1 and Plesovice used for instrument monitoring and stability had Concordia ages ca. 602 ± 1.4 Ma \((n = 13, \text{MSWD} = 0.036)\) and ca. 338 ± 0.96 Ma \((n = 8, \text{MSWD} = 2.6)\), respectively. The data reduction was performed using an ICPMS DataClav10.8 and Isoplot/Ex 3.0 [47]. The results of the LA-ICP-MS age dating on the Imgye gabbroic diorite (IG-9) are shown in Table S6.

The handpicked zircon grains from the Jungbongsan granite (IG-15) and Jangsan quartzite (TB-7) were mounted onto an epoxy disk with the zircon standards SL13 (U = 238 ppm) and FC1 \(206^{\text{Pb}}/238^{\text{U}} = 0.1859\). After the mount was polished to expose observed cross-sectional views, cathodoluminescence (CL) images were obtained using a Jeol JSM-6610LV scanning electron microscope. The zircon U–Pb isotope analysis was conducted using a SHRIMP IIe/MC instrument at the Korea Basic Science Institute (KBSI), Ochang, Republic of Korea. The primary beam was a 4–6 nA negative ion oxygen \((O^{2-})\) beam with a 20–30 \(\mu\)m diameter. The U–Pb age dating procedures were based on those reported in [48,49]. The data reduction was performed using an Isoplot/Ex 3.4 program and SQUID 2.5 Excel macro. The age and common Pb correction were conducted following the methods described
in [50,51], and the decay constants used were those determined by the International Union of Geological Sciences Subcommission on Geochronology [52]. The SHRIMP age dating results on the Jungbongsan granite (IG-15) and Jangsan quartzite (TB-7) are shown in Tables S7 and S8, respectively.

3.4. Zircon Lu–Hf Isotope Analysis

Zircon Lu–Hf isotope analysis of the Jungbongsan granite was measured by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) at the KBSI, Ochang, Republic of Korea. The instrument comprises an ESI NWA193 UC LA system and a Nu plasma II MC-ICP-MS. The analysis was conducted with approximately 5.0 J/cm² laser energy, a 50 µm diameter, and a 10–13 Hz repetition rate. The in-situ Lu–Hf isotope analyses were conducted on the same zircon domains that were used for the U–Pb age dating. The zircon standards 91500 and FC1 used for instrument monitoring and stability had $^{176}\text{Hf}/^{177}\text{Hf}$ weighted averages of $0.2822979 \pm 0.0000089$ ($n = 34$, MSWD = 1.11) and $0.282165 \pm 0.0000014$ ($n = 8$, MSWD = 1.9), respectively. These standard values were close to the recommended values [53].

The zircon Lu–Hf isotope of the Imgye gabbroic diorite was analyzed using a NEPTUNE MC-ICP-MS. The analysis was conducted with approximately 10 J/cm² laser energy, a 44 µm diameter, and an 8 Hz repetition rate. The in-situ Lu–Hf isotope analyses were conducted on the same zircon domains that were used for the U–Pb age dating. The zircon standards 91500, GJ-1, and Plesovice used for instrument monitoring and stability had $^{176}\text{Hf}/^{177}\text{Hf}$ weighted averages of $0.282297 \pm 0.000010$ ($n = 6$, MSWD = 0.21), $0.282016 \pm 0.000013$ ($n = 4$, MSWD = 0.82), and $0.2824782 \pm 0.0000052$ ($n = 16$, MSWD = 0.70), respectively. The zircon Lu–Hf isotope data from the Imgye gabbroic diorite (IG-9) and Jungbongsan granite (IG-15) are given in Tables S9 and S10, respectively, and are reported at an uncertainty level of 2σ.

4. Results

4.1. Whole-Rock Geochemistry

The geochemistry of Imgye gabbroic diorite and Jungbongsan granite has low loss-on-ignition (LOI) values of 0.81–2.03 and 0.88–1.05, respectively, and shows Ce* values of 1.01–1.02 and 1.05–1.08, respectively. These indicate that the whole-rock geochemistry was immobile (0.9 < Ce* < 1.1) (Tables S1 and S2) [54]. The geochemical data of each sample show similar values without significant differences (Figure 3). They also represent no change in their whole-rock geochemical data of igneous rocks by hydrothermal alteration and metamorphism.

Figure 3. Cont.
The chondrite-normalized rare-earth element (REE) patterns of the Imgye gabbroic diorite show relative enrichment in light REEs (LREEs) compared to heavy REEs (HREEs), with (La/Yb)\textsubscript{N} = 7.91–8.90 and Eu/Eu* = 0.82–0.94 (Figure 5a; Table S1). The Jungbongsan granite samples show more enrichment in LREEs than HREEs, with (La/Yb)\textsubscript{N} values of 42.90–54.80 and strong negative Eu anomalies (Eu/Eu* = 0.216–0.234; Figure 5c; Table S2).

