ABSTRACT

Phanerozoic internal and peripheral orogens in Northeast Asia converge toward the Korean Peninsula situated between cratonic Asia and the outboard magmatic arc. Widespread Mesozoic plutons in the peninsula provide first-hand information about the magmatic response to the continental and oceanic plate subduction. The present study addresses this issue using comprehensive (n >1100) whole-rock geochemical, zircon U-Pb geochronological, and O-Hf isotopic data obtained from Triassic gabbro-pyroxenite-mangerite-monzonite-syenite-granodiorite-granite plutons in the central and southern parts of the peninsula. The intrusion of ca. 265–250 Ma calc-alkaline granitoids, including the high-silica adakite, along the outboard (in present coordinates) Yeongnam Massif are coeval with or slightly younger than the Barrovian metamorphism recognized in fold-and-thrust belts surrounding the inboard (northward, present coordinates) Gyeonggi Massif, suggesting a close link between the collisional orogenesis and subduction initiation as commonly documented in Phanerozoic supercontinents. Subsequent Late Triassic plutons emplaced in the Yeongnam Massif are subdivided into the older (232–224 Ma) magnesian and alkali-calcic to calc-alkaline group and the younger (220–217 Ma) ferroan and alkali-calcic to calc-alkaline group temporally intervened by the geochronologically arc-like Andong ultramafic complex (222 Ma). Zircon O-Hf isotopic compositions of the older plutons reflect the mixing of metasomatized lithospheric mantle, young (probably Paleozoic) arc crust, and Precambrian basement crust, whereas those of the younger plutons reflect input of the asthenospheric/lithospheric mantle and mafic lower crust. Meanwhile, the Late Triassic (233–224 Ma) potassic plutons in and around the Gyeonggi Massif represent post-collisional magmatism most likely induced by slab breakoff, which may also have been responsible for the shoshonitic magmatism in the Yeongnam Massif. Spatial differences in the age pattern and O-Hf isotopic signature of inherited and synmagmatic zircons from the potassic plutons indicate a selective contribution from an ancient metasomatized lithospheric mantle beneath the North China-like craton and an allochthonous South China-like lithosphere. The formation of the Triassic plutons could be explained by a series of tectonomagmatic events consisting sequentially of the ridge subduction, low-angle subduction, slab breakoff beneath the collisional orogen, tectonic switch to an extension-dominated arc system, and delamination of an overthickened arc mantle.

INTRODUCTION

Orogenic belts have formed in response to interior collisional and peripheral accretionary plate convergence since the onset of plate tectonics on Earth. These two end-member types of subduction, with a broad continuum between them, have left their own characteristic geological and geochemical features among the orogens and associated igneous rocks (Bally, 1981; Ernst, 2005, 2010; Cawood et al., 2009; Collins et al., 2011). Because orogenesis basically reflects the resistance of a buoyant lithosphere to plate underflow, the driving mechanism is more obvious in the case of continental subduction. Continental collisional [also referred to as “Alpine” or Bally’s (1981) “type-A”] orogens, represented by wrinkled mountain belts in the internal part of the assembled (super)continent, mark the termination of a Wilson cycle of ocean opening and closing. The collisional boundaries are characterized by distinct geologic features, such as oceanward verging thrust sheets neighboring by elongated foreland basins, regional Barrovian metamorphism linked to crustal thickening, and exhumation of (ultra)high-pressure rocks containing diamond or coesite (e.g., Ernst et al., 1997; Rumble et al., 2003; Song et al., 2014). On the other hand, accretionary [also termed as “Pacific” or Bally’s (1981) “type-B”] plate convergence at sites of oceanic subduction has produced subparallel belts consisting of an outboard trench complex, a medial forearc basin, and an inboard arc, each of which has undergone contrasting pressure-temperature conditions (Miyashiro, 1961). The negative buoyancy of the sufficiently aged and cooled oceanic lithosphere provides most of the force required for its sinking and rollback in subduction zones and consequent mantle convection (Stern, 2004, and references therein). This “Western Pacific” type [or “Mariana” (Uyeda and Kanamori, 1979) type] of subduction leads to the development of a retreating arc system, where upper plate extension promotes the formation of arc-flanking basins. Conversely, the advancing or “Andean” [or “Chilean” (Uyeda and Kanamori, 1979) type] arc system induced by the subduction of buoyant oceanic lithosphere, terrane accretion, or plate reorganization.
The Paleozoic–Mesozoic history of the northwestern edge of the circum-Pacific is characterized by the interplay of continental and oceanic plate convergence (Engebretson et al., 1985; Ernst et al., 2007). Phanerozoic internal and peripheral orogens in Northeast Asia converge toward the Korean Peninsula, situated in a tectonic link between cratonic Asia and an outboard magmatic arc. Widespread Mesozoic plutons exposed in the peninsula provide firsthand information about the individual or superimposed roles of collisional and accretory orogenies in making the magma. The present study addresses this issue using new and published whole-rock geochemical, in situ zircon U-Pb geochronological, and O-Hf isotopic data obtained from gabbro-pyroxenite-mangerite-monzonite-syenite-granodiorite-granite plutons in the central and southern parts of the peninsula that intruded approximately coevally during the Triassic, a period marking the culmination of the collisional and accretory orogenies. This comprehensive data set (n >1100) bears important implications for deciphering key issues concerning the magmatic response to the continental and oceanic plate subduction, such as the driving mechanism of collision- and arc-related magmatism, the geodynamic evolution of the arc system, and the specific contributions of mantle and crustal reservoirs to the generated magmas.

GEOLOGICAL BACKGROUND

The Pacific (and the former Panthalassic) Ocean, created at the breakup of Rodinia, has never been closed during its life (Dalziel, 1991; Hoffman, 1991). Prolonged subduction of the (paleo-)Pacific plate, initiated in the latest Neoproterozoic and still ongoing, has left quasi-continuous accretionary orogens along the margin of the circum-Pacific. Opposed accretionary orogens existing on either side of the Pacific Ocean differ substantially in the kinematic framework of the overriding plate, as exemplified in the classic classification scheme of oceanic subduction zones (Uyeda and Kanamori, 1979; Uyeda, 1982). The present-day western Pacific margin has undergone several episodes of tectonic switch between retreating and advancing arc systems since the late Paleozoic (Li et al., 2012).

Eurasia is a tectonic collage of Gondwanan landmasses that have been transported northward since the middle Paleozoic (Sengör et al., 1988; Li and Powell, 2001; Collins, 2003). The successive collisional orogens developed between continental blocks in the interior of Eurasia tend to be progressively younger southward from the Paleozoic Caledonides in Europe to the Cenozoic Himalayan orogen between India and Asia. The Qinling-Dabie-Sulu orogen in central-eastern China is in the middle of such a spatiotemporal sequence. Triassic (ca. 240–220 Ma) high-pressure and ultrahigh-pressure mineral parageneses have been reported from the leading edge of the Yangtze Block in South China (Hacker et al., 2000, 2004). Before the Triassic continental collision, the Qinling-Tongbai-Hong’an areas to the west of the Dabie-Sulu Mountains had experienced a series of oceanic subduction and arc-continent collision from the latest Cambrian to the Carboniferous (Wu and Zheng, 2013, and references therein). The tectonic evolution of the sinistral linear orogen extending eastward from the Qinling-Dabie-Sulu belt is complicated by severe tectonic and magmatic overprinting and transverse fault activities (Ernst et al., 2007), making it difficult to trace the continuation of this belt into the Korean Peninsula.

Widespread Phanerozoic plutons in Northeast Asia are believed to have been chiefly produced in association with the (paleo-)Pacific plate subduction and, to a lesser extent, with continental collision between the North and South China cratons (Sagong et al., 2005; Yang et al., 2005, 2007a, 2007b; Jahn, 2010; Zhang et al., 2014; Zhu et al., 2014; Cheong and Jo, 2017). Such a presumed connection between plate convergence and magma generation is corroborated by the distribution of the plutons concentrated along the plate boundaries (Fig. 1). The initiation of Phanerozoic magmatism in the Northeast Asian margin is marked by the occurrence of latest Paleozoic (267–256 Ma) calc-alkaline granitoids in southeastern China, southeastern Korea, and southwest Japan (Li et al., 2006; Horie et al., 2010; Yi et al., 2012a, 2012b; Cheong et al., 2013, 2014). The magmatism then culminated in the Triassic, Jurassic, and Cretaceous periods, with magmatic lulls of ~20–50 m.y. between the flare-ups (Sagong et al., 2005; Cheong and Kim, 2012; Zhang et al., 2014; Zhu et al., 2014). The tectonic significance of such cyclic igneous activities has been discussed mainly in view of arc system evolution (Sagong et al., 2005; Li and Li, 2007, Choi et al., 2012; Li et al., 2012).

The basement of the Korean Peninsula is composed of three Precambrian (mostly Paleoproterozoic) massifs (Nangrim— or Rangeum, Gyeonggi, and Yeongnam) intervened by Neoproterozoic to Paleozoic fold-and-thrust belts (Imjingang and Okcheon— or Ockcheon) (Figs. 1 and 2). The southeastern margin of the peninsula forms the Cretaceous Gyeongsang arc system comprising an arc platform and a backarc basin (Chough and Sohn, 2010). The Korean Peninsula has traditionally been
considered to be a coherent part of the North China Craton, as reflected by its alternative name, the Sino-Korean Craton. The shared lithologies and metamorphic evolution histories of the three Precambrian massifs suggest that they collectively comprise the Paleoproterozoic (ca. 2.0–1.85 Ga) arc system and a collisional orogen probably stretching from the eastern North China Craton (Cho et al., 2017b). After a long magmatic quiescence from the Paleoproterozoic to the middle Paleozoic, the peninsula experienced another series of tectonothermal events related to the internal continental collision and external oceanic plate subduction.

Many tectonic models have proposed that the Qinling-Dabie-Sulu belt extends into the Korean Peninsula. The tectonic schemes of Cluzel et al. (1991) and Yin and Nie (1993) led many...
Figure 2. Distribution of Phanerozoic plutonic rocks in the central and southern Korean Peninsula and sampling sites (modified from Cheong and Kim, 2012).
to suggest that the Imjingang and Okcheon belts correspond to the geographic position of the suture(s) (Rhee et al., 1996; Chough et al., 2000; Ernst et al., 2007). Alternatively, the schematically proposed Hongseong-Imjingang or Hongseong-Odaeasan (for locations, see Fig. 2) belts were considered to be the extended collision zone (Oh, 2006, 2016; Kwon et al., 2009; Oh et al., 2015). More recently, Cho et al. (2017a) suggested that the Imjingang, Okcheon, and Taean-Hongseong belts, collectively referred to as the Gyeonggi Marginal Belt, represent the Neoproterozoic to Paleozoic rift- and arc-related tectonic slivers built upon the North China-like Gyeonggi Massif.

