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Recognition of the Phanerozoic "Young Granite Gneiss" in the central Yeongnam Massif

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ABSTRACT: Up to now, all the high-grade gneisses of the Korean peninsula have been regarded as Precambrian basement rocks and presence of the Phanerozoic high-grade metamorphic rocks have remained unknown. However, such granite gneiss is discovered through this study from the central Yeongnam massif near Gimcheon. SHRIMP zircon U-Pb age determinations on the granite gneiss, having well-developed gneissic foliations and migmatitic textures, reveal concordant age of ca. 250 Ma indicating the Early Triassic emplacement of this pluton, which is in contradict to the previous belief that it is a Precambrian product. Even though the granite gneiss reveals well-developed gneissic foliations and some zircons show rather low Th/U ratios, the metamorphic age has not been determined successfully. However, the age of metamorphism can be constrained as middle Triassic considering the absence of any evidences of metamorphism from the nearby granitic plutons having emplacement ages of ca. 225 Ma. Early Triassic emplacement and subsequent Middle Triassic metamorphism of the granite gneiss from the Yeongnam massif bear a remarkable resemblance to the case of South China block. We suggest the possibility that Early to Middle Triassic metamorphism of the Korean peninsula might be products of the intracontinental collisional events not directly related with the Early Triassic continental collision event.

Key words: Yeongnam massif, granite gneiss, SHRIMP, Triassic, metamorphism, intracontinental collision

1. INTRODUCTION

The age span from the late Permian to early Triassic is the period when Asian continent was assembled from numerous continental fragments (e.g., Metcalfe, 1988, 2006; Chen et al., 1999; Li, 2006; Lin et al., 2008). During the processes of such amalgamation, individual continental blocks experienced various kinds of tectonic events, including syn- and post-tectonic magmatism, high-pressure (HP) and even ultrahigh pressure (UHP) metamorphism (e.g., Wang et al., 1989; Wang and Liou, 1991). Continental collision between the North and South China blocks is surely one of the events that have been attracted a lot of attention. Especially, the discovery of ultrahigh-pressure metamorphic rocks from the Sulu Belt, Eastern China (Zhang et al., 1990; Enami and Zang, 1990), brought debates about possibility of extension of the continental collision belt between North and South China blocks toward Korean peninsula (e.g., Yin and Nie, 1993; Liu, 1993; Ree et al., 1996; Oh, 2006; Oh et al., 2006b, 2006c; Zhai et al., 2007). The location of such collision boundary within the Korean peninsula has not been clearly resolved yet. Such a long-lasting debate, however, has yielded a considerable number of geochronology data of Korean peninsula and has necessitated looking into Korean geology in further detail, especially because some of them contradict the traditional views. The discoveries of the sedimentation during the great-hiatus period of long-held belief (Cho, 2007; Choi et al., 2008) and widespread Neoproterozoic events (e.g., Lee, K.-S. et al., 1998; Lee, S.R. et al., 2003; Kim et al., 2008; Oh et al., 2012) would be the most familiar examples.

Here we present another case dissimilar to the long-held belief. We conducted Sensitive High Resolution Ion Microprobe (SHRIMP) U-Pb zircon age determination on the Gimcheon granite gneiss which has been considered as a Precambrian intrusive body so far (e.g., Lee et al., 1992, 2001), but surprisingly it turns out that its actual emplacement occurred at ca. 250 Ma and also subsequent metamorphism occurred shortly after then, i.e., ca. 230 Ma. Such ages not only indicate the presence of magmatism near the boundary between Permian and Triassic in South Korea, but also provide evidence of high-grade regional metamorphism that matches approximately the period of continental collision between South and North China blocks. In this paper we report the results of SHRIMP U-Pb zircon age determination and reinterpret the previously reported geochemical data from this granite gneiss in the light of early Triassic magmatism rather than Precambrian intrusive along with their tectonic implications. All the ages quoted in this paper are results from SHRIMP U-Pb zircon determinations, except mentioned otherwise.

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2. GENERAL GEOLOGY

The studied area is located within the central Yeongnam massif where Precambrian high-grade gneisses and Mesozoic granitoids are the main rock types (Fig. 1). The orthogneiss and metasediments distributed here correspond mostly to the low-pressure facies series, with the amphibolite facies metamorphism in the series being predominant (Song, 1989; Song and Lee, 1989). These high-grade gneisses are known to be Paleoproterozoic (Park, 1996; Lee et al., 2002; Sagong et al., 2003) as those of northeastern and southwestern parts of the Yeongnam massif (e.g., Park et al., 2000, 2001; Sagong et al., 2003; Kim and Cho, 2003; Chang et al., 2003; Kim et al., 2012). The studied granite gneiss mass, exposed about 20–40 kilometers southward from the Gimcheon city, has also been considered as Precambrian basement rock before this study (Kim et al., 1989; Song, 1989; Song and Lee, 1989; Lee et al., 1992, 2001; Lee, H.-S. et al., 2002).