In the primitive-mantle-normalized spider diagram, the Imgye gabbroic diorite shows positive Rb and Pb anomalies and negative Ta, Nb, and P anomalies (Figure 5b). In comparison, the Jungbongsan granite has relatively strong positive Rb, Th, K, and Pb anomalies with strong negative Ba, Ta, Nb, Sr, P, Eu, and Ti anomalies (Figure 5d). The Nb–Ta negative anomalies in both units support their formation in an arc tectonic setting.

Almost all samples from the Imgye gabbroic diorites are plotted in the gabbro to gabbroic diorite field. The Jungbongsan granites are plotted in the granite field on the total alkali (Na\textsubscript{2}O + K\textsubscript{2}O) vs. SiO\textsubscript{2} diagram (Figure 3a). On the K\textsubscript{2}O vs. SiO\textsubscript{2} (wt%) diagram, most of the Imgye gabbroic diorite and Jungbongsan granite samples show the medium-K calc-alkaline series and high-K calc-alkaline series characters, respectively (Figure 3b). The Imgye gabbroic diorites are tholeiitic, whereas the Jungbongsan granites are calc-alkaline (Figure 3c). The Jungbongsan granite consists of quartz (40%), K-feldspar (45%), and plagioclase (55%). It is classified as typical monzogranite among the granite series based on the CIPW normative mineral composition (Figure 3d). The Imgye gabbroic diorite plots in the calc-alkaline basalt and volcanic arc basalt fields in the Y/15-La/10-Nb/8 and Ti vs. Zr diagrams, respectively (Figure 3a, c). In the Ti/100-Zr-Y*3 and Th\textsubscript{N} vs. Nb\textsubscript{y} diagrams, the Imgye gabbroic diorite falls in the calc-alkaline basalt field (Figure 3c, d). The Jungbongsan granite sample plots in the volcanic arc granite + syn-collision granite field in the Nb vs. Y diagram (Figure 4e), and plot between the syn-collision granite and volcanic arc granite fields in the Rb vs. Y + Nb diagram (Figure 4f).
Figure 4. Tectonic discrimination diagrams for the Imgye gabbroic diorite and Jungbongsan granite in the Imgye area and the Paleoproterozoic mafic and felsic igneous rocks in the Gyeonggi and Yeongnam massifs: (a) Y/15-La/10-Nb/8 ternary diagram after [66]; (b) Ti vs. Zr diagram after [67]; (c) Ti/100-Zr-Y*3 diagram after [68]; (d) ThN vs. NbN diagram after [69]; (e) Nb vs. Y diagram after [70]; (f) Rb vs. Yb + Ta diagram after [70]. The symbols are the same as those in Figure 3. Abbreviations: VAB, volcanic arc basalt; MORB, mid-ocean ridge basalt; WPB, within-plate basalt; IAT, island arc tholeiite; CAB, calc-alkaline basalt; MTB, medium-Ti basalt; SSZ D-MORB, supra-subduction zone depleted mid-ocean ridge basalt; G-MORB, garnet-influenced mid-ocean ridge basalt; E-MORB, enriched mid-ocean ridge basalt; P-MORB, plume mid-ocean ridge basalt; AB, alkaline basalt; OIB, ocean island basalt; VAG, volcanic arc granite; ORG, ocean ridge granite; Syn-COLG, syn-collisional granite; WPG, within-plate granite; Post-COLG, post-collisional granite.
The chondrite-normalized rare-earth element (REE) patterns of the Imgye gabbroic diorite show relative enrichment in light REEs (LREEs) compared to heavy REEs (HREEs), with (La/Yb)\textsubscript{N} = 7.91–8.90 and Eu/Eu* = 0.82–0.94 (Figure 5a; Table S1). The Jungbongsan granite samples show more enrichment in LREEs than HREEs, with (La/Yb)\textsubscript{N} values of 42.90–54.80 and strong negative Eu anomalies (Eu/Eu* = 0.216–0.234; Figure 5c; Table S2). In the primitive-mantle-normalized spider diagram, the Imgye gabbroic diorite shows positive Rb and Pb anomalies and negative Ta, Nb, and P anomalies (Figure 5b). In comparison, the Jungbongsan granite has relatively strong positive Rb, Th, K, and Pb anomalies with strong negative Ba, Ta, Nb, Sr, P, Eu, and Ti anomalies (Figure 5d). The Nb–Ta negative anomalies in both units support their formation in an arc tectonic setting.