The compilation of sensitive high-resolution ion microprobe (SHRIMP) data has confirmed that the Gyeonggi Massif experienced two distinct tectonothermal events, in Paleoproterozoic and Triassic times (Cho et al., 2017a). The Triassic crustal thickening event resulted in high-pressure metamorphism highlighted by the occurrence of eclogitic amphibolite in the western Gyeonggi Massif (Oh et al., 2005). The SHRIMP zircon dates (ca. 230 Ma) of the eclogite facies metamorphism, reported by Kim et al. (2006), are mostly discordant, and thus may not constrain the timing of peak metamorphism exactly. The post-collisional stage is represented by the Late Triassic gabbro-mangerite-monzonite-syenite-granite suite, occurring commonly as small stocks in the internal and marginal parts of the Gyeonggi Massif (Fig. 2) (Cheong et al., 2015a, 2016, and references therein). This suite is approximately coeval with rare earth element (REE)-enriched carbonatite in Hongcheon, in the central Gyeonggi Massif (for location, see Fig. 2) (Kim et al., 2016), and silica-undersaturated alkaline silicate rocks occurring to the north of the Imjingang Belt (Peng et al., 2008; Yang et al., 2010). The Triassic crustal thickening event was followed by a gravitational collapse at ca. 225 Ma to form the Gyeonggi Shear Zone (Kim et al., 2000).

The initiation of extensive arc magmatism in southeastern Korea is marked by the occurrence of late Permian (257 Ma) Jangsari and immediately subsequent (253–257 Ma) Yeongdeok plutons (Yi et al., 2012a) (Fig. 2). The high Sr/Y ratios (>140), intermediate felsic compositions, and light REE (LREE)-enriched patterns of the Yeongdeok samples (Cheong et al., 2002) are typical for the high-silica adakite derived by slab melting (Martin et al., 2005). Sodic metagranitoids (tonalitic-trondhjemitic-granodioritic gneisses) occurring in the adjacent Andong-Choengsong area, and the “young gneisses” near Gimcheon (for locations, see Fig. 2) yielded coeval (ca. 250 Ma) zircon core ages (Cheong et al., 2014; Song et al., 2015). Approximately comparable SHRIMP zircon ages (262–252 Ma) were reported from gabbros and granites recovered from a drill core (~3400–2700 m in depth) in Pohang (Lee et al., 2014) (see Fig. 2), indicating that Permian rocks comprise the upper part of the basement of the Gyeongsang arc. The Paleozoic–Mesozoic transitional arc magmatism in the Yeongdeok-Andong-Choengsong-Gimcheon area was followed by the intrusion of Late Triassic plutons in the central and southwestern parts of the Yeongnam Massif (Park et al., 2006; Kim et al., 2011b). The latest stage of Triassic magmatism in the Yeongnam Massif is represented by the occurrence of geochemically arc-like (i.e., enriched in large-ion lithophile elements [LILEs], but depleted in high-field-strength elements [HFSEs]) Andong peridotite-pyroxenite complexes (Whattam et al., 2011) and the Daegang A-type granite (for locations, see Fig. 2), of which emplacement ages were constrained at 222 Ma and 220 Ma, respectively (Cho et al., 2008; Jeong et al., 2014).

After the Permian–Triassic tectonomagmatic events, the Korean Peninsula was subjected to an accretionary orogenic system. The Jurassic and Cretaceous magmatism migrated inland and trenchward, respectively (Kee et al., 2010; Cheong and Kim, 2012; Choi et al., 2012), perhaps resulting from the tectonic switch between the advancing and retreating arc systems. The Phanerozoic plutons comprise around one-third of the total landmass of the southern Korean Peninsula (Fig. 2). They are subdivided into four spatiotemporal groups that intruded episodically in the Permian–Triassic, the Early Jurassic, the Middle Jurassic, and the Cretaceous to Paleogene (Cheong and Kim, 2012). Triassic, Jurassic, and Cretaceous igneous activities were also identified by detrital and magmatic zircons collected from the North Korean territory (Wu et al., 2007a, 2007b).

**MATERIALS AND METHODS**

This study used new and published whole-rock geochemical, zircon U-Pb geochronological, and O-Hf isotopic data for 21 gabbro-pyroxenite-mangerite-monzonite-syenite-granodiorite-granite samples collected from Triassic plutons in the Gyeonggi (10 samples) and Yeongnam (11 samples) massifs. The sample locations are shown in Figure 2, and their GPS coordinates are presented in Table DR1, with petrographic and mineralogic summaries. Eleven new samples were collected for this study. They were three granites from the western Gyeonggi Massif (Taean, Seosan, and Namyang) and eight monzonierte-mangerite-syenite-granodiorite-granite samples from the central Yeongnam Massif (Daegang, Macheon, Hamyang, Hapcheon, Sancheong, and Sangju).

The other ten samples were collected previously for geochemical and isotopic studies. Three (monzonite and syenite), two (gabbro and monzonite), and two (mangerite) samples were collected from the western (Gwangcheon and Haemi), central (Yangpyeong), and eastern (Odaeasan) Gyeonggi Massif, respectively, by Cheong et al. (2015a). Two orthopyroxenites from the Andong ultramafic complex (Jeong et al., 2014) and one granodiorite from the Yeongdeok pluton (Yi et al., 2012a) were also analyzed in this study.

Zircon U-Th-Pb isotopic analyses were carried out using a SHRIMP He/Me at the Korea Basic Science Institute (KBSI) (Ochang, Korea). Prior to the SHRIMP analysis, cathodoluminescence (CL) and backscattered electron (BSE) images of separated zircon grains were examined using a scanning electron microscope (JEOL-JSM-6610LV) at the KBSI. Zircon U-Pb ages were newly determined for four samples from Taean in the Gyeonggi Massif, and Hapcheon and Sancheong in the Yeongnam Massif. In addition, seven samples from the Gyeonggi Massif and four samples from the Yeongnam Massif were dated again in this study considering the relatively high scatter of previous SHRIMP zircon ages (i.e., relative error >1%, mean square weighted deviation [MSWD] >5). Whole-rock major element analyses for eleven samples (three from the Gyeonggi Massif and eight from the Yeongnam Massif) were performed at Pukyong National University (Busan, Korea) and Activation Laboratories Ltd. (Canada) using an X-ray fluorescence spectrometer. Trace element compositions of sodium peroxide-fused whole-rock powders (ten samples from the Gyeonggi Massif and eight samples from the Yeongnam Massif) were determined at Activation Laboratories Ltd. with a quadrupole inductively coupled plasma–mass spectrometer (ICP-MS). Zircon oxygen isotopes were measured for seventeen samples (eight from the Gyeonggi Massif and nine from the Yeongnam Massif) using the Cameca IMS 1280 ion probe at the secondary ion mass spectrometer laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing, China. Zircon Lu-Yb-Hf isotopes

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1GSA Data Repository item 2018374, Tables DR1–DR4: GPS coordinates and petrographic and mineralogic summaries of whole-rock samples, SHRIMP U-Th-Pb results for zircon, whole-rock major and trace element compositions, and zircon O and Lu-Yb-Hf isotopic compositions, is available at http://www.geosociety.org/datarepository/2018 or by request to editing@geosociety.org.
were measured for nineteen samples (eight from the Gyeonggi Massif and eleven from the Yeongnam Massif) using a Plasma II multicolon-
ector ICP-MS (Nu Instruments) equipped with an NWR193-nm ArF Excimer laser ablation system at the KBSI. Laser ablation was targeted on the points selected for the determination of U-Th-Pb-O isotopes or new points within the same CL domains. Details of the zircon anal-yses are available in Appendix 1.

RESULTS
Zircon Texture and U-Pb Age
Representative CL and BSE images of the zircon grains are shown in Figure 3. The SHIRMP zircon U-Th-Pb data are listed in Table DR2 (see footnote 1).

Gyeonggi Massif Plutons
Figure 4 shows the zircon U-Pb isotopic composition of eight samples from the Gyeonggi Massif in concordia diagrams.

Zircon grains from the Taean granite (sample 170329-04) were generally euhedral and prismatic. Some grains showed clear oscillatory CL zoning, indicating their symmagmatic growth. Their magmatic origin was also corroborated by the mostly high (>0.7) Th/U ratios (i.e., Rubatto, 2002). Some grains containing high levels of uranium (~23,000–9700 ppm) were dark in BSE images, and typically had a sponge-like texture. This study focused on the domains targeted for the analysis. Zircons from the Taean granite and, to a lesser extent, in the Gyeonggi Massif and Odaesan mangerite (sample 070809-03) were dated by Cheong et al. (2015a). In this study, we obtained similar but more tightly constrained 206Pb/238U ages for these samples: 229.5 ± 1.7 Ma (n = 20, MSWD = 1.9), 229.6 ± 2.2 Ma (n = 20, MSWD = 3.4), 232.1 ± 1.5 Ma (n = 12, MSWD = 0.9), 228.0 ± 1.5 Ma (n = 16, MSWD = 1.4), and 231.2 ± 2.4 Ma (n = 16, MSWD = 3.9), respectively (Fig. 4). From the Yangpyeong monzonite, we found Neoarchean and Paleopro-tozoic (2.65 and 1.88–1.81 Ga) zircon cores.

Yeongnam Massif Plutons
Zircon U-Pb isotopic compositions of seven samples from the Yeongnam Massif are graphically displayed in Figure 5.

The Hapcheon and Sancheong samples were newly dated here. Zircon grains from the Hapcheon syenite (sample 150312-03) and mangerite (sample 150312-04A) had banded, sector, or oscillatory CL zoning. The Th/U ratios were lower in the former (<0.5) than in the latter (∼0.9), but were still higher than the generally accepted boundary value between magmatic and metamorphic domains (Th/U = 0.1; Rubatto, 2002). The U-Pb isotope data yielded a weighted mean 206Pb/238U age of 216.9 ± 0.9 Ma for the syenite (n = 31, MSWD = 1.6) and 227.4 ± 1.5 Ma for the mangerite (n = 29, MSWD = 2.6). Zircons from the San- cheong syenite (sample 140424-04) typically showed fine-scale oscillatory zoning in CL images. Some samples contained corroded early magmatic (i.e., not xenocrystic) cores. The U-Pb data yielded a weighted mean 206Pb/238U age of 218.5 ± 1.0 Ma (n = 20, MSWD = 1.2). The Hapcheon and Sancheong syenites had the same age, within error ranges.