The studied Gimcheon granite gneisses are leucocratic and show a well-developed gneissic fabric and migmatitic structures such as vein and schollen type (Fig. 2). They are generally medium-grained and relatively homogeneous in grain size and lithology, although alkali feldspar porphyroblasts, often augenic in shape, are locally and sparsely developed (Figs. 2 and 3). They consist of quartz, plagioclase, alkali feldspar, and biotite with minor amount of zircon and opaque minerals. Garnets are rarely and locally present. Plagioclases mostly show rounded and elongate shape with smoothly curved grain boundary. Quartz have irregular curved boundary and are often present as subgrained aggregates showing undulatory extinction. Alkali feldspars are also anhedral, often include granular quartz and plagioclase grains and mostly show myrmeckitic intergrowth in the contact regions with plagioclase. Biotites with reddish brown color are aligned wrapping around plagioclase grains. Feldspar and quartz grains as well as biotite are preferredly oriented on the whole to

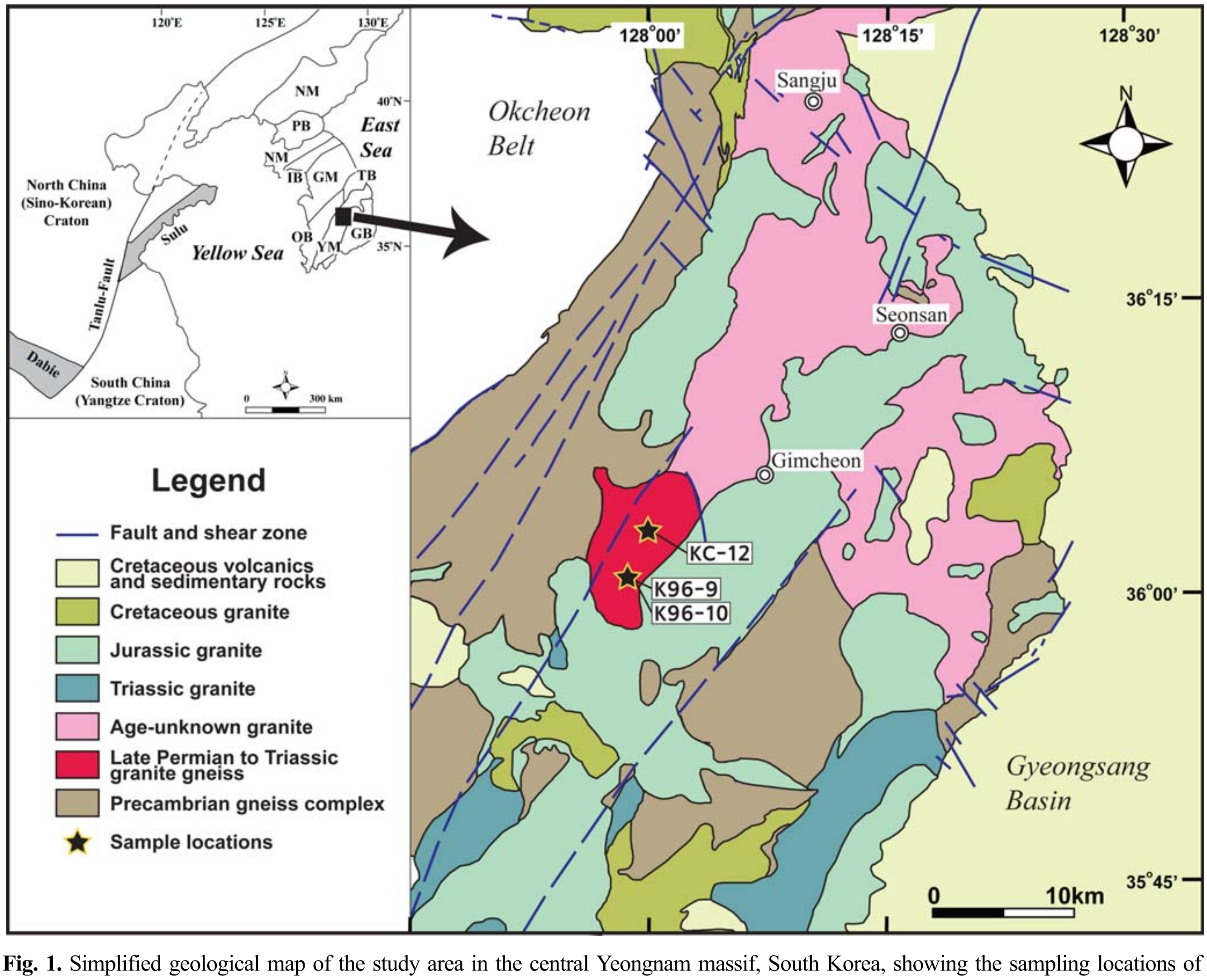

Fig. 1. Simplified geological map of the study area in the central Yeongnam massif, South Korea, showing the sampling locations of the analyzed samples (modified after Hwang et al., 1996). Insert shows simplified tectonic boundaries of the Korean peninsula and East China.