4.2. Mineral Chemistry

In the case of Imgye gabbroic diorite, the colors of the core and rim of the amphiboles were observed to be different under the microscope. Thus, we carried out a mineral analysis to confirm the change in the amphibole composition. In the Imgye gabbroic diorite, the chemical composition of the amphibole changes from core to rim (Table S3). The amphibole cores have X\textsubscript{Fe} = 0.239–0.354, X\textsubscript{Mg} = 0.646–0.761, and T\textsubscript{Si} = 7.384–7.737, while the amphibole rims have X\textsubscript{Fe} = 0.344–0.571, X\textsubscript{Mg} = 0.429–0.656, and T\textsubscript{Si} = 6.174–7.125. The Mg/(Mg + Fe\textsuperscript{2+}) ratio decreases, and the T\textsubscript{Si} component decreases toward the rim. The amphibole cores have the actinolite to actino hornblende compositions, while the amphibole rims have magnesio hornblende to hornblende tschermakite compositions in the Mg/(Mg + Fe\textsuperscript{2+}) vs. T\textsubscript{Si} diagram (Figure 6a). The plagioclases are mostly albite (Table S4). Although the X\textsubscript{Ab} component in plagioclase slightly increases toward the rim, there are no significant
compositional differences between the core and rim. Most plagioclases show oligoclase to andesine components in the Or-Ab-An diagram (Figure 6b). Biotite has $X_{Fe} = 0.511–0.995$ and $A_{IV} = 2.713–3.841$ (Table S5). They are plotted between phlogopite and siderophyllite in the $X_{Fe}$ vs. $A_{IV}$ diagram.

![Figure 6. Mineral chemistry plots of (a) amphibole [72] and (b) plagioclase in the Imgye gabbroic diorite [73]. Abbreviations: Tr, tremolite; Hbl, hornblende; Tsch, tschermakite; Ab, albite; An, anorthite; Or, orthoclase.](image)

### 4.3. Zircon U–Pb Isotope Analysis

#### 4.3.1. Imgye Gabbroic Diorite

The zircon grains in the Imgye gabbroic diorite (IG-9) are fine- to medium-grained (20–100 µm) with an irregular shape and sector or irregular zonings (Figure 7a). The zircons have Th and U concentrations of 16–571 and 71–630 ppm, respectively, and Th/U ratios of 0.23–1.56, representing an igneous origin. As a result of checking whether the zircon was affected by hydrothermal using the $(Sm/La)_N$ vs. La and Ce/Ce* vs. $(Sm/La)_N$ diagrams suggested by [74], all thirty points except two points were confirmed as magmatic zircons (La: 0.002–0.093 ppm; $(Sm/La)_N$: 34.92–1817.32) unaffected by hydrothermal. The results of the U–Pb isotope analyses of thirty-two grains are plotted on a Tera–Wasserburg diagram (Figure 7b; Table S6) and give $207^{\text{Pb}}/206^{\text{Pb}}$ dates ranging between 2021 ± 14 Ma and 1854 ± 33 Ma. The upper intercept age is 1948 ± 21 Ma ($n = 28$ of 32, MSWD = 1.4).

#### 4.3.2. Jungbongsan Granite

Zircons from the Jungbongsan granite (IG-15) are medium- to coarse-grained (50–250 µm) with angular or elongated shapes and show oscillatory zoning, representing an igneous origin (Figure 7c). The zircons have Th and U concentrations of 48–123 and 71–630 ppm, respectively, and Th/U ratios of 0.46–0.78, supporting an igneous origin. The zircons have Th and U concentrations of 16–571 and 71–630 ppm, respectively, and Th/U ratios of 0.23–1.56, representing an igneous origin. As a result of checking whether the zircon was affected by hydrothermal using the $(Sm/La)_N$ vs. La and Ce/Ce* vs. $(Sm/La)_N$ diagrams suggested by [74], all thirty points except two points were confirmed as magmatic zircons. The results of the U–Pb isotope analyses of thirty-two grains are plotted on a Tera–Wasserburg diagram (Figure 7b; Table S6) and give $207^{\text{Pb}}/206^{\text{Pb}}$ dates ranging between 2021 ± 14 Ma and 1854 ± 33 Ma. The upper intercept age is 1948 ± 21 Ma ($n = 28$ of 32, MSWD = 1.4).

#### 4.3.3. Jangsan Quartzite

Zircons from the Jangsan quartzite (TB-7) are medium- to coarse-grained (80–200 µm) with rounded or elongated shapes and show various zonings, such as oscillatory zoning, sector zoning, and unzoning (Figure 7e). The zircons have Th and U concentrations of 11–334 and 21–315 ppm, respectively, and Th/U ratios of 0.36–1.75. The results of the U–Pb isotope analyses of sixty grains are plotted on a Tera–Wasserburg diagram (Figure 7f; Table S8). The date analyses obtained from the detrital zircons in the Jangsan quartzite gave $207^{\text{Pb}}/206^{\text{Pb}}$ dates ranging between 3064 ± 13 Ma and 1856 ± 10 Ma ($n = 50$ of 60, discordance < 10%), with a strong peak at around 2.5 Ga.
Figure 7. SEM CL images and Concordia plot of U–Pb isotopic analyses of zircons from the (a,b) Imgye gabbroic diorite, (c,d) Jungbongsan granite, and (e,f) Jangsan quartzite in the Imgye area. (a,c,e) Solid circles and dotted circles indicate the locations of U–Pb and Lu–Hf analyses, respectively, and the numbers represent the analyzed spot numbers and $^{207}\text{Pb}/^{206}\text{Pb}$ ages of zircons. (b,d) Filled solid ellipses represent data used for obtaining intercept age. (f) Filled solid and dashed ellipses represent concordant age (concordance > 90%) and discordant age (discordance > 10%).
4.4. Zircon Lu–Hf Isotope Analysis