Zircon grains from the Daegang alkali granite (sample DGA1-2) were typically euhedral and prismatic crystals that frequently showed dark-CL emissions. The relatively bright-CL domains were targeted for the analysis. Zircons from the Macheon monzonite (sample 140424-02) had banded, sector, or oscillatory CL zoning. They yielded a weighted mean 206Pb/238U age of 232.4 ± 1.4 Ma (n = 21, MSWD = 1.6), which was marginally consistent with a previously published result (236.8 ± 3.4 Ma; Kim et al., 2011b). Zircon grains from a K-feldspar megacryst-bearing granodiorite from Hamyang (sample 140423-06) had oscillatory CL zoning at a fine scale. The grains typically contained corroded cores (Fig. 3) yielding Paleopro- tozoic 207Pb/206Pb dates (1.91–1.77 Ga). The presence of Paleoproterozoic inherited cores was also reported by Kim et al. (2011b). Our dating result for the magmatic oscillatory CL domains of zircons from the Hamyang granodiorite (226.8 ± 1.3 Ma, n = 21, MSWD = 2.3) was younger than the previous estimate by Kim et al. (2011b) (232.2 ± 2.9 Ma, MSWD = 9.1). The reason for this discrepancy is unknown, but the relatively high scatter of the age data of Kim et al. (2011b) is noteworthy. Zircon grains from the monzonite (sample 140423-02) and granite (sample 140423-04), collectively constituting the Sangju pluton, were characterized by banded and oscillatory CL zoning, respectively (Fig. 3). Some recrystallized grains from the former had a relatively high U content (>1000 ppm) and low Th/U ratios (<0.1). These grains were not considered in the age calculation. In the latter sample, zircon grains contained cores with truncated CL domains (Fig. 3). These cores yielded consistently Paleoproterozoic 207Pb/206Pb dates (1.90–1.85 Ga). The U-Pb isotope data for the synmagmatic zircons in the monzonite and granite yielded identical weighted mean 206Pb/238U ages (224.3 ± 1.9 Ma, n = 17, MSWD = 2.2; 225.9 ± 1.4 Ma, n = 16, MSWD = 1.0), which were younger than the previous results (238.8 ± 4.4 and 230.6 ± 2.5 Ma; Kim et al., 2011b) reported with relatively high MSWD values (>5).

Whole-Rock Chemical Composition
Whole-rock major and trace element compositions of the plutons are listed in Table DR3 (see footnote 1). Some major element classification diagrams are presented in Figure 6 using new data obtained in this study and previous results from the literature (Cheong et al., 2002, 2015a; Oh et al., 2006b; Choi et al., 2009; Williams et al., 2009; Kim et al., 2011b, 2011d; Yi et al., 2012a).

In the classification scheme of Frost et al. (2001), mafic to intermediate (SiO2 ≤ 60 wt%) samples from the Gyeonggi Massif were invariably magnesian (Fig. 6A). Granite samples from the western parts of the massif (Taean, Seosan, Hongseong, Haemi, and Namyang) were scattered between magnesian and ferroan fields. Of the Yeongnam Massif samples analyzed in this study, only alkali granite and syenite samples from Daegang, Hapcheon, and Sancheong were ferroan. These ferroan samples were relatively young (220–217 Ma) compared with the other Yeongnam samples (232–224 Ma) mostly belonging to the magnesian group. The Gyeonggi Massif samples were plotted predominantly
Figure 3. Representative back-scattered electron (marked with a “BSE” label) and cathodoluminescence images of zircon grains, from the Triassic plutons in the Korean Peninsula, recording results for U-Pb dating (for inherited cores only) and O-Hf isotopic measurements. The scale is referenced by Hf isotope spot (large dotted circle, diameter = 50 µm).
Figure 4. Concordia diagrams of sensitive high-resolution ion microprobe zircon U-Pb data from the Gyeonggi Massif, central Korean Peninsula, with weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages, uncertainties at the 95% confidence level, and statistical parameters. Error ellipses are at the 1-sigma level. Gray and dashed ellipses represent the inherited cores and outliers determined by t-tests in the calculation of the weighted mean ages, respectively. Data points represent $^{208}\text{Pb}$-corrected ratios. MSWD—mean square weighted deviation.
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Figure 5. Concordia diagrams of sensitive high-resolution ion microprobe zircon U-Pb data from the Yeongnam Massif, southern Korean Peninsula. Statistical treatments and symbols are the same as in Figure 4.
in alkalic and alkali-calcic fields, whereas the Yeongnam Massif samples straddled the region between alkali-calcic to calc-alkalic fields, except for two syenites from Hapcheon and Sancheong that were plotted distinctly in the alkalic field (Fig. 6B). At the given SiO\textsubscript{2} content, the Gyeonggi samples tended to be more enriched in K than the Yeongnam samples (Fig. 6C). Mafic to intermediate (SiO\textsubscript{2} = 60–45 wt%) samples from the Gyeonggi Massif were mostly plotted in the shoshonite series field, whereas felsic (SiO\textsubscript{2} ≥ 70 wt%) samples were dispersed from the shoshonite to high-K series fields. The Yeongnam Massif samples straddled the region between the high-K and medium-K series fields, except for the ferroan samples and the Macheon monzonite plotted in the shoshonite series field. The geochemical difference between the Gyeonggi and Yeongnam samples was most sharply distinguished by the K\textsubscript{2}O/Na\textsubscript{2}O ratio (Fig. 6D). The dominantly potassic (K\textsubscript{2}O > Na\textsubscript{2}O, in wt%) and sodic (Na\textsubscript{2}O > K\textsubscript{2}O) signatures of the Gyeonggi and Yeongnam samples were not correlated with their SiO\textsubscript{2} contents. Among the Yeongnam samples analyzed in this work, only the Daegang alkali granite was higher than unity in K\textsubscript{2}O/Na\textsubscript{2}O ratio. The A/CNK (molar Al\textsubscript{2}O\textsubscript{3}/[CaO + Na\textsubscript{2}O + K\textsubscript{2}O]) ratio of the samples from the two massifs were mostly below 1.1, which is the conventionally

Figure 6. Major element classification diagrams for the Triassic plutons from the Gyeonggi and Yeongnam massifs in the central and southern Korean Peninsula, respectively, analyzed in this study and previous works (Cheong et al., 2002, 2015a; Oh et al., 2006b; Choi et al., 2009; Williams et al., 2009; Kim et al., 2011b, 2011d; Yi et al., 2012a). (A) A plot of FeO\textsubscript{total}/(FeO\textsubscript{total} + MgO) versus SiO\textsubscript{2} showing the ranges of ferroan and magnesian fields (Frost et al., 2001). (B) A plot of (Na\textsubscript{2}O + K\textsubscript{2}O – CaO) versus SiO\textsubscript{2} showing the ranges of alkalic, alkali-calcic, calc-alkalic, and calcic rock fields (Frost et al., 2001). (C) A plot of K\textsubscript{2}O versus SiO\textsubscript{2} showing the shoshonite, high-K, medium-K, and low-K series fields (Rickwood, 1989). (D) A plot of K\textsubscript{2}O/Na\textsubscript{2}O versus SiO\textsubscript{2}. Data for some high-K\textsubscript{2}O/Na\textsubscript{2}O (>3.5) samples from the Gyeonggi Massif are not shown in (D) for clarity.
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accepted boundary value between I- and S-type granites (Chappell and White, 1992).

Of the samples analyzed in this study, the mafic to intermediate rocks from the Gyeonggi Massif had distinctly higher Ba contents (3040–1950 ppm) than the other samples (<1300 ppm). At given SiO$_2$ contents, the Gyeonggi samples tended to have higher Cs, Rb, and Pb content than the Yeongnam samples. Five syenite-granodiorite-granite samples from Hapcheon, Sancheong, Hamyang, and Daegang in the Yeongnam Massif, and Taean in the Gyeonggi Massif were relatively abundant in Y (62–44 ppm) compared with the other samples (<30 ppm). The Zr and Hf concentrations of all samples were strongly and positively correlated ($R^2 > 0.95$). The Sancheong syenite had the largest abundance of these elements (Zr = 1020 ppm, Hf = 20 ppm). The Nb concentration was the highest in the Taean granite (49 ppm). Overall, both the U and Th contents increased but the V, Cr, and Ni contents decreased progressively with increasing SiO$_2$ content. The Haemi syenite from the western Gyeonggi Massif was exceptionally high in Th (53 ppm).

Figure 7 shows the normalized geochemical patterns of the plutons analyzed in this study. The average composition of the Yeongdeok adakite pluton (Cheong et al., 2002) is also shown for reference. Most Gyeonggi samples displayed LREE-enriched chondrite-normalized patterns (Fig. 7A). The exception was the Taean granite, which displayed the “seagull” chondrite-normalized pattern (see Glazner et al., 2008) with a deep Eu anomaly (Eu/Eu* = 0.02). The older (232–224 Ma) Yeongnam Massif samples had LREE-enriched normalized patterns, without conspicuous Eu anomalies, except for the Hamyang granodiorite, which had a high heavy REE content and stronger negative Eu anomaly (Eu/Eu* = 0.39). The younger (220–217 Ma) ferroan Yeongnam Massif samples mimicked the REE pattern of the Hamyang granodiorite. In the normal mid-oceanic ridge basalt-normalized spider diagram, which arranges the elements according to their compatibility with the basaltic liquid, the Gyeonggi and Yeongnam samples exhibited apparent arc affinities characterized by an enrichment in LILEs and relative depletion in HFSEs (Fig. 7B). Peaks for K and Pb, and troughs for Nb, P, and Ti were prominent in most samples. The troughs were particularly distinct in the Taean granite.

Zircon O-Hf Isotopes

The new zircon O and Lu-Yb-Hf isotope data are listed in Table DR4 (see footnote 1). The Gyeonggi Massif plutons are hereafter subdivided into the western and central-eastern groups, considering their substantial differences in inherited zircon age patterns. Cheong et al. (2015a) revealed that these two spatial groups differ profoundly in their whole-rock Nd and zircon Hf isotopic compositions. It is also noted that the western group occurs within the Taean-Hongseong Complex composing the Gyeonggi Marginal Belt proposed by Cho et al. (2017a). The zircon ages and whole-rock geochemical

![Figure 7](http://pubs.geoscienceworld.org/gsa/gsabulletin/article-pdf/131/3-4/609/4651432/609.pdf)

**Figure 7.** (A) Chondrite-normalized rare earth element distribution patterns and (B) normal-mid oceanic ridge basalt (N-MORB)-normalized spidergrams of the Triassic plutons from the Gyeonggi and Yeongnam massifs in the central and southern Korean Peninsula, respectively. The chondrite and N-MORB values are from McDonough and Sun (1995) and Sun and McDonough (1989), respectively.
compositions described above allowed us to subdivide the Yeongnam Massif plutons into the older (232–224 Ma) magmasnian group and the younger (220–217 Ma) ferroan group. Zircon U-Pb ages and O-Hf isotope data are summarized in Table 1 for the four subgroups using data from the present analyses and the literature (Jeong et al., 2014; Cheong et al., 2015a).