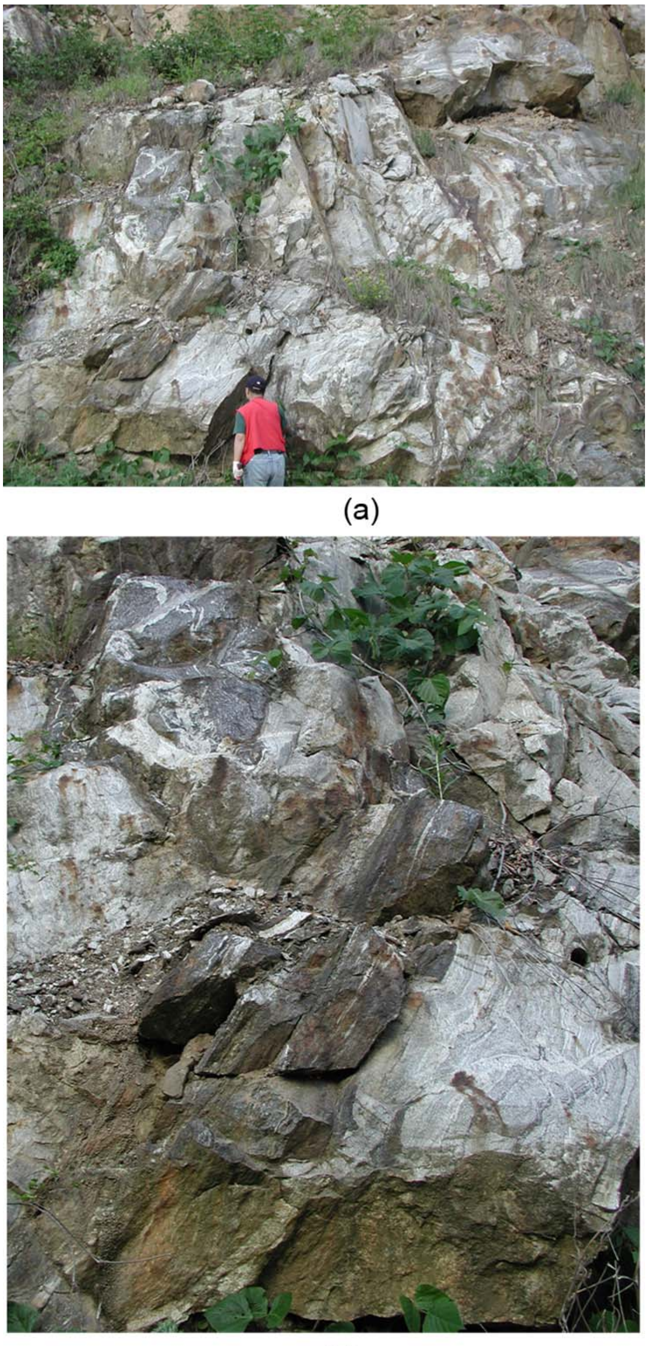

Fig. 2. (a) An outcrop photograph of studied foliated felsic granite gneiss. KC-12 was sampled from this outcrop. (b) Enlarged photograph showing the contact between the foliated granite gneiss and a mass of biotite gneiss captured in it.

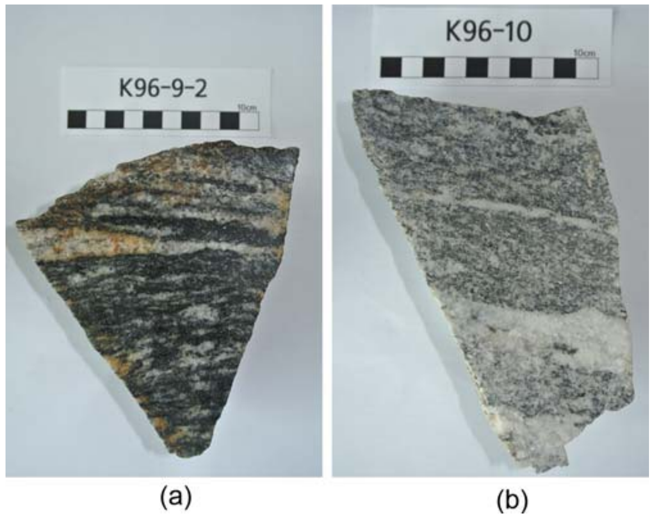

Fig. 3. Slap photographs of the (a) biotite gneiss K96-06 and (b) granite gneiss K96-10, showing well-developed gneissic foliations.

form distinct foliation (Figs. 3 and 4).

Biotite gneisses with the width of a few to tens of meters are often intercalated with the granite gneisses. In some places, the biotite gneiss shows characteristics of xenoliths. They show intensely foliated texture and generally mm-scale banded structure in which biotite-rich mafic layer alternates with quartzo-feldspathic layer. Mineralogy of the biotite gneisses is similar to that of the granite gneisses but that they have larger amount of mafic minerals and are dark grey in color. They consist of quartz, plagioclase, alkali feldspar, biotite and minor amount of zircon, apatite, opaque minerals, and small retrograde muscovite flakes with minor and variable amount of almandine garnet and/or hornblende. Hypersthene is rarely present and the presence of hypersthene, though rare, implies up to lower granulite-facies metamorphism.

Lee et al. (1992, 2001) reported major element compositions, rare earth element abundances and Nd, Ce isotopic systematics of the both gneisses. Lee et al. (1992, 2001) also reported Sm-Nd whole rock ages of these gneisses. Because of the rather poor linear alignments on Sm-Nd isotopic plot, the calculated ages have large errors; 818 ± 114 Ma for the biotite gneiss and 1484 ± 810 Ma for the granite gneiss (Lee et al., 2001). However, such a result of the biotite gneiss having younger age than the granite gneiss is not relevant to their occurrence as xenoliths within the granite gneiss. Another puzzling matter is the initial isotopic composition of Nd. If we apply the age reported by Lee et al. (1992, 2001), initial ε_{Nd} value of the granite gneiss is +7 (Lee et al., 2001) or +9.5 (Lee et al., 1992), which are extremely high values and very unlikely for the normal granitic rock in general.