The $^{176}\text{Lu}/^{177}\text{Hf}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the dated zircons from the Imgye gabbroic diorite (IG-9) are 0.000317–0.001628 and 0.281661–0.281853, respectively (Table S9). The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios are almost constant at 0.281646–0.281820 (Figure 8a). The Imgye gabbroic diorite zircons give positive $\varepsilon_{\text{Hf}}(t)$ values of 3.5–9.7 and two-stage model ages ($T_{\text{DM2}}$) of 2803–1982 Ma (Figure 8b,c). Zircons from the Jungbongsan granite (IG-15) have $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of 0.00042–0.00100 and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.281486–0.281584 (Table S10). The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios are 0.281465–0.281563 (Figure 8a). This sample shows mostly negative $\varepsilon_{\text{Hf}}(t)$ values from −2.9 to 0.6 with $T_{\text{DM2}}$ model ages of 3851–3389 Ma (Figure 8b,d).

5. Discussion

5.1. Paleoproterozoic Igneous Event in the Imgye Area

The following results are from the study on the Imgye gabbroic diorite and Jungbongsan granite in the Taebaeksan basin. The Imgye gabbroic diorite plots in the calc-alkaline basalt and volcanic arc basalt fields in the tectonic discrimination diagrams (Figure 4a–d). In addition, the Imgye gabbroic diorite shows slightly enriched LREEs compared to HREEs, with negative Ta and Nb anomalies (Figure 5a,b), suggesting their subduction-related environment. These trace elements’ characteristics indicate that the Imgye gabbroic diorite formed in the subduction-related arc tectonic environment. The Imgye gabbroic diorite does not show a geochemical change by metamorphism or alteration. In the Imgye gabbroic diorite, the amphibole core has a brighter color than the
amphibole rim under a microscope (Figure 2b). From core to rim, the $X_{Fe}$ of amphibole increases from 0.239–0.354 to 0.344–0.571, and the $X_{Mg}$ and $T_{Si}$ components decrease from 0.646–0.761 to 0.429–0.656 and from 7.384–7.737 to 6.174–7.125, respectively (Figure 6a). These compositional changes may indicate fractional crystallization. The intrusion age obtained for the Imgye gabbroic diorite is ca. 1948 Ma (Figure 7b). The positive $e_{Hf}(t)$ values of 3.5–9.7 for zircon in the Imgye gabbroic diorite imply a depleted mantle source (Figure 8b). The $T_{DM2}$ ages (2803–1982 Ma) of the Imgye gabbroic diorite are similar to the intrusion age (Figure 8c). These geochemical characteristics suggest that the Imgye gabbroic diorite was derived from a juvenile source at 1948 Ma. In the Zr/Yb vs. Nb/Yb diagram, the Imgye gabbroic diorites plot in the enriched part of the mantle array, but they plot above the mantle array in the Th/Yb vs. Nb/Yb diagram, indicating that their source was a mantle that underwent metasomatism by fluid supplied from the subducted oceanic crust and sediments within an arc setting (Figure 9a,b). In the Sm/Yb vs. La/Yb diagram, they plot in the melting curve of spinel lherzolite with a starting composition of primitive mantle, suggesting that the Imgye gabbroic diorite formed at a relatively shallow depth (<60 km) (Figure 9c) [75]. In addition, the partial-melting modeling reveals that the primary magma source of the Imgye gabbroic diorite was generated by a low degree of partial melting (less than 5%) of the spinel-bearing mantle source.

Figure 9. The Imgye gabbroic diorite and other Paleoproterozoic mafic rocks in the northern Yeongnam massif plotted in the (a) Zr/Yb vs. Nb/Yb [55] and (b) Th/Yb vs. Nb/Yb diagrams [76], and in the (c) Sm/Yb vs. La/Yb diagram [77], in which melt curves were calculated using the modal batch melting equations [78]. Curves for garnet–lherzolite (with mode OI0.60 + Cpx0.20 + Cpx0.10 + Grt0.10), spinel–lherzolite (with mode OI0.53 + Cpx0.27 + Cpx0.17 + SpI0.03), and garnet–spinel lherzolite (with mode OI0.55 + Opx0.22 + Cpx0.15 + Grt0.06 + SpI0.02) are after [79].