Western Group of Gyeonggi Massif Plutons

In zircons from the Gwangcheon monzonite (sample 140403-03), there was little variation in δ18O (8.05 ± 0.27‰) and εHf(t) (–12.2 ± 0.8) values (t = zircon crystallization age, ± 1 standard deviation [SD], statistical treatment of Hf isotope data from the Gyeonggi samples included data from Cheong et al., 2015a, same hereafter unless otherwise stated). Comparable δ18O (7.96 ± 0.17‰) and slightly lower εHf(t) (–14.5 ± 0.7) values were obtained from zircons in the Haemi syenite. Zircons from the Taean granite were divided into lower (<6‰) and higher (>6‰) groups with respect to δ18O. Except for one grain, the lower group zircons were significantly high in U (>9700 ppm), with a decreasing trend in δ18O with increasing U concentrations. The high-δ18O group yielded an average δ18O value of 7.53 ± 0.26‰, with lower εHf(t) values (–14.2 ± 1.5) and εHf(t) (–22.5 ± 0.8). The εHf(t) values of the high-δ18O zircons tended to decrease with decreasing Lu/Hf ratios, reaching –16.1 for a rim spot of grain 2–8, which had the lowest 187Lu/177Hf (0.00033). Synmagmatic zircons from the Seosan granite were divided into two groups; one with relatively low δ18O and high εHf(t) values (δ18O = 8.4–7.0‰, εHf(t) = –6.8 to –11.9) and the other in the opposite side (δ18O = 9.8–8.3‰, εHf(t) = –20). The Paleoproterozoic (2107 Ma) inherited core had the highest δ18O value (8.79‰) and the lowest εHf(t) (–4.7). Conversely, two Mesoproterozoic (1385 and 1304 Ma) cores had the lowest δ18O values (5.47 and 5.87‰), with εHf(t) ranging from 5.4 to –2.0. The most abundant Neoproterozoic (0.82–0.68 Ga) cores had modest variation in δ18O (8.4–6.9‰) and εHf(t) (5.0 to –2.0). Synmagmatic zircons from the Namyang granite had narrow ranges of O and Hf isotopic compositions (δ18O = 7.66 ± 0.22‰, εHf(t) = –15.4 ± 1.3). Their εHf(t) values were weakly and positively correlated with their Lu/Hf ratios, reaching –18.8 in the lower Lu/Hf side. The Paleoproterozoic (2346 Ma) inherited core from the Namyang granite had an inner part with moderate δ18O (6.51‰) and negative εHf(t) (–5.2) values and an outer part yielding slightly higher δ18O (6.88‰) and lower εHf(t) (–8.3) values. The Neoproterozoic (1076 Ma) core had much lower δ18O (5.04‰) and positive εHf(t) (3.9) values. The outer part of this core had a

| Subgroup                     | Inherited core age (Ga) | Syenforce data (°C) | Syenforce data (%) | O-Hf data (°C) | Mean ± SD (°C) | Mean ± SD (‰) | εHf(t) (°C) | εHf(t) (°C) |
|----------------------------|-------------------------|---------------------|-------------------|----------------|----------------|----------------|-------------|-------------|
| Younger ferroan group       | 226–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Older magnesian group        | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Central-eastern group of Gyeonggi Massif Plutons | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Hapcheon syenite (Gyeonggi Massif Plutons) | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Yeongnam Massif plutons, and | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Other magnesian group of Gyeonggi Massif Plutons | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Younger ferroan group       | 226–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Older magnesian group        | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Central-eastern group of Gyeonggi Massif Plutons | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Hapcheon syenite (Gyeonggi Massif Plutons) | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Yeongnam Massif plutons, and | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
| Other magnesian group of Gyeonggi Massif Plutons | 233–234                 | 633–679             | 0.37–1.7           | 7.48–7.39      | –15.2 ± 1.1     | 10.4 ± 1.5     | 1.1 ± 0.8    | 3.0 ± 1.0   |
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Central-Eastern Group of Gyeonggi Massif Plutons
Zircons from the Yangpyeong gabbro in the central Gyeonggi Massif showed little variation in O and Hf isotopic compositions ($\delta^{18}$O = 7.26 ± 0.14‰, $\varepsilon_{Hf}(t) = -22.5 ± 0.8$). Synmagmatic zircons from the Yangpyeong monzonite had slightly lower $\delta^{18}$O (6.85 ± 0.24‰) and comparable $\varepsilon_{Hf}(t)$ (–23.1 ± 1.4) values. These two Yangpyeong samples had the lowest $\varepsilon_{Hf}(t)$ among the samples analyzed in this study. Three grains (2-7, 2-9, and 2-10) from the monzonite showed core-to-rim increases in $\delta^{18}$O (–6.4 → +7.0‰) that were marginally outside the limit of analytical uncertainty. Their Lu/Hf ratios decreased toward the rims, but the core and rim $\varepsilon_{Hf}(t)$ values did not vary consistently. The Neoarchean and Paleoproterozoic inherited cores from the monzonite had moderate to high $\delta^{18}$O values (8.4–6.9‰) and consistently negative $\varepsilon_{Hf}(t)$ (–3.6 to –8.9). Zircons from the Odaesan mangerite (sample 070809-03) had narrow ranges of $\delta^{18}$O (7.36 ± 0.17‰) and $\varepsilon_{Hf}(t)$ (–19.5 ± 0.8).

Older Group of Yeongnam Massif Plutons
Zircon grains from the Maechon monzonite had little variation in $\delta^{18}$O and $\varepsilon_{Hf}(t)$. Two spots from grain 2-2 had relatively high $\delta^{18}$O (7.77 and 7.72‰) and $\varepsilon_{Hf}(t)$ (–1.2 and 0.1) values. One grain (#2-64) showed a distinct core-to-rim increase in $\varepsilon_{Hf}(t)$ (–2.2 → 2.8) outside analytical uncertainties. Except for these spots, $\delta^{18}$O and $\varepsilon_{Hf}(t)$ values were highly consistent ($\delta^{18}$O = 7.55 ± 0.08‰, $\varepsilon_{Hf}(t) = -3.8 ± 0.8$). Symmagmatic zircons from the Hamyang granodiorite also had little variation in $\delta^{18}$O (7.63 ± 0.17‰), except for two spots in grain 2-1 that had substantially higher values (8.44 and 8.33‰). The $\varepsilon_{Hf}(t)$ values of symmagmatic zircons varied from –3.8 to –9.1 and had a weak positive correlation with the Lu/Hf ratio. The Paleoproterozoic cores had significantly high $\delta^{18}$O (9.4–8.7‰) and variable $\varepsilon_{Hf}(t)$ (4.1 to –2.3). Zircons from the Hapcheon gneiss exhibited low $\delta^{18}$O values (6.65 ± 0.22‰) and consistently positive $\varepsilon_{Hf}(t)$ (6.4 ± 0.7). The Sangju monzonite and granite were comparable in their zircon $\varepsilon_{Hf}(t)$ values (–9.1 ± 0.7 and –8.4 ± 1.2). The $\varepsilon_{Hf}(t)$ values of the Paleoproterozoic inherited cores from the granite ranged from 3.7 to –3.7. Zircons from the Yeongdeok granodiorite showed little variation in O and Hf isotopic compositions ($\delta^{18}$O = 5.69 ± 0.26‰, $\varepsilon_{Hf}(t) = 11.1 ± 0.8$). Their significantly high $\varepsilon_{Hf}(t)$ values are consistent with previous data for the Yeongdeok pluton (11.7 ± 1.3; Cheong et al., 2013).

Younger Group of Yeongnam Massif Plutons
Except for dark-CL spots, the zircon $\delta^{18}$O values of the Daegang alkali granite were quite consistent (6.04 ± 0.19‰). As shown by zircon grains from the Taean granite in the western Gyeonggi Massif, the unanferous dark-CL spots had comparatively low $\delta^{18}$O values (5.63 and 5.89‰). The $\varepsilon_{Hf}(t)$ values varied moderately from 1.1 to –5.3. Zircons from the Hapcheon syenite had the lowest $\delta^{18}$O (5.10 ± 0.17‰) and the second highest $\varepsilon_{Hf}(t)$ (8.1 ± 1.1) values among the symmagmatic grains from the plutons analyzed in this study. Zircon $\delta^{18}$O values of the Sancheong syenite varied from 8.41‰ to 6.50‰. But this sample yielded consistent zircon $\varepsilon_{Hf}(t)$ values (3.0 ± 0.6). Combined with data from Jeong et al. (2014), the zircon Hf isotopic compositions of the two pyroxenites from Andong differed slightly from each other ($\varepsilon_{Hf}(t)$ = 1.7 ± 1.0 and 3.6 ± 1.2). However, their zircon O isotopic compositions were comparable, yielding an average $\delta^{18}$O value of 7.08 ± 0.26‰.

DISCUSSION
Temporal Correspondence of Collisional Orogeny and Arc Magmatism
After Paleoproterozoic (ca. 2.0–1.85 Ga) accretionary and collisional events, the cratonic part of the Korean Peninsula remained tectonically and magmatically calm until the continental collision between the North and South China cratons, although it should be noted that Neo-proterozoic–Paleozoic magmatic and metamorphic events have occurred along the fold-and-thrust belts surrounding the Gyeonggi Massif (Yeongdeok Marginal Belt; Cho et al., 2017a, 2018). The Phanerozoic orogenies left a strong imprint on pre-existing rocks, and directly or indirectly caused the formation of magma. In the following, the temporal relation between the Phanerozoic orogenic event(s) that affected the Gyeonggi Massif and the surrounding Imjingang and Okcheon belts, and arc magmatism along the Yeongnam Massif is discussed based on our dating results combined with available age data from the literature. The age data for the Permian–Triassic metamorphic and magmatic events are compiled in Table 2.

Metamorphic ages reported from the Imjingang Belt are rare. Lee et al. (1996) reported an earliest Triassic Sm-Nd age (249 ± 31 Ma) using hornblende, garnet, and plagioclase separated from a Paleoproterozoic amphibolite comprising the southern part of the belt (the Samgot unit). This age was later confirmed by SHRIMP U-Pb dating of zircon overgrowth rims from a garnet-biotite gneiss (252.9 ± 1.9 Ma; Cho et al., 2005). Recently, Late Triassic magmatic ages were reported from the adjacent Nangrim Massif in the North Korean territory. Peng et al. (2008) presented a zircon crystallization age of 224 ± 4 Ma for a biotite syenite that comprises a gabbro-pyroxenite-syenite complex (the so-called Tokdal Complex) probably stretching from eastern China. A comparable Rb-Sr age (223.3 ± 6.6 Ma) was obtained from phlogopite in a kimberlite associated with the Tokdal Complex (Yang et al., 2010). These two age data, together with a monazite Th-Pb age of the Hongcheon carbonate in the Gyeonggi Massif (232.9 ± 1.6 Ma; Kim et al., 2016), confirm the occurrence of Late Triassic mantle-derived magmatism in central Korea.