The studied granite gneiss has been considered as a part of the Precambrian Yeongnam massif, because it has the appearance indistinguishable from the basement metamorphic rocks. Moreover, high-grade metamorphism is presumed, because the granite gneiss usually reveals well-developed gneissic foliation and magmatic injection textures in some places. Due to an essentially very simple mineral assemblage, however, the granite gneiss does not have distinct high-grade metamorphic minerals except rare occurrences of fine-grained garnet. Therefore, sometimes it is hard to distinguish the granite

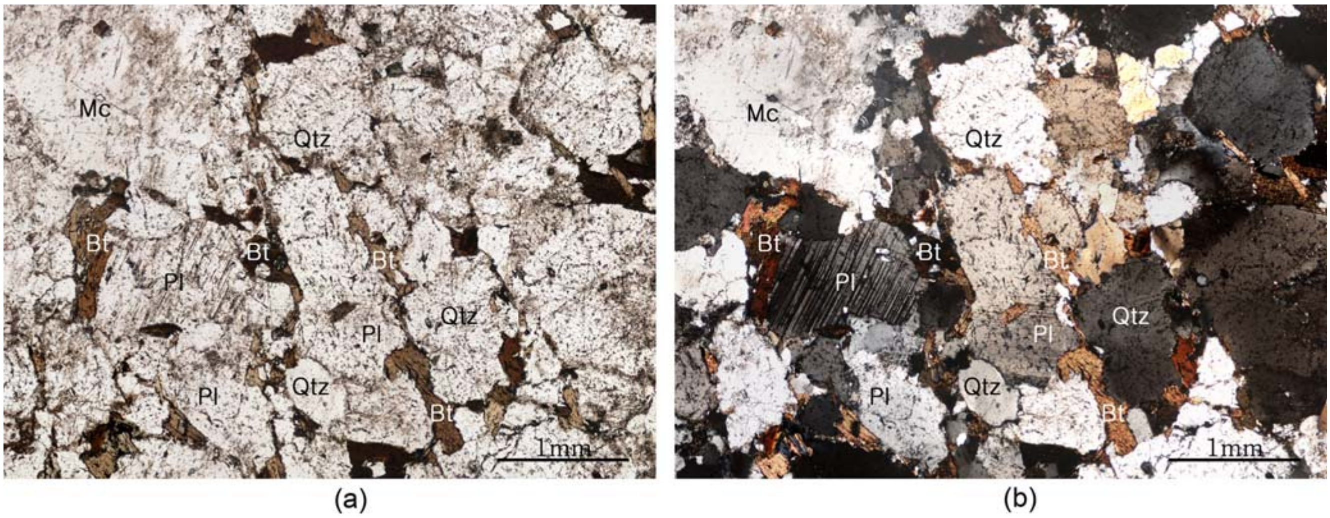

Fig. 4. Microphotographs of the thin section of the Gimcheon granite gneiss K96-10, (a) open and (b) crossed nicols. This granite gneiss is mainly composed of quartz, plagioclase, K-feldspar and biotite. Preferred alignment of biotite grains is apparent.

gneiss from non-metamorphosed granite in places where recrystallizational alignment is not well-developed. Nonetheless, well-developed gneissic foliation can be easily recognized from the granite gneiss of the area in general, which is distinct from the foliation produced by localized ductile shear commonly observed from the later granitoids of adjacent regions.

3. ANALYTICAL METHOD

Samples were collected from the Gimcheon granite gneiss in the central Yeongnam massif (Fig. 1). This granite gneiss, about 5 km in width and 10 km in length, borders with the Jurassic granite to the east, age-known granite to the north and the Precambrian basement gneiss complex of the Yeongnam massif to the west (Fig. 1). In this study, two granite gneisses (K96-10 and KC-12) and two biotite gneisses (K96-09 and KC-12B) were collected for the U-Pb zircon dating. The granitic gneisses show well-developed gneissic foliation formed by preferred alignment of biotite grains and are mainly composed of quartz, plagioclase, and K-feldspar (Figs. 3 and 4). The biotite gneiss samples are dark in color with evident gneissic foliation, mainly comprising biotite, quartz, plagioclase, and K-feldspar (Fig. 3).

Zircons were separated by panning and hand picking under a stereomicroscope. Zircon grains were mounted in an epoxy disk together with grains of Sri Lanka reference zircon CZ3 for U concentration and U-Pb age calibration. Conventional thermal ionization mass spectrometry (TIMS) U-Pb isotopic data on this CZ3 zircon standard gives a uranium concentration of approximately 550 ppm and a concordant age of 564 Ma (Pidgeon et al., 1994; De Laeter and Kennedy, 1998). The zircon grains were ground to be sectioned approximately in half and polished. Images were obtained by both optical microscopy and cathodoluminescence (CL) on a scanning electron microscope. The zircons were analyzed using SHRIMP II at the Tectonics Special Research Center, Curtin University of Technology under standard operating conditions and analytical procedures are outlined by De Laeter and Kennedy (1998) and Williams (1998). SHRIMP data were processed by using programs SQUID 2.50 (Ludwig, 2009) and ISOPLOT 3.75 (Ludwig, 2012). All the reported errors on age determination in this study are based on 95% confidence level except where mentioned otherwise.