The Jungbongsan granites plot in the syn-collision granite and volcanic arc granite fields in the tectonic discrimination diagrams (Figure 4e,f). The Jungbongsan granite has more enriched LREEs compared to HREEs (Figure 5c). The Jungbongsan granites show a negative Eu anomaly (Eu/Eu* = 0.216–0.234) and negative Ba, Sr, P, Eu, and Ti troughs (Figure 5c,d), suggesting that the magma from which the Jungbongsan granite formed underwent the fractional crystallization of K-feldspar and P-Ti-bearing oxide minerals. The fractional crystallization of K-feldspar increased in Rb and decreased Sr and Ba (Figure 10). The increase in Rb due to a fractional crystallization can make it difficult to determine the tectonic setting. In the Yeongnam massif, which can be correlated to the Imgye area, as discussed in Section 5.2, the Rb contents in the Paleoproterozoic granitoid rocks increase from typical granite to leucogranite to pegmatite due to the fractional crystallization [62–65]. Typical granite, such as the 1.98 Ga Pyeonghae and 1.97 Ga Buncheon granite, plot in the volcanic arc tectonic setting, whereas the leucogranite plots both in the volcanic arc and syn-collisional fields in the Rb vs. Y + Nb tectonic discrimination diagram (Figure 4e,f). The pegmatite underwent a strong fractional crystallization compared to the leucogranite plot in the syn-collision field (Figure 4e,f). Considering the effect of fractional crystallization with the fact that ca. 1.87 Ga mafic igneous rocks in the northern margin of the Yeongnam massif...
formed in an arc tectonic setting [21], the leucogranite and pegmatite, which intruded at ca. 1.87 Ga in the northern margin of the Yeongnam massif, can be considered to have formed in an arc tectonic setting instead of syn-collisional tectonic setting. Therefore, it is reasonable to assume the Jungbongsan granite shows geochemical characteristics similar to leucogranite formed in the arc tectonic setting, although they plot in both the volcanic arc and syn-collisional fields. The Jungbongsan granites show mostly negative zircon \( t_{DM} \) values from −2.9 to 0.6, suggesting an origin from the pre-existing crustal material (Figure 8b). Their \( T_{DM2} \) ages (3851–3389 Ma) indicate input from the Archean crust (Figure 8d). After the intrusion of the Imgye gabbroic diorite, the Jungbongsan granite formed from pre-existing crust material in the arc tectonic setting at 1873 Ma.

Figure 10. Plot of the Jungbongsan granite and Paleoproterozoic felsic igneous rocks in the northern Yeongnam massif in the (a) Ba vs. Sr and (b) Ba vs. Rb diagrams, showing a feldspar-dominated fractional crystallization trend. The same abbreviations in Figure 2 are used.

5.2. Comparison between Paleoproterozoic Igneous Activities in the Study Area with Those in Other Paleoproterozoic Basements in the Korean Peninsula and China Craton

The Yeongnam massif, one of the Precambrian basements in the Korean Peninsula (Figure 1b), had been long considered to be correlative with the Nangnim and Gyeonggi massifs until Yin and Nie proposed a tectonic model [2] in which the Yeongnam and Nangnim massifs are correlated with the North China Craton and the Gyeonggi massif with the South China Craton. Furthermore, recent studies have reported that the southern Gyeonggi massif and Yeongnam massif underwent a different Paleoproterozoic tectonic evolution compared to that of the Nangnim massif, suggesting the possibility that they belonged to different cratons [20–24]. The Nangnim massif and the northern Gyeonggi massif experienced a collision-related event at ca. 1.93–1.90 Ga due to a collision between the Longgang block in the northeastern North China Craton and the Nangnim massif in the South China Craton [12,16]. After that, magmatism and metamorphism occurred in a post-collisional environment at ca. 1.89–1.83 Ga in the Jiao–Liao–Ji collision belt, Nangnim massif, and northern Gyeonggi massif (Figures 4 and 11a) [11,43]. The post-collisional event occurred due to the heat supplied by the asthenospheric mantle, which uplifted through the opening formed by the slab break-off between continental and oceanic slabs during the post-collisional stage (Figure 11d). In contrast, the southern Gyeonggi massif underwent subduction-related igneous and metamorphic activities at ca. 1.94–1.92 Ga, followed by post-collisional magmatism and metamorphism at ca. 1.84–1.78 Ga (Figure 11b; Table 1) [12,16,17]. Based on these events, it has been suggested that the southern Gyeonggi massif is correlated to the Yangtze block in the South China Craton [12,16]. In contrast, there were continuous subduction-related igneous and metamorphic activities along the northern margin of the Yeongnam massif at ca. 2.02–1.96 Ga and 1.90–1.85 Ga (Figures 4 and 11c,e; Table 1).
hypothesis was proposed that the Yeongnam massif could be correlated with the Cathaysia block in the South China Craton, although it remains to be confirmed further [12].