Cho et al. (2017a) constrained the timing of Triassic crustal thickening event in the Gyeonggi Massif to 245–230 Ma based on a compilation of the SHRIMP U-Pb and Th-Pb ages of accessory minerals. Their new SHRIMP monazite (235–231 Ma) and zircon ages (ca. 226 Ma) from the Mount Cheonggye area near Seoul, Korea, may indicate that the Triassic collisional orogeny was accompanied by rapid cooling and exhumation. However, we note that at least part of zircon rim ages reported previously from the Gyeonggi Massif should be interpreted with caution. Importantly, it is quite difficult to distinguish the age of a regional metamorphic event from that of a local thermal overprint. The influence of the magmatic overprint on the zircon age was typically exemplified in the Yangpyeong area, where Paleoproterozoic basement gneisses yielded a zircon U-Pb age of ca. 235 Ma from overgrowth rims or newly grown grains (Oh et al., 2015). This age is indistinguishable from the crystallization ages of symmagmatic zircons from gabbros and monzonites in this area (232–228 Ma; Cheong et al., 2015a; this study), considering the error ranges. This is especially true when the pooled age of zircon cores from the monzonite (238.4 ± 5.0 Ma; Cheong et al., 2015a) is taken to represent the crystallization timing of “ancryst” (see Miller et al., 2007). Moreover, among the samples analyzed by Oh et al. (2015), the cor-dierite-sillimanite-garnet-biotite gneiss (sample no. YP182F), located closest to the gabbro (<1 km), contained an abundance of newly grown zircon grains. The maximum age of Triassic metamorphism was determined by Cho et al. (2017a) (245 Ma) on the basis of zircon ages from basement rocks in the Odaesan area (Oh et al., 2006a; Cho, 2014). In fact, however, the Paleoproterozoic spinel granulite and migmatitic gneiss in this area yielded highly scattered zircon rim dates ranging from 265 Ma to 230 Ma.
TABLE 2. SUMMARY OF GEOCHRONOLOGICAL DATA FOR THE PERMIAN–TRIASSIC METAMORPHIC AND MAGMATIC EVENTS REPORTED FROM CENTRAL AND SOUTHERN KOREA

| Locality                | Rock type                  | Method                        | Result (Ma)  | Source                        |
|-------------------------|----------------------------|-------------------------------|--------------|-------------------------------|
| **Imjingang Belt and Nangrim Massif** |                            |                               |              |                               |
| Yeoncheon               | Amphibolite                 | Mineral Sm-Nd                 | 249 ± 11     | Lee et al. (1996)             |
| Daejak Island           | Tonalitic gneiss            | Allanite U-Th-Pb              | 229 ± 4      | Cho et al. (2009)             |
| Daejak Island           | Tonalitic gneiss            | Allanite U-Th-Pb              | 229 ± 4      | Cho et al. (2009)             |
| Daejak Island           | Tonalitic gneiss            | Allanite U-Th-Pb              | 229 ± 4      | Cho et al. (2009)             |
| Hwangseong              | Amphibolite-bearing granitic gneiss | Zircon U-Pb                  | 239 ± 10     | Cheong et al. (2006)          |
| Hongseong               | Biotite granitic gneiss     | Zircon U-Pb                   | 235 ± 8      | Kim et al. (2008b)            |
| Hongseong               | Eclogite amphibolite        | Zircon U-Pb                   | 231 ± 3      | Kim et al. (2006)             |
| Hongseong               | Mafic granulite             | Zircon U-Pb                   | 236 ± 5      | Kim et al. (2008b)            |
| Hongseong               | Mafic dyke                  | Zircon U-Pb                   | 233 ± 4      | Kim et al. (2008b)            |
| Hongseong               | Porphyroblastic orthogneiss | Zircon U-Pb                   | 237 ± 5      | Kim et al. (2008b)            |
| Mount Cheonggye         | Biotite quartzofeldspathic gneiss | Zircon U-Pb                  | 232 ± 2      | Cho et al. (2017b)            |
| Mount Cheonggye         | Biotite quartzofeldspathic gneiss | Zircon U-Pb                  | 232 ± 2      | Cho et al. (2017b)            |
| Mount Cheonggye         | Cordierite-garnet-biotite gneiss | Monazite U-Pb               | 235 ± 2      | Cho et al. (2017a)            |
| Mount Cheonggye         | Biotite quartzofeldspathic gneiss | Monazite U-Pb               | 235 ± 2      | Cho et al. (2017a)            |
| Mount Cheonggye         | Biotite quartzofeldspathic gneiss | Monazite U-Pb               | 235 ± 2      | Cho et al. (2017a)            |
| Yangpyeong              | Cordierite-sillimanite-garnet-biotite gneiss | Zircon U-Pb              | 236 ± 7      | Yengkhom et al. (2014)        |
| Yangpyeong              | Sillimanite-garnet-biotite gneiss | Zircon U-Pb              | 237 ± 4      | Oh et al. (2015)              |
| Hongseong               | Augen gneiss                | Titanite U-Th-Pb              | 224 ± 14     | Kim et al. (2008a)            |
| Hwacheon                | Amphibolite                 | Titanite U-Th-Pb              | 223 ± 3      | Yi and Cho (2009)             |
| Hwacheon                | Amphibolite-granulite       | Monazite U-Pb                 | 236 ± 8      | Yi and Cho (2009)             |
| Hwacheon                | Amphibolite-granulatetanetan | Monazite U-Th-Pb            | 229 ± 11     | Yi and Cho (2009)             |
| Odaesan                 | Biotite schist              | Zircon U-Pb                   | 234 ± 6      | Kim et al. (2017b)            |
| Odaesan                 | Spinel granulate            | Zircon U-Pb                   | 245 ± 10     | Oh et al. (2006a)             |
| **Ochcheon Belt**       |                            |                               |              |                               |
| Gwangcheon              | Monzonite                  | Zircon U-Pb                   | 229.5 ± 1.7  | This study                    |
| Gwangcheon              | Monzonite                  | Zircon U-Pb                   | 227.3 ± 3.7  | Cheong et al. (2015a)         |
| Haemi                   | Syenite                    | Zircon U-Pb                   | 229.0 ± 2.2  | This study                    |
| Haemi                   | Granite                    | Zircon U-Pb                   | 235 ± 2      | Cho et al. (2009)             |
| Taean                   | Granite                    | Zircon U-Pb                   | 229.8 ± 2.2  | This study                    |
| Seosan                  | Granite                    | Zircon U-Pb                   | 224 ± 2.3    | This study                    |
| Namyang                 | Granite                    | Zircon U-Pb                   | 232 ± 1.5    | This study                    |
| Yangpyeong              | Hornblende gabbro          | Zircon U-Pb                   | 232.1 ± 1.5  | This study                    |
| Yangpyeong              | Monzonite                  | Zircon U-Pb                   | 239.4 ± 5.0  | Cheong et al. (2015a)         |
| Yangpyeong              | Monzonite                  | Zircon U-Pb                   | 238.0 ± 1.5  | This study                    |
| Yangpyeong              | Syenodiorite               | Zircon U-Pb                   | 233.3 ± 1.3  | Yi et al. (2016)              |
| Hongcheon               | Garnet gneiss              | Monazite Th-Pb                | 239.9 ± 1.6  | Kim et al. (2010)             |
| Yangyang                | Syenite                    | Zircon U-Pb                   | 233 ± 1      | Seo et al. (2015)             |
| Odaeasan                | Pyroxene-mica gabbro       | Zircon U-Pb                   | 231.3 ± 1.3  | Kim et al. (2011d)            |
| Odaeasan                | Mangerite                  | Zircon U-Pb                   | 231.9 ± 1.6  | Cheong et al. (2015a)         |
| Odaeasan                | Mangerite                  | Zircon U-Pb                   | 227.1 ± 2.5  | Cheong et al. (2015a)         |
| **Yeongnam Massif**     |                            |                               |              |                               |
| Yeongdeok               | Granodiorite               | Zircon U-Pb                   | 250 ± 3      | Yi et al. (2012a)             |
| Yeongdeok               | Diorite xenolith           | Zircon U-Pb                   | 261.3 ± 2.4  | Yi et al. (2012b)             |
| Yeongdeok               | Granodiorite xenolith      | Zircon U-Pb                   | 265.9 ± 2.2  | Ye et al. (2013)              |
| Janggae                 | Gabbro                    | Zircon U-Pb                   | 255.7 ± 1.4  | Yi et al. (2013a)             |
| Janggae                 | Granite                   | Zircon U-Pb                   | 257.3 ± 2.0  | Ye et al. (2012a)             |
| Andong                  | Granodioritic gneiss       | Zircon core U-Pb              | 262.4 ± 2.6  | Cheong et al. (2014)          |
| Andong                  | Granodioritic gneiss       | Zircon core U-Pb              | 252 ± 1.1    | Cheong et al. (2014)          |
| Andong                  | Trondhjemitic gneiss       | Zircon core U-Pb              | 251 ± 2.7    | Cheong et al. (2014)          |
| Cheongsong              | Trondhjemitic gneiss       | Zircon core U-Pb              | 251 ± 2.7    | Cheong et al. (2014)          |
| Sangju                  | Monzonite                 | Zircon U-Pb                   | 234.3 ± 1.9  | This study                    |
| Sangju                  | Granite                   | Zircon U-Pb                   | 229 ± 9.4    | This study                    |
| Daeang                  | Alkalai granite            | Zircon U-Pb                   | 219 ± 0.9    | Cho et al. (2008)             |
| Macheon                 | Monzonite                 | Zircon U-Pb                   | 232 ± 4.4    | This study                    |
| Hanmyang                | K-feldspar megacyrst-bearing granodiorite | Zircon U-Pb              | 226.8 ± 1.3  | This study                    |
| Sandeong                | Syenite                   | Zircon U-Pb                   | 218.9 ± 1.0  | This study                    |
| Hapcheon                | Mangerite                 | Zircon U-Pb                   | 227 ± 1.5    | This study                    |
| Hapcheon                | Syenite                   | Zircon U-Pb                   | 216.9 ± 0.9  | This study                    |
| Kimcheon                | Granite gneiss            | Zircon U-Pb                   | 206 ± 2.9    | Song et al. (2015)            |
| Kimcheon                | Granite gneiss            | Zircon U-Pb                   | 241 ± 7.2    | Song et al. (2015)            |

Note: REE—rare earth element; CHIME—chemical Th-U-total Pb isochron method.
The exotic feature of the protolith of the Early Jurassic (245–250 Ma) magmatism may be traced back to the middle Paleozoic, considering the SHRIMP zircon ages (266–261 Ma) of diorite-granodiorite xenoliths found in the Yeongdeok pluton and Andong tonalitic gneisses (Yi et al., 2012a; Cho et al., 2013). An even older, middle Paleozoic magmatism was suggested from the margin of the Yeongnam Massif (269–265 Ma; Oh et al., 2012a). This age is also close to the younger boundary of these rim overgrowths. Although the median values of the zircon rim ages are from the Pibanryeong unit (Kim et al., 2007). Adachi et al. (1996) reported that the zircon age pattern of theÿPibanryeong and Poeun units is close to the young end of the Yeongnam Massif. The initiation of arc magmatism and the middle Paleozoic arc magmatism was suggested from the margin of the Yeongnam Massif (269–265 Ma; Oh et al., 2012a). This age is also close to the younger boundary of these rim overgrowths. Although the median values of the zircon rim ages are from the Pibanryeong unit (Kim et al., 2007). Adachi et al. (1996) reported that the zircon age pattern of the Pibanryeong area (265–230 Ma; Oh et al., 2006a) leaves the possibility that the crustal thickening event occurred in the Yeongnam Massif diachronously (i.e., in the late Permian and in the Middle-Late Triassic).