4. RESULTS

Zircon grains of the granite gneisses (K96-10 and KC-12) are characterized predominantly by euhedral long- and short-prismatic morphology (Fig. 5). Zircon grains of the biotite gneisses (K96-09 and KC-12B), in contrast, typically display rounded prismatic shapes. The inherited cores of zircon grains are not uncommon in all the samples. Most of the zircon grains show oscillatory growth zoning in the CL images (Fig. 5). One granite gneiss (KC-12) and one biotite gneiss (K96-09) display well-developed overgrowth rims surrounding older oscillatory-zoned cores. Some zircons grains of one granite gneiss sample K96-10 also develop very thin outer overgrowth rims, usually less than 10 μm and we were not able to perform U-Pb spot analysis from this sample.

The U-Pb zircon analyses were performed at 38 analytical points on 29 grains. Results of the SHRIMP analyses are shown in Figure 6 and listed in Table 1, showing apparent U-Pb ages in the range from ca. 230 to 2270 Ma. Obviously analyzed samples display bimodal age distribution. While the granite gneisses show mainly Triassic to Permian U-Pb zircon spot ages, the biotite gneisses and inherited zircon cores of the granite gneisses show predominantly Paleoproterozoic ages.

The biotite gneiss K96-09 reveals concordia age of 1882

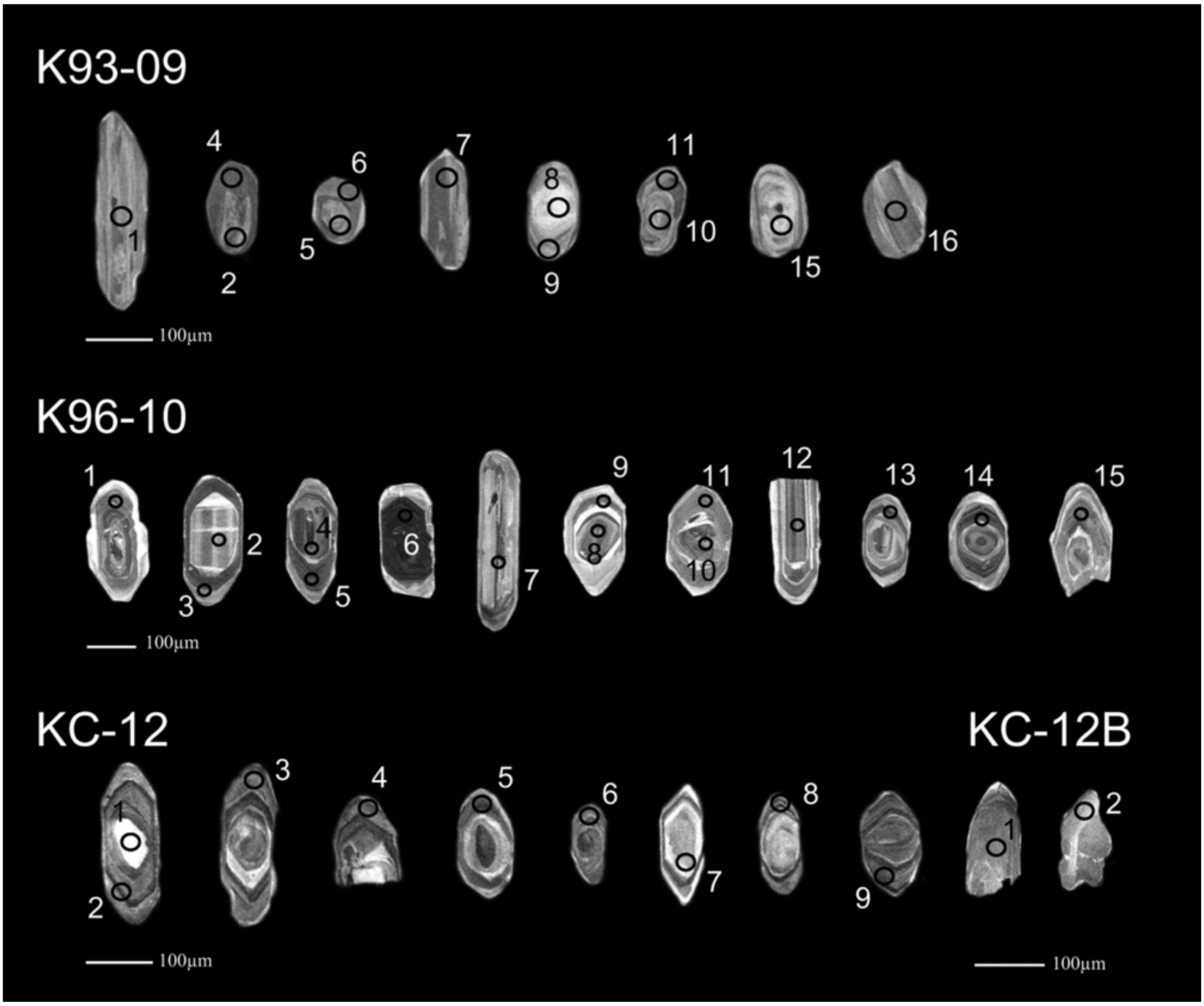

Fig. 5. Cathodoluminescence images of the analyzed zircons separated from the Gimcheon granite gneisses (K96-10, KC-12) and biotite gneiss xenoliths (K96-09, KC-12B) in it.