Figure 11. Histograms of reported age from Paleoproterozoic igneous and metamorphic rocks in the (a) northern Gyeonggi massif, (b) southern Gyeonggi massif, and (c) Yeongnam massif. The data for the northern Gyeonggi, southern Gyeonggi, and Yeongnam massifs are in Table S11. (d) Simplified model of the tectonic evolution of the northern and southern Gyeonggi massifs at 1.89–1.83 Ga. (e) Simplified model of the tectonic evolution of the northern Yeongnam massif at 1.90–1.85 Ga (modified from [14]). The same abbreviations in Figure 1 are used.
Table 1. The summary of the tectonic evolution of the Paleoproterozoic massifs in the Korean Peninsula and northeastern North China Craton (modified after [43]).

<table>
<thead>
<tr>
<th>Time (Ga)</th>
<th>Event</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2–2.1</td>
<td>Magmatism</td>
<td>Taebaeksan Basin (Imgye)</td>
</tr>
<tr>
<td></td>
<td>Metamorphism</td>
<td>-</td>
</tr>
<tr>
<td>2.1–2.0</td>
<td>Magmatism</td>
<td>Northern Yeongnam Massif</td>
</tr>
<tr>
<td></td>
<td>Metamorphism</td>
<td>-</td>
</tr>
<tr>
<td>1.99–1.96</td>
<td>Magmatism</td>
<td>Southern Gyeonggi Massif</td>
</tr>
<tr>
<td></td>
<td>Metamorphism</td>
<td>-</td>
</tr>
<tr>
<td>1.95–1.90</td>
<td>Magmatism</td>
<td>Northern Gyeonggi Massif</td>
</tr>
<tr>
<td></td>
<td>Metamorphism</td>
<td>-</td>
</tr>
<tr>
<td>1.89–1.85</td>
<td>Magmatism</td>
<td>Nangnim Massif</td>
</tr>
<tr>
<td></td>
<td>Metamorphism</td>
<td>-</td>
</tr>
<tr>
<td>1.84–1.80</td>
<td>Magmatism</td>
<td>Jiao–Liao–Ji Belt in North China Craton</td>
</tr>
</tbody>
</table>

The relevant references are mentioned in [80–82].

As discussed in Section 5.1, the Imgye gabbroic diorite was derived from a depleted mantle source within an arc tectonic setting at 1948 Ma, and the Jungbongsan granite formed from pre-existing crust material in an arc tectonic setting at 1873 Ma. These data suggest that the Precambrian basement of the Taebaeksan basin underwent magmatism in the arc tectonic setting at ca. 1948 Ma and 1873 Ma (Figure 11c). This tectonic evolution of the Precambrian basement of the Taebaeksan basin is different from that of the Nangnim and northern Gyeonggi massifs, in which the collision-related activities occurred at ca. 1.93–1.90 Ga and the post-collisional-related activities occurred at ca. 1.89–1.83 Ga. It is also different from that of the southern Gyeonggi massif in which post-collisional igneous activities occurred at ca. 1.84–1.78 Ga, whereas the tectonic evolution of the Precambrian basement of the Taebaeksan basin can be well correlated to the tectonic evolution of the northern Yeongnam massif, which underwent arc-related igneous activities at ca. 2.02–1.96 Ga and 1.90–1.85 Ga (Figure 11).

The Jangsan quartzite in the Imgye area dated herein contains detrital zircons ranging in age mainly between ca. 3.06 Ga and ca. 1.86 Ga, with a peak age of 2.5 Ga (Figure 7f). This pattern is well matched with that in the quartzite deposited unconformably on the Paleoproterozoic basement in the northeastern Yeongnam massif [36]. The depositional age of the Jangsan quartzite is still uncertain and has been suspected to be Neoproterozoic or Paleozoic in age [34,83]. In the northern Gyeonggi and Nangnim massifs, the Paleoproterozoic basements are uncomfortably overlain by Meso- and Neoproterozoic sediments deposited in a rift tectonic setting with an intrusion of within-plate type mafic and felsic igneous rocks [21]. The Meso- and Neoproterozoic sedimentary rocks mainly consist of biotite schist, marble, and quartzite. The detrital zircons in them contain not only Paleoproterozoic detrital zircons but also Meso- and Neoproterozoic detrital zircons [84–88]. In the southern Gyeonggi massif, Meso- and Neoproterozoic detrital zircons were also found in the Meso- and Neoproterozoic metasedimentary rocks, which overlie the Paleoproterozoic basement [89]. Therefore, the quartzite without Meso- and Neoproterozoic detrital zircons is another piece of evidence that supports the correlation between the Paleoproterozoic basement of the Imgye area and the northeastern Yeongnam massif. As discussed above, the Yeongnam massif underwent a different Paleoproterozoic tectonic evolution compared to the North China Craton, suggesting that the basement of the Tae-
baeksan basin cannot be correlated to the North China Craton. This suggestion is well matched with Oh and Kusky’s tectonic model [6] in which the Taebaeksan basin was correlated to the South China Craton but contradicted a paleontological interpretation in which trilobite fossil in the Taebaeksan basin was correlated with that in the North China Craton [90,91]. More studies will be needed to solve the contradiction between the Petrological and Paleontological interpretations.