Regional structures in the metamorphic rocks of the Okcheon Belt are considered to have been governed by large-scale thrust faults. Cluzel et al. (1990) divided the metamorphosed southwestern part of the belt (Okcheon Metamorphic Belt [OMB]) into five thrust-bounded lithotectonic units: the structurally overlying units of Pibanryeong and Chungju and the lower ones of Tunungsan, Poeun, and Ihwaryeong. The isotopic imprint of metamorphism is relatively weak in the OMB, probably due to the moderate peak temperature conditions (490–630 °C; Cho and Kim, 2005). Adachi et al. (1996) reported an earlier Triassic chemical Th-U-total Pb isochron method (CHIME) age of 251 ± 10 Ma for allanite in muscovite-chlorite-quartz schist in the Tunungsan unit (traditionally referred to as the Munjunri Formation). On the other hand, early Permian ages (ca. 290–280 Ma) were obtained by whole-rock Pb isotopic and uraninite CHIME data of black slates in the Poeun unit (Cheong et al., 2003). The early Permian ages were later confirmed by U-Pb isotope data of acid step-leaching experiments conducted on pelitic and quartz-hornblende-garnet schists of the Pibanryeong unit (Kim et al., 2007). Allanite Th-Pb dating for REE ores distributed in the Chungju unit (traditionally referred to as the Kyemyeongsan Formation) revealed the presence of multiple age components in the Late Ordovician (445 ± 8 Ma), Permian to Triassic (ca. 300–220 Ma), and Early Jurassic (199–183 Ma) (Cheong et al., 2015c). The significance of the oldest age is not clear yet, but the latter two ages—albeit scattered—may broadly represent the timing of crustal thickening orogeny and subsequent paleo-Pacific plate subduction. Kim et al. (2013b) also reported a Permian metamorphic age (259.7 ± 3.3 Ma), based on SHRIMP U-Pb analyses of zircon rims from a Neoproterozoic volcanic rock in the Kyemyeongsan area. Cho et al. (2018) attributed the thrusting event between the Pibanryeong and Poeun units to the middle-late Permian (ca. 270–250 Ma) “Ochyon Orogeny.” They distinguished this event from the successive Middle-Late Triassic “Songrim Orogeny” related to the North and South China collision. Further geochronological, petrological, and structural studies are required to confirm this hypothesis.

The Paleozoic–Mesozoic metamorphism in central Korea is broadly synchronous with magmatic and thermal events that occurred in the Yeongnam Massif. The arc magmatism occurred extensively along the margin of the Yeongnam Massif in the earliest Triassic (ca. 250 Ma), as represented by the Yeongdeok adakite (Yi et al., 2012a), and sodic metagranitoids and orthogneisses in the adjacent area (Cheong et al., 2014; Song et al., 2015). The initiation of arc magmatism may be traced back to the middle Permian, considering the SHRIMP zircon ages (266–261 Ma) of diorite-granodiorite xenoliths found in the Yeongdeok pluton and Andong tonalitic gneisses (Yi et al., 2012b; Cheong et al., 2013, 2014). An even older, middle Paleozoic magmatism was suggested from the margin of the Yeongnam Massif on the basis of single age populations of detrital zircons (ca. 330–310 Ma, Kim et al., 2012; ca. 430–370 Ma, Cheong et al., 2015b) as typically displayed by zircons from arc-flanking basins (Cawood et al., 2012). It is noted that many detrital and inherited zircons from the Paleoproterozoic basement gneisses in the northeastern Yeongnam Massif and overlying Cambrian supracrustal rocks (the Myeonsan Formation) have experienced severe Pb loss events (Kim et al., 2013a, 2014). Some of them yielded a cluster of lower intercept U-Pb ages at ca. 380 Ma (Kim et al., 2014), suggesting a possible link between the Pb loss event and the middle Paleozoic arc magmatism. These zircon data collectively indicate that the margin of the Yeongnam Massif has been activated recurrently during the Paleozoic. Further studies are necessary to understand the linkage between the orogenic event and arc magmatism that occurred in the Paleozoic–Mesozoic.

In conclusion, as graphically summarized in Figure 8, the middle Permian to earliest Triassic (ca. 265–250 Ma) arc magmatism in the Yeongnam Massif is coeval with or slightly younger than the metamorphic events recorded in the Gyeonggi Massif and the Imjingang and Okcheon belts (ca. 285–250 Ma). This coincidence may suggest that internal orogenic event(s) transferred shortening to the margin of the Yeongnam Massif, although there remains uncertainty about what specific orogeny was primarily responsible for subduction initiation. The temporal correspondence between interior collisional and external accretionary orogenesis was well established by a previous study of Phanerozoic supercontinents (Cawood and Buchan, 2007).

Source Characterization by Zircon Data

The age pattern and isotopic signature of inherited zircons provide first-hand information regarding the magma source deep in the crust (Hawkesworth and Kemp, 2006; Roberts and Spencer, 2015). In this study, we found inherited zircon cores from five granitoid samples (Seosan and Namyang granites from the western Gyeonggi Massif, Yangpyeong monzonite from the central Gyeonggi Massif, and Hamyang granodiorite and Sangju granite from the Yeongnam Massif). Their age patterns are shown in Figure 9, together with those of the inherited zircon cores from the Jurassic granitoids in the Gyeonggi Massif and the Okcheon Belt (Jo et al., 2018). As shown in this figure, the age pattern of the zircon inheritance differs profoundly between the western Gyeonggi Massif and the Yeongnam Massif. The Neoproterozoic (0.83–0.65 Ga) component is predominant in the former with subordinate Paleoproterozoic (2.3–2.1 Ga) and Mesoproterozoic (1.4–1.1 Ga) populations. In contrast, the Orosirian (ca. 1.85 Ga) component is overwhelming in the latter, which is also the case for the Yangpyeong monzonite and Middle Jurassic (177–167 Ma) granitoids in the interior Gyeonggi Massif. Meanwhile, the Early Jurassic (194–184 Ma) granitoids in the central Okcheon Belt have a comparable inherited zircon age pattern with the Seosan and Namyang granites analyzed in this study. To summarize, whereas the ca. 1.85 Ga zircon inheritance is predominant in the interior Gyeonggi and Yeongnam massifs, the Neoproterozoic inheritance is prominent in the western Gyeonggi Massif and the Okcheon Belt. The former is typically observed in North China, in association with the collision between the eastern and western blocks (Zhao et al., 2002), while the latter is more popular in South China related to the assembly and breakup of the Rodinia supercontinent (Li et al., 2003).

The exotic feature of the protolith of the Early Jurassic granitoids was further highlighted by the significantly low δ18O values 4.9 to –0.9‰ of Cryogenian (ca. 750–700 Ma) zircon cores.
Neoproterozoic rocks and zircons from South China, especially from the northern margin of the Yangtze Block, commonly have $\delta^{18}$O values substantially lower than the normal mantle range ($5.3 \pm 0.3\%\epsilon$; Valley et al., 1998), possibly resulting from the high-temperature reaction of their source rocks with glacial water (Zheng et al., 2008, and references therein). Jo et al. (2018) therefore interpreted that the geochemical and oxygen isotopic contrasts of inherited zircon cores observed between the Early and Middle Jurassic granitoids resulted from selective contributions from South and North China-like terranes that had been juxtaposed infracrustally along the margin of the Gyeonggi Massif during the prior collisional orogeny.

The zircon $\epsilon_{Hf}(t)$ and $\delta^{18}$O values of the Triassic plutons are plotted against their corresponding crystallization ages in Figure 10. In this figure, O and Hf isotope data for the inherited zircon cores from the Jurassic granitoids (Jo et al., 2018) are also shown for reference. Although the Cryogenian oxygen isotopic feature was not observed in the Neoproterozoic zircon cores from the Triassic Seosan and Namyang granites ($\delta^{18}$O $= 8.4–6.9\%\epsilon$), zircon Hf isotopes reveal the fundamental difference in the evolutionary history of the crustal source between granitoid rocks in the western Gyeonggi Massif and the Okcheon Belt, and those in the interior Gyeonggi and Yeongnam massifs. As shown in Figure 10B, Neoproterozoic zircon cores in the former granitoid group have chondritic or positive $\epsilon_{Hf}(t)$ values. This range cannot be explained by the evolution of the North China crust, which has a zircon Hf model age typically between 3.4 and 2.7 Ga (Geng et al., 2012; Kim et al., 2014), but is most strongly correlated with $\epsilon_{Hf}(t)$ values of the Neoproterozoic (780–750 Ma) rocks in the northern and western margins of the Yangtze Block in South China (~11–2; Liu et al., 2009; Zheng et al., 2007). Jo et al. (2018) suggested that mixing between this Neoproterozoic component with near chondritic $\epsilon_{Hf}(t)$ ($t$ = Jurassic), and the Archean–Paleoproterozoic component with significantly negative $\epsilon_{Hf}(t)$ ($t$ = Jurassic) resulted in a diverse range of Hf isotopic compositions of the magmatic zircons in the Early Jurassic granitoids. In summary, the inherited zircon data of the Triassic and Jurassic granitoids collectively indicate that the infracrustal basements of the interior Gyeonggi and Yeongnam massifs and the marginal parts of the Gyeonggi Massif (the western Gyeonggi Massif and the Okcheon Belt) were composed of North China- and Yangtze-like terranes, respectively. The conspicuous lack of a ca. 1.85 Ga zircon inheritance in the Seosan and Namyang granites suggests that the basement crust beneath the western Gyeonggi Massif consisted of solely Yangtze-like rocks during the Late Triassic.

Oxygen and hafnium isotope data of synmaggmatic zircons from the Triassic plutons are shown in Figure 11. The data from uraniferous zircon domains in the Taean and Daegang granites were not considered here because the correlation between U contents and $\delta^{18}$O values indicates the post-crystallization interaction of metasomatized parts with hydrothermal fluids (see Gao et al., 2014). The significantly negative zircon $\epsilon_{Hf}(t)$ values of the Yangpyeong gabbro and the Odaesan mangerite (~18 to ~24) make it evident that the chemical fractionation of the lithospheric mantle beneath the interior Gyeonggi Massif occurred in the distant past. This antiquity is also evidenced by a substantially negative $\epsilon_{Hf}(t)$ (~26) value of monazite from the Hongcheon carbonatite (Kim et al., 2016). The exact mechanism and timing of this event are difficult to ascertain, but broad geochemical affinities of the gabbro and mangerite (Fig. 7B) and the Re-Os isotopic study of Lee and Walker (2006) imply that it occurred in the Paleoproterozoic time under an arc environment. Probably, the lithospheric mantle beneath the Nangrim Massif also formed in geologically ancient time, considering the significantly negative whole-rock $\epsilon_{Hf}(t)$ values of the Tokdal Complex (~14 to ~20; Peng et al., 2008). The metasomatized lithospheric mantle origin of the Yangpyeong gabbro and Odaesan mangerite is consistent with their zircon $\delta^{18}$O values (7.49–6.94‰) being far from the normal mantle range. The Neosarchean to Paleoproterozoic zircon inheritance and core-to-rim increase in $\delta^{18}$O observed from some synmagmatic zircons in the Yangpyeong monzonite suggest the interaction...
between the lithospheric mantle and basement crust, of which Hf isotopic coupling is indicated by comparable ε\text{Hf}(t) values of the zircon cores and rims.