± 17 Ma and weighted mean $^{207}Pb/^{206}Pb$ age of 1876.8 ± 8.9 Ma. Two spot analyses from the biotite gneiss sample KC-12B also reveal slightly discordant $^{207}Pb/^{206}Pb$ ages of 1869 ± 11 Ma and 1836 ± 15 Ma (Fig. 6a, Table 1), similar to K96-09. Such Paleoproterozoic ages are quite different from the Sm-Nd age of 818 ± 114 Ma reported for the biotite gneisses of the area (Lee et al., 2001), but agree very well with ages of the basement rocks commonly found not only from Yeongnam massif but also from whole Korean peninsula including Gyeonggi and Nangnim massifs (e.g., Turek and Kim, 1996; Park et al., 2000; Song et al., 2001, 2009, 2011; Sagong et al., 2003; Cho et al., 2006; Oh et al., 2006a; Zhao et al., 2006; Kim, S.W. et al., 2008; Kim, N. et al., 2012). Such similarity in ages between the biotite gneiss and the basement rocks leads us to suggest that studied biotite gneisses seem to be xenoliths captured from the Precambrian basement of the Yeongnam massif during the emplacement of the protolith of Gimcheon granite gneiss.

Contrastingly, granite gneisses K96-10 and KC-12 reveal clustering of data points on concordia curve at ca. 250 Ma with several discordant points having Paleoproterozoic apparent $^{207}Pb/^{206}Pb$ ages (Figs. 6b and c). All of the analysis points yielding Paleoproterozoic ages are from the inherited cores, suggesting that the granite gneiss was derived by the partial melting of the Paleoproterozoic source such as, very likely, the basement rocks of the Yeongnam massif.

The granite gneiss sample K96-10 shows a cluster at ca. 250 Ma on a concordia diagram (Fig. 6c). However, apparent $^{238}U/^{206}Pb$ ages of K96-10 seem to be divided into two groups (Fig. 6d). Weighted mean $^{238}U/^{206}Pb$ age of 252.3 ± 5.0 (n = 7) Ma is calculated from the major group excluding two younger points and similar concordia age of 252.3 ± 2.9 Ma is obtained from the same group. We suggest this concordia age of 252.3 ± 2.9 Ma from K96-10 as the emplacement age of