5.3. Paleoproterozoic Tectonic Evolution of the Northern Yeongnam Massif and the Imgye Area

In the northeastern Yeongnam massif, three types of (meta)granitoid rocks and Ok-bang amphibolite occur. The three types of (meta)granitoids are banded or augen biotite gneisses (group I: Pyeonghae and Buncheon metagranitoids), massive cordierite or two-mica granitic gneisses (group II: Hongjesa and Icheonri granitic metagranitoids), and garnet-bearing leucogranite (group III: Imwon leucogranite and S-type leucogranite) [18,61,63,92,93]. The intrusion ages of the first two groups are indistinguishable within their error ranges: 1.98 Ga (Pyeonghae gneiss), 1.97 Ga (Buncheon gneiss), 1.99 Ma (Icheonri granitic gneiss), and 1.98 Ga (Hongjesa granitic gneiss). The Imwon and S-type leucogranites intruded at 1.90–1.85 Ga. The Okbang amphibolite intruded 1.87 Ga and metamorphosed at 1.86 Ga [61]. The group I and II granitoids were interpreted to have formed in a continental arc tectonic setting at 1.99–1.97 Ga (Figure 4) [18,63,92,93]. The leucogranite also formed in an arc tectonic setting, as discussed in Section 5.1 (Figure 4e,f), and the Okbang amphibolites plot in the back-arc basin field in the Y/15-La/10-Nb/8 diagram and the island arc tholeiite field in the ThN vs. NbN diagram (Figure 4a,d). These data suggest that the 1.90–1.85 Ga leucogranites and Okbang amphibolites intruded in the island arc tectonic setting with the back-arc basin. Similar to the northeastern Yeongnam massif, in the northcentral and northern Yeongnam massif, 2.02–1.96 Ga granitoids intruded in a continental arc tectonic setting, and then 1.87 Ga mafic igneous rocks intruded in an island arc tectonic setting (Figure 4) [20–22].

This study reveals that the 1.95 Ga Imgye gabbroic diorite and 1.87 Ga Jangbongsan granite formed in an arc tectonic setting. This study, together with the data in previous studies, suggests igneous activities in an arc tectonic setting at ca. 2.02–1.95 Ga and igneous activities in an island arc tectonic setting at 1.90–1.85 Ga in the northern Yeongnam massif. The Okbang amphibolite was metamorphosed at 1.86 Ga, and the paragneiss in the northeastern Yeongnam massif also underwent low-P/T type metamorphism at 1.87–1.86 Ga [61,92,93]. During this low-P/T type metamorphism, the northeastern Yeongnam massif underwent metamorphism from the greenschist facies to granulite facies. As a peak metamorphic condition, Kim and Cho [93] reported 750–800 °C/4–6 kbar, and Cheong and Na [92] reported 740–800 °C/4.8–5.8 kbar. In the northcentral Yeongnam massif, the 1.87–1.86 Ga metamorphism (720–730 °C and 7.3–7.4 kbar) was also reported [21]. The arc tectonic setting in the northern Yeongnam massif can also be supported by the low-P/T metamorphism at ca. 1.87–1.86 Ga because low-P/T type metamorphism has been reported from the arc environment [61].

The data in this and previous studies suggest that there was a continental arc during 2.02–1.95 Ga along the northern margin of the Yeongnam massif, and a continental arc may have transformed into an island arc at ca. 1.90–1.85 Ga with low-P/T metamorphism. In the previous studies on the Mesozoic arc-related igneous activities along the eastern margin of Northeastern Asia, ca. 0.5 Ga magmatic gap was reported during continuous subduction [94–97]. No igneous activities other than arc-related igneous activities occurred from 1.95 Ga to 1.90 Ga in the northern margin of the Yeongnam massif. Therefore, although there is ca. 0.5 Ga gap between the two arc-related igneous activities, these data suggest continuous subduction along the northern margin of the Yeongnam massif during 2.02–1.85 Ga.
6. Conclusions

1. In the Imgye area, the Imgye gabbroic diorite intruded ca. 1948 Ma and the Jungbongsan granite intruded ca. 1873 Ma in an arc tectonic setting.

2. The zircons in the Imgye gabbroic diorite have positive $\varepsilon_{\text{Hf}}(t)$ values from 3.5 to 9.7, whereas the zircons in the Jungbongsan granite show mostly negative $\varepsilon_{\text{Hf}}(t)$ values from $-2.9$ to $0.6$. These data indicate that the Imgye gabbroic diorite was derived from a depleted mantle, and the Jungbongsan granite was derived from pre-existing Archean crust in an arc tectonic environment.

3. The Jangsan quartzite in the Imgye area has the youngest detrital zircon of ca. 1856 Ma, with a peak concentration of ca. 2.5 Ga. These characteristics correlate well with the quartzite in the northeastern Yeongnam massif.