As seen in Figure 11, the Gwangcheon monzonite and the Haemi syenite in the western Gyeonggi Massif have distinctly higher zircon ε\text{Hf}(t) (–11 to –16) and δ\text{18O} (8.5–7.6‰) values than those of mafic-intermediate rocks in Yangpyeong and Odaesan, suggesting the fundamental difference of mantle lithosphere between the two areas. Synmagmatic zircons from the granites in the western area (Seosan, Namyang, and Taean) have wide variations in ε\text{Hf}(t) (–6 to –21) and δ\text{18O} (9.8–7.0‰) values, encompassing the ranges of zircon values from the adjacent Gwangcheon monzonite and Haemi syenite. The Hf isotopic range of the source crust could be estimated using the inherited zircon data in the granites. For example, as could be assumed in Figure 10B, the age and Hf isotope data of the Neoproterozoic zircon cores yield moderately negative ε\text{Hf}(t = 230 Ma) values (–6.3 ± 2.2) for the Neoproterozoic component in the source crust if the average crustal 176Lu/177Hf ratio (0.0116; Rudnick and Gao, 2003) is employed. When the typical 176Lu/177Hf ratio of the mafic crust (0.024) is adopted, the ε\text{Hf}(t = 230 Ma) of the source crust increases to –1.7 ± 2.5. These values are comparable with the highest ε\text{Hf}(t) of synmagmatic zircon in the Seosan granite (–5.8). Much lower ε\text{Hf}(t = 230 Ma) values are calculated for the Mesoproterozoic (–8 to –17 or –1 to –8, depending on the assumed Lu/Hf ratio) and Paleoproterozoic (–32 to –38 or –16 to –21) components. This calculation shows that the Hf isotopic variation of synmagmatic zircons in the Seosan and Namyang granites is attributable to the contribution from diverse age components in the source crust. The correlation between ε\text{Hf}(t) and Lu/Hf observed in synmagmatic zircons from the Taean and Namyang granites suggests that the mixing of the crustal components was accompanied with magmatic differentiation (i.e., DePaolo, 1981).

The oxygen isotopic evolution of the source crust is more difficult to trace, because low- and high-temperature surface processes could modify the original value significantly (Valley, 2003; Bindeman, 2008; Jo et al., 2016). On the other hand, oxygen and hafnium isotope data of synmagmatic zircons from the older magnesian group in the Yeongnam Massif reflect the contribution of diverse mantle and crustal reservoirs under arc setting. The lithospheric mantle component could be best represented by zircons from the Andong pyroxenites that formed magmatically in a suprasubduction zone (Whattam et al., 2011). Their δ\text{18O} values
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Figure 10. Plots of zircon (A) δ¹⁸O and (B) ε₃⁶⁶⁶ versus crystallization ages for the Triassic and Jurassic plutons in the Korean Peninsula, using data from this study and Jo et al. (2018). Synmagmatic zircon data from the Triassic plutons are plotted in the enlarged inset figures. (A) The dashed lines indicate the δ¹⁸O range for the mantle zircon (5.3 ± 0.3‰; Valley et al., 1998). (B) The depleted mantle evolutionary path was extrapolated from the average modern-day values of ¹⁷⁶Hf/¹⁷⁷Hf = 0.28325 and ¹⁷⁶Lu/¹⁷⁷Hf = 0.0384 (Griffin et al., 2000). Also shown is the evolutionary path of “arc mantle” suggested by Dhuime et al. (2011) could be explained by the mixing of these three mantle and crustal components: the metasomatized lithospheric mantle as represented by the Andong pyroxenite (zircon δ¹⁸O = 7.1 ± 0.3‰, ε₃⁶⁶⁶ = 6.2 to –0.6), young arc crust as represented by the Yeongdeok adakite (zircon δ¹⁸O = 5.7 ± 0.3‰, ε₃⁶⁶⁶ > 10), and the Paleoproterozoic basement crust (δ¹⁸O > 7.7‰, ε₃⁶⁶⁶ < –10) contributing most intensively to the Hamyang granodiorite and the Sangju granite. The negative array of zircon ε₃⁶⁶⁶(t) and δ¹⁸O values from the older magnesian plutons (Fig. 11) could be explained by the mixing of these three mantle and crustal components: the metasomatized lithospheric mantle as represented by the Andong pyroxenite (zircon δ¹⁸O = 7.1 ± 0.3‰, ε₃⁶⁶⁶ = 6.2 to –0.6), young arc crust as represented by the Yeongdeok adakite (zircon δ¹⁸O = 5.7 ± 0.3‰, ε₃⁶⁶⁶ > 10), and the Paleoproterozoic basement crust (δ¹⁸O > 7.7‰, ε₃⁶⁶⁶ < –10) contributing most intensively to the Hamyang granodiorite and the Sangju granite. The addition of Precambrian basement rocks into the magma source of the Hamyang granodiorite was probably accompanied with magmatic differentiation, considering the correlation of synmagmatic zircons between ε₃⁶⁶⁶(t) and Lu/Hf.

Zircons from the younger ferroan plutons in the Yeongnam Massif have their own distinct O and Hf isotopic compositions. The low δ¹⁸O (~5.1‰) and highly positive ε₃⁶⁶⁶ (~8) of zircons from the Hapcheon syenite, higher range of δ¹⁸O (8.4–6.5‰) and lower but consistently positive ε₃⁶⁶⁶ (~3) of zircons from the Sanchoeg syenite, and intermediate δ¹⁸O (~5.2) and slightly positive or negative ε₃⁶⁶⁶ (~1.2 to ~5.2) of zircons from the Daegang alkali granite may reflect the dominance of asteospheritic mantle, lithospheric mantle, and lower crustal sources, respectively.
Triassic Tectonomagmatic Evolution

The geochronological, geochemical, and O-Hf isotopic data described above allow us to propose a tectonomagmatic model depicted schematically in Figure 12. This model starts with the generation of adakite and sodic magmas along the Yeongnam Massif at ca. 250 Ma.

The Yeongdeok adakite pluton is believed to have been produced under a hot subduction regime possibly triggered by ridge subduction (Yi et al., 2012a) (Fig. 12A). The subduction of the ridge and consequent development of a slab window may have facilitated partial melting of lower crustal rocks that produced the protolith magma of sodic metagranitoids in the adjacent Andong-Cheongsong area. Their REE pattern and zircon εHf(t) range (−0.3 ± 2.4) support this interpretation (Cheong et al., 2014). The subduction of the young and hot ridge likely increased the coupling between the subducting and overriding plates (i.e., Murphy et al., 1998). Under this advancing arc system, magmatism may have ceased or migrated inboard. Based on our new SHRIMP zircon results, after the emplacement of the Yeongdeok adakite at ca. 250 Ma, arc magmatism was temporarily shut off in the Yeongnam Massif until the intrusion of the Ma- cheon monzonite at 232 Ma. Interestingly, this reinitiation of magmatism was synchronous with the commencement of potassic and carbonatite magmatism (ca. 233 Ma) in and around the Gyeonggi Massif (Haemi, Namyang, Yangpyeong, Hongcheon, Yangyang, Odaeans, and Goesan; see Fig. 2 for locations) (Table 2). This correspondence may suggest that the Late Triassic magmatism along the Yeongnam Massif was related to the post-collisional event on the other side.

The Late Triassic plutons in and around the Gyeonggi Massif intruded in a relatively short time interval (<10 Ma). Mafic to intermediate silicate plutons among them are considerably enriched in K and Ba, and are predominantly metaluminous, alkalic to alkali-calcic, and magnesian (Figs. 6 and 7). This rock type, classified as “Caledonian type” (Pitcher 1983), “post-orogenic granitoids” (Mantiar and Piccoli 1989), “shoshonitic granitoids” (Duchesne et al., 1998), “K-feldspar porphyritic calc-alkaline granitoids” (Barbarin, 1999), or “appinite” suite (Murphy, 2013), is commonly associated with the post-collisional relaxation (Bonin et al., 1998). As shown in Figure 7A, they invariably display LREE-enriched normalized patterns without prominent Eu anomalies, indicating the presence of garnet or amphibole, but the absence of plagioclase feldspar in the source resi- due. The coeval occurrence of carbonatite and silica-undersaturated potassic and ultrapotassic rocks (Peng et al., 2008; Yang et al., 2010; Kim et al., 2016) manifests that mantle materials were extensively involved in the post-collisional magma. Detachment models to explain the asthenospheric upwelling and its impingement on the lithospheric mantle surface include the convective thinning and removal of the lithospheric mantle (Housman et al., 1981; Turner et al., 1992) and slab breakoff (Davies and von Blanckenburg, 1995). Of the two models, the slab breakoff may better explain the limited range in time and space for the occurrence of post-collisional plutons in central Korea, as previous works have suggested (Oh et al., 2006b; Seo et al., 2010). In this model, the breakoff of subducted oceanic slab results in upwelling of the hot asthenospheric through the breakage and consequent melting of the metasomatized part of the overriding lithospheric mantle which has relatively low solidus temperatures. As illustrated in Figure 12B, it is suggested that the slab breakoff not only triggered the generation of potassic/ultrapotassic magmas in and around the Gyeonggi Massif but also facilitated the reinitiation of magmatism in the Yeongnam Massif. It is notable that the Macheon monzonite is uniquely shoshonitic in the magnesian Yeongnam plutons (Fig. 6C). Calc-alkaline arc magma then intruded further inland in parts of the Yeongnam Massif and the Okcheon Belt at ca. 225 Ma (Sangju monzonite-granite and Cheongsan-Baegnom granodiorite; see Fig. 2 for locations).

The geochemical composition of the 222 Ma Andong ultramafic rocks is consistent with their formation in a suprasubduction zone (Whattam et al., 2011), possibly in response to the sinking of the cold, old, and dense oceanic lithosphere, which left a gap fed by melts flowing upwards from the asthenosphere shortly after the initiation of subduction (Stern and Bloomer, 1992). If this hinge rollback model is correct, the occurrence of the Andong ultramafic complex is indicative of the initiation of a new extension-dominated arc system. The narrow age range (220–217 Ma) and consistent geochemical peculiarities of the ferroan granitoids in the Yeongnam Massif and Okcheon Belt (Ian-Daegang alkali granites and Sancheong-Hapcheon syenites) suggest their common tectonic setting. Ferroan granitoids reflect a close affinity to dry, silica-undersaturated potassic and ultrapotassic rocks (Peng et al., 2008; Yang et al., 2010; Kim et al., 2016) manifests that mantle materials were extensively involved in the post-collisional magma. Detachment models to explain the asthenospheric upwelling and its impingement on the lithospheric mantle surface include the convective thinning and removal of the lithospheric mantle (Housman et al., 1981; Turner et al., 1992) and slab breakoff (Davies and von Blanckenburg, 1995). Of the two models, the slab breakoff may better explain the limited range in time and space for the occurrence of post-collisional plutons in central Korea, as previous works have suggested (Oh et al., 2006b; Seo et al., 2010). In this model, the breakoff of subducted oceanic slab results in upwelling of the hot asthenospheric through the breakage and consequent melting of the metasomatized part of the overriding lithospheric mantle which has relatively low solidus temperatures. As illustrated in Figure 12B, it is suggested that the slab breakoff not only triggered the generation of potassic/ultrapotassic magmas in and around the Gyeonggi Massif but also facilitated the reinitiation of magmatism in the Yeongnam Massif. It is notable that the Macheon monzonite is uniquely shoshonitic in the magnesian Yeongnam plutons (Fig. 6C). Calc-alkaline arc magma then intruded further inland in parts of the Yeongnam Massif and the Okcheon Belt at ca. 225 Ma (Sangju monzonite-granite and Cheongsan-Baegnom granodiorite; see Fig. 2 for locations).