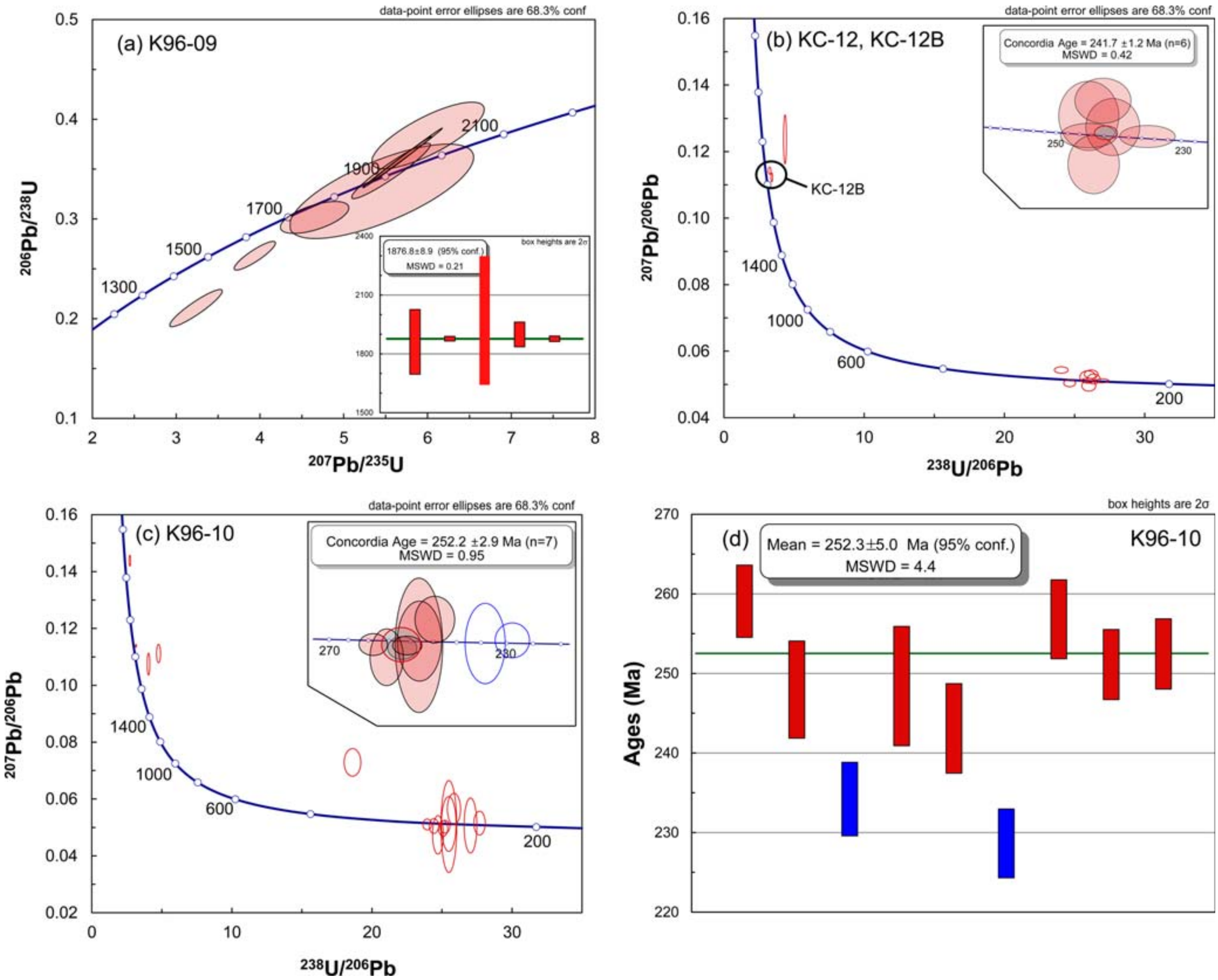

Fig. 6. Tera-Wasserburg concordia diagrams for the zircons from (a) biotite gneiss K96-09 with inset diagram of weighted average $^{207}Pb^*/^{206}Pb^*$ age, (b) granite gneiss KC-12, and (c) granite gneiss K96-10, and (d) weighted average $^{238}U/^{206}Pb$ age of K96-10. There are also inset diagrams for the concordia ages of KC-12 and K96-10 within (b) and (c) respectively. All the reported errors on age determination are based on 95% confidence level and uncertainties in the size of the symbols are 1σ.

the igneous protolith of the Gimcheon granite gneiss. Slightly younger concordia age of 231.3 ± 1.7 Ma is yielded by the minor group with two points. Obviously the two concordia ages do not overlap within their 2-sigma error ranges. Such a difference in age can be interpreted as a granitic magma emplacement at ca. 250 Ma and some Pb loss afterwards. However, we cannot rule out the possibility of later metamorphism at ca. 230 Ma.

The other granite gneiss KC-12 also shows a cluster with apparent $^{238}U/^{206}Pb$ ages between ca. 250 Ma and ca. 230 Ma on a concordia curve yielding a concordia age of 241.7 ± 1.2 (n = 6) Ma (Fig. 4b). Comparatively younger age of KC-12 than K96-01 needs to be explained and seems to have relevance to its relatively low Th/U ratios of the analyzed zircons (Table 1). It is a common practice to examine thorium/uranium ratios to distinguish metamorphic event from the magmatic one, because the former are usually much smaller than the latter (e.g., Rubatto et al., 2001; Williams, 2001). The usual reference value for such division is 0.1 (e.g., Chen et al., 2010), although it is not an absolute criterion. If we compare Th/U ratios of the zircons from the two analyzed granite gneiss samples, we can find quite contrast between them. Between the two, the older one K96-10, which is 252.2 ± 2.9 Ma, reveals rather high Th/U values compared to those of KC-12 with concordia age of 241.7 ± 1.2 Ma. K96-10 shows Th/U ratios in the range of 0.21–1.09 with an average of 0.40 ± 0.26, in contrast to KC-12 which shows the range of 0.04–0.68 with an average of 0.20 ± 0.21. More importantly, not only four out of eight zircon analyses from KC-12 reveal Th/U ratios equal or less than 0.10 that is the ratio commonly set for the differentiation of metamorphism from magmatism, but also CL images of such analysis points with low Th/U ratios show flat rims

Table 1. SHRIMP U-Pb zircon isotopic data for the Early Triassic Gimcheon granite gniess and Precambrian biotite gneiss from the central Yeongnam Massif, South Korea