4. The tectonic evolution of the Paleoproterozoic igneous rocks in the Imgye area differs from those of the Gyeonggi and Nangnim massifs but can be correlated well with that of the northern Yeongnam massif. Therefore, the Taebaeksan basin can be correlated to the northern Yeongnam massif.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min13060752/s1, Table S1: Whole-rock compositions of the Imgye gabbroic diorite in the Imgye area. Table S2: Whole-rock compositions of the Jungbongsan granite in the Imgye area. Table S3: Representative compositions of amphibole from the Imgye gabbroic diorite in the Imgye area. Table S4: Representative compositions of plagioclase from the Imgye gabbroic diorite in the Imgye area. Table S5: Representative compositions of biotite from the Imgye gabbroic diorite in the Imgye area. Table S6: LA-ICP-MS zircon age data of the Imgye gabbroic diorite in the Imgye area. Table S7: SHRIMP zircon age data of the Jungbongsan granite in the Imgye area. Table S8: SHRIMP zircon age data of the Jangsan quartzite in the Imgye area. Table S9: The results of zircon Lu–Hf analysis of the Imgye gabbroic diorite in the Imgye area. Table S10: The results of zircon Lu–Hf analysis of the Jungbongsan granite in the Imgye area. Table S11: Summary of Paleoproterozoic U–Pb age data reported from Gyeonggi massif [8,11,12,16,43,98–113] and Yeongnam massifs [18–22,62–64,80,114–123].

Author Contributions: Formal analysis, writing—original draft, review, and editing, B.Y.L.; supervision and investigation, D.-L.C.; supervision, review, and editing, C.W.O.; conceptualization, review and editing, B.C.L.; review and editing, S.H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by grants (GP2020-003) and (GP2021-004) from the Basic Research Project of the Institute of Geoscience and Mineral Resources (KIGAM) funded by the Korean Ministry of Science and ICT, and grants (NRF-2017K1A1A2013180) and (RS-2023-00210128) from the National Research Foundation of Korea (NRF) funded by the Korean Government.

Data Availability Statement: All data analyzed during this study are included in this published article (Table 1, Supplementary Table S11).

Acknowledgments: We sincerely thank three anonymous reviewers for their constructive comments and suggestions that helped to improve the manuscript. We would like to thank Keewook Yi and Shinae Lee from the KBSI Ochang Center in the Republic of Korea and Hongfang Chen from the Sample Solution Company in China for helping with the zircon age dating. We also appreciate Yongheon Kim, Minsu Kang, Jinhyeok Choi, and Soyeon Kim from the Jeonbuk National University for their help with the geological field survey.

Conflicts of Interest: The authors declare no conflict of interest.

References

2. Yin, A.; Nie, S. An indentation model for the north and South China collision and the development of the Tan-Lu and Honam fault systems, eastern Asia. Tectonics 1993, 12, 801–813. [CrossRef]
3. Zhang, K.J. North and South China collision along the eastern and southern North China margins. Tectonophysics 1997, 270, 145–156. [CrossRef]

5. Oh, C.W. A new concept on tectonic correlation between Korea, China and Japan: Histories from the late Proterozoic to cretaceous. *Gondwana Res.* 2006, 9, 47–61. [CrossRef]

6. Oh, C.W.; Kusky, T. The Late Permian to Triassic Hongseong-Odesan Collision Belt in South Korea, and Its Tectonic Correlation with China and Japan. *Int. Geol. Rev.* 2007, 49, 636–637. [CrossRef]


12. Lee, B.C.; Oh, C.W.; Kim, T.S.; Yi, K. The metamorphic evolution from ultrahigh-temperature to amphibolite facies metamorphism in the Odae area after the collision between the North and South China Cratons in the Korean Peninsula. *Lithos* 2016, 256, 109–131. [CrossRef]


15. Kim, S.W.; Williams, I.S.; Kwon, S.H.; Oh, C.W. SHRIMP zircon geochronology, and geochemical characteristics of metaplutonic rocks from the southwestern Gyeonggi Block, Korea: Implications for Paleoproterozoic to Mesozoic tectonic links between the Korean Peninsula and eastern China. *Precambrian Res.* 2008, 162, 475–497. [CrossRef]


24. Kim, S.W.; Oh, C.W.; Ryu, I.-C.; Williams, I.S.; Sajeev, K.; Santosh, M.; Rajesh, V.J. Neoproterozoic Bimodal Volcanism in the Okcheon Belt, South Korea, and its comparison with the Nanhuah Rift, South China: Implications for rifting in Rodinia. *J. Geol. 2006, 114, 717–733. [CrossRef]


55. Streckeisen, A. To each plutonic rock its proper name. *Earth-Sci. Rev.* 1976, 12, 1–33. [CrossRef]


119. Lee, Y.; Cho, M.; Kim, T.; Kim, H. Incipient charnockite formation at the waning stage of Paleoproterozoic hot orogenesis, Yeongnam Massif, Korea. Precambrian Res. 2021, 365, 106388. [CrossRef]


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.