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Figure 12.
Figure 12. Schematic cartoons summarizing the Triassic tectonomagmatic evolution of the Korean Peninsula, with oxygen and hafnium isotopic compositions of mantle and crustal reservoirs. (A) In this model, the Yeongdeok adakite (ca. 250 Ma) was produced by slab melting in association with the ridge subduction. The development of a slab window facilitated the formation of sodic magmas (i.e., the Andong-Cheongsong tonalite and trondhjemite) from the lower crust. (B) The subduction of the hot ridge increased the coupling between the subducting and overriding plates. Consequently, after the emplacement of the Yeongdeok adakite, the arc magmatism was shut off in the Yeongnam Massif until the intrusion of the Macheon monzonite at 232 Ma. This reinitiation of magmatism was synchronous with the commencement of post-collisional magmatism in and around the Gyeonggi and Yeongnam Massifs. During or after the continental collision, the subducted oceanic slab broke off and the asthenosphere upwelled through the breakage. The consequent melting of the lithospheric mantle produced potassic and shoshonitic magmas. Calc-alkaline arc magmas then intruded further inland in parts of the Yeongnam Massif and the Okcheon Belt. Three mantle and crustal sources are recognized for the older magnesian plutons in the Yeongnam Massif: metasomatized lithospheric mantle as represented by the Andong pyroxenite, young (probably Paleozoic) arc crust as represented by the Yeongdeok adakite, and Paleoproterozoic basement crust. The late Triassic post-collisional plutons in the interior Gyeonggi Massif and and the Taeon-Hongsong Complex (present-day western Gyeonggi Massif) formed by the selective melting of an ancient metasomatized lithospheric mantle and an allochthonous South China-like lithosphere, respectively. (C) At 222 Ma, the arc system switched to an extension-dominated environment, along with the formation of the Andong ultramafic complex. The ferroan plutons in the Yeongnam Massif formed in association with the eventual foundering of an eclogitized crustal base at 220–217 Ma. Zircon O-Hf isotopic data for the ferroan plutons reflect the contributions from asthenospheric mantle, lithospheric mantle, and mafic lower crust. The Gyeonggi and Yeongnam massifs may have shared an extensional environment in the late stage of Triassic tectonomagmatic evolution. GM–Gyeonggi Massif; THC–Taeon-Hongsong Complex; OMB–Okcheon Metamorphic Belt; YM–Yeongnam Massif; YDA–Yeongdeok adakite; ACT–Andong-Cheongsong tonalite and trondhjemite; MCM–Macheon monzoni; AUC–Andong ultramafic complex.

under eclogite facies. We postulate that the formation of the ferroan granitoids resulted from the eventual foundering of such an eclogitized crustal base at 220–217 Ma (Fig. 12C). Considering the limited occurrence of the ferroan granitoids, the size of the drips must have been quite small, which is the case in many areas suspected to have undergone recent delamination (Ducaea, 2011, and references therein). This presumed lithospheric delamination and consequent intrusion of the Daegang and Ian A-type granites were virtually coeval with the onset of an extensional arc system indicated by the occurrence of the Andong ultramafic complex, suggesting a close link between the two tectonic events. It is also notable that the emplacement of the Andong complex was only slightly younger than the development of the Gyeonggi Shear Zone (ca. 225 Ma; Kim et al., 2000) that may have resulted from a gravitational collapse of thickened crust. This temporal correspondence indicates that the Gyeonggi and Yeongnam massifs shared an extensional environment in the late stage of Triassic tectonomagmatic evolution.

CONCLUSIONS

This geochronological, geochemical, and O-Hf isotopic study of the Triassic plutons in central and southern Korea reached the following conclusions.

(1) The emplacement of ca. 265–250 Ma calc-alkaline granitoids in southeastern Korea is coeval with or slightly younger than the Barrovian metamorphism (ca. 285–250 Ma) recorded in the Neoproterozoic–Paleozoic fold-and-thrust belts in central Korea. This temporal correspondence suggests a close link between the collisional orogenesis and subduction initiation.

(2) The Late Triassic mangerite-monzonite-syenite-granodiorite-granite plutons emplaced in the Yeongnam Massif could be divided into two geochemically distinct age groups: the older (232–224 Ma) magnesian and alkalic-calcic to calc-alkaline group and the younger (220–217 Ma) ferroan and alkalic-calcic-calcic group, which were temporally intervened by a geochemically arc-like ultramafic complex (222 Ma). Zircon O-Hf isotopic data indicate that the former was generated by the mixing of the relatively young (most likely Paleozoic) metasomatized lithospheric mantle and arc crust and Paleoproterozoic crust, whereas the latter formed through the melting of asthenospheric/lithospheric mantle and lower crust.

(3) The inherited zircon age patterns indicate that the infracrustal basements of the interior Gyeonggi and Yeongnam massifs, and the western Gyeonggi Massif are composed of typically North China-like and allochthonous South China-like terranes, respectively.

(4) The Late Triassic K- and Ba-rich, metaluminous, alkalic to alkali-calcic, and magnesian plutons in the Gyeonggi Massif were derived from lithospheric mantle and basement crust. Zircon O-Hf data indicate ancient (most probably Paleoproterozoic) chemical fractionation of the lithospheric mantle beneath the interior Gyeonggi Massif. The fundamental difference of lithospheric mantle between the western and central-eastern Gyeonggi Massif is evidenced by contrasting Hf isotopic compositions of synmagmatic zircons from the mafic-intermediate plutons. The Late Triassic granites in the western Gyeonggi Massif were derived from the Yangtze-like basement crust composed of diverse age components with significantly different Hf isotopic compositions.

(5) Geochronological, geochemical, and O-Hf isotopic data collectively indicate that during the Triassic, the Korean Peninsula experienced complex tectonomagmatic events consisting of: (1) ridge subduction and generation of high-silica adakite and sodic granitoids along the margin of the Yeongnam Massif (ca. 250 Ma), (2) development of an advancing arc system and magmatic quiescence, (3) post-collisional slab breakoff and consequent potassic/ultrapotassic magmatism in and around the Gyeonggi Massif and shoshonitic magmatism in the Yeongnam Massif (ca. 230 Ma), (4) inland migration of arc magmatism until 224 Ma, and (5) tectonic switch to the extension-dominated arc system and delamination of an overthickened arc lithosphere that resulted in the formation of the ferroan plutons in the Yeongnam Massif (222–217 Ma).

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APPENDIX 1. ANALYTICAL METHODS

SHRIMP Zircon U-Pb Dating

The primary O₂ beam was focused into a ~25-μm-diameter spot at an accelerating voltage of 10 kV. The collector slit width was fixed at 100 μm, achieving a mass resolution of ~5000 at 1% peak height. FCI (1999 Ma; Paces and Miller, 1993) and SL13 (U = 238 ppm) standard zircons were used for Pb/U calibration and to determine U abundance, respectively.
Pb/U ratios were calibrated according to FC1 according to the power law relationship between Pb/U" and U/Th. U/Th ratios were estimated using a fractionation factor derived from the measured 237Th/233U vs. 206Pb/204Pb of the SL3 standard. The common Pb was removed by the 207Pb (for spots <1000 Ma) or 206Pb (for spots >1000 Ma) correction method (Williams, 1998) using the model of Stacey and Kramers (1979). Data processing was conducted using the SQUID 2.50 and Isoplot 3.75 programs (Ludwig, 2008, 2009). Weighted mean ages were calculated after excluding the outliers with the t-test and reported at the 95% confidence level. Spots with high U concentrations (>2000 ppm) were not considered in the age calculation (see White and Ireland, 2012).

Zircon Oxygen Isotope Analysis

The Gaussian focused Cs+ primary ion beam was accelerated at 10 kV, with an intensity of ~1.6 nA. The spot size was ~20 µm in diameter (10 µm beam + 10 µm raster). A normal incidence electron flood gun was used to compensate for sample charging. The magnetic field was stabilized using a nuclear magnetic resonance controller. Negative secondary ions were extracted with a ~10 kV potential. The field aperture was 6000 × 6000 µm². A 120 µm entrance slit, 40 eV energy slit, ~133 transfer magnification, and 500 µm exit slit provided a mass resolution of ~2300 at 1% peak height. Under these conditions, the count rate of 18O was typically ~1 × 10⁶ cps/nA. The 16O and 18O ions were detected simultaneously by two Faraday cups with 10⁴ and 10¹ µA resistors, respectively. Measured 18O/16O ratios were normalized to Vienna standard mean oceanic water (V-SMOW) (100.0020052, Baertschi, 1976) and presented as δ18O notation. The in-run precision was typically better than 0.2‰ (2 standard errors). The instrumental mass fractionation (IMF) was corrected based on the 91500 zircon isotope suggested by Valley (2003) (δ18O = 10.7 ± 0.03‰). The spot-to-spot reproducibility of 91500 zircon for a single analytical session ranged from 0.5‰ to 0.2‰ (1SD). The FC1 and Penglai zircons yielded average IMF-corrected δ18O values of 5.89 ± 0.21‰ (n = 42, 1SD) and 5.28 ± 0.26‰ (n = 47, 1SD), respectively. The running results for the Penglai zircon standard (see Table DR4) were consistent with the recommended value (5.31 ± 0.10‰; Li et al., 2010).

Zircon Lu-Yb-HF Isotope Analysis

Ten Faraday collectors were set to simultaneously detect the required isotopes: 177Yb, 176Yb, (176+178)Hf, 176Lu, 174Hf(Lu+Yb), 177Hf, 175Hf, 173Hf, and 172Hf. Data were acquired by ablating 50-µm-diameter laser spots. The instrument parameters were a 10 Hz repetition rate and an energy density of 6–8 J/cm². Helium (650 ppm H²O and 900 ppm O²) was used as carrier gases to obtain high Hf isotope intensities (Iizuka and Hirata, 2005). The interferences of 176Lu on 177Hf and 176Hf were corrected using a fractionation correction method (Willets et al., 2001) and the chondritic values suggested by Chu et al. (2002) and Iizuka and Hirata, 2005). The interferences of 176Hf on 177Hf were corrected using a fractionation correction method (Willets et al., 2001) and the chondritic values suggested by Chu et al. (2002) and Iizuka and Hirata, 2005). The interferences of 176Hf on 177Hf were corrected using a fractionation correction method (Willets et al., 2001) and the chondritic values suggested by Chu et al. (2002) and Iizuka and Hirata, 2005). The interferences of 176Hf on 177Hf were corrected using a fractionation correction method (Willets et al., 2001) and the chondritic values suggested by Chu et al. (2002) and Iizuka and Hirata, 2005). The interferences of 176Hf on 177Hf were corrected using a fractionation correction method (Willets et al., 2001) and the chondritic values suggested by Chu et al. (2002) and Iizuka and Hirata, 2005). The interferences of 176Hf on 177Hf were corrected using a fractionation correction method (Willets et al., 2001) and the chondritic values suggested by Chu et al. (2002) and Iizuka and Hirata, 2005). The interferences of 176Hf on 177Hf were corrected using a fractionation correction method (Willets et al., 2001) and the chondritic values suggested by Chu et al. 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