Spot Name	ppm U	ppm Th	$^{232}Th/^{238}U$	ppm ^{206}Pb	$^{238}U/^{206}Pb^*$	% err	$^{207}Pb/^{206}Pb$	% err	Apparent ages (Ma)
K96-10: Medieum grained granite gneiss									
K96-10.1	750	154	0.21	26.68	24.41	0.90	0.0504	3.4	259.1 ± 2.3
K96-10.2	173	156	0.93	37.01	4.09	1.57	0.1074	2.4	1754.6 ± 43.4
K96-10.3	465	111	0.25	16.04	25.49	1.34	0.0512	12.4	248.0 ± 3.0
K96-10.4	965	1141	1.22	259.49	3.20	0.82	0.1138	0.3	1860.8 ± 5.7
K96-10.5	648	210	0.33	21.11	27.03	1.14	0.0507	12.6	234.3 ± 2.3
K96-10.6	2711	705	0.27	98.03	23.95	0.87	0.0510	2.5	263.8 ± 2.3
K96-10.7	201	212	1.09	7.15	25.48	1.44	0.0502	21.3	248.5 ± 3.7
K96-10.8	590	357	0.62	184.28	2.76	1.34	0.1437	0.8	2272.5 ± 14.5
K96-10.9	300	77	0.27	10.09	25.85	1.19	0.0564	6.5	243.1 ± 2.8
K9610.10	442	298	0.70	78.97	4.81	2.02	0.1110	1.9	1816.6 ± 34.5
K9610.11	757	264	0.36	23.93	27.66	0.96	0.0514	5.4	228.7 ± 2.2
K9610.12	550	165	0.31	19.63	24.73	1.04	0.0474	9.5	256.8 ± 2.5
K9610.13	708	199	0.29	24.34	25.20	0.90	0.0502	2.9	251.1 ± 2.2
K9610.14	197	71	0.37	9.13	18.63	2.14	0.0728	4.3	329.4 ± 7.0
K9610.15	918	564	0.63	31.75	25.09	0.89	0.0496	3.7	252.5 ± 2.2
KC-12: Medieum grained granite gneiss									
KC12.1	55	49	0.93	10.90	4.31	1.61	0.1238	4.0	2011.1 ± 70.9
KC12.2	27	4	0.14	0.90	26.93	1.22	0.0510	0.8	235.0 ± 2.8
KC12.3	7	1	0.10	0.20	25.88	1.37	0.0521	2.4	244.1 ± 3.3
KC12.4	4	0	0.04	0.10	26.31	1.21	0.0515	2.0	240.4 ± 2.9
KC12.5	71	18	0.26	2.40	25.87	1.28	0.0510	0.9	244.5 ± 3.1
KC12.6	7	0	0.06	0.30	24.58	1.17	0.0502	1.5	257.5 ± 3.0
KC12.7	19	13	0.68	0.60	26.13	1.27	0.0529	1.5	241.5 ± 3.0
KC12.8	44	10	0.24	1.60	24.00	1.26	0.0542	1.2	262.3 ± 3.3
KC12.9	8	1	0.08	0.30	25.96	1.17	0.0495	2.1	244.1 ± 2.8
KC-12B: Biotite gneiss									
KC-12B.1	788	366	0.48	18.0	3.21	1.5	0.1143	0.6	1868.9 ± 11.4
KC-12B.2	509	434	0.88	20.6	3.36	1.5	0.1123	0.8	1836.3 ± 14.5
K96-09: Biotite gneiss									
K96-09.1	582	25	0.05	150.7	3.32	3.5	0.1122	4.6	1835.3 ± 83.5
K96-09.2	994	76	0.08	224.5	3.81	3.6	0.1089	1.9	1781.0 ± 34.6
K96-09.4	605	27	0.05	109.4	4.76	5.8	0.1118	2.6	1829.7 ± 46.2
K96-09.5	217	326	1.55	62.3	2.99	4.9	0.1321	1.3	2126.3 ± 22.3
K96-09.6	352	116	0.34	115.9	2.61	5.8	0.1138	4.6	1860.5 ± 82.5
K96-09.7	569	647	1.17	178.3	2.74	4.8	0.1148	0.3	1876.4 ± 6.1
K96-09.8	38	26	0.71	10.9	3.05	9.6	0.1209	9.2	1969.5 ± 164.2
K96-09.9	368	42	0.12	116.8	2.71	6.1	0.1430	2.2	2263.3 ± 37.6
K96-09.10	363	138	0.39	58.1	5.37	5.2	0.1035	1.1	1687.0 ± 19.9
K96-09.11	471	35	0.08	140.8	2.87	5.3	0.1162	1.8	1898.5 ± 31.9
K96-09.15	155	77	0.51	47.7	2.80	5.1	0.1209	1.4	1970.3 ± 24.9
K96-09.16	365	192	0.54	111.8	2.80	4.8	0.1148	0.4	1876.3 ± 7.0

Errors are 1-sigma.
Common lead correction was applied ^{207}Pb-method for the ages younger than 1,000 Ma and ^{204}Pb-method for the ages older than 1,000 Ma.
Apparent ages were calculated based on $^{206}Pb/^{238}U$ ratios for the ages younger than 1,000 Ma and $^{207}Pb/^{206}Pb$ ratios for the ages older than 1,000 Ma.

indicating metamorphic overgrowth. Therefore, we suggest that apparently younger age and lower Th/U ratios of KC-12 reflect high-grade metamorphism that is also assumed by its gneissic texture. At this moment, however, it is hard to determine precise age of metamorphism, because there are only a few SHRIMP U-Pb analysis points which indicate such metamorphism and their ages are indistinguishable from the ages obtained from the igneous oscillatory zones. Therefore, we have to make an effort to find a lot more zircon overgrowth rims to constrain the timing of the metamorphism more precisely by SHRIMP U-Pb analysis. We will discuss about the timing of the metamorphism further later.

5. DISCUSSION

5.1. Late Permian to Early Triassic Magmatism of the Korean Peninsula

On the contrary to the traditional belief that all the high-grade metamorphic rocks of the Yeongnam massif are Precambrian, the discovery of early Triassic age for the granite gneiss in Korea is very significant in several respects. First of all, the granite gneiss studied here is surprisingly younger than previously thought. Until this study, the Gimcheon granite gneiss has been considered as a part of the Precambrian basement rocks composing the Yeongnam massif (Yun and Park, 1968; Park and Lee, 1969; Kim et al., 1989; Song, 1989; Song and Lee, 1989; Lee et al., 1992, 2001; Hwang et al., 1996). However, SHRIMP U-Pb zircon age determination of this study reveals that it is actually an early Triassic intrusive body.

The emplacement age around the Permian-Triassic boundary of the Gimcheon granite gneiss obtained in this study surely indicates that previous age determination by Sm-Nd system, yielded 1484 ± 810 Ma (Lee et al., 2001), is incorrect. Lee et al. (1992, 2001) also reported abnormally very high ε_{Nd}(t) value of +7 or +9.5 for the granite gneiss, requiring abnormally extreme fractionation process. If we apply our newly determined early Mesozoic age, such abnormally high ε_{Nd}(t) values are reduced into the range from –15 to –12. Such recalculated values are compatible to the Nd isotopic composition of the overall Triassic to Jurassic granitoids within Korean peninsula (e.g., Cheong and Chang, 1997; Kim, C.-B. et al., 2003; Kee et al., 2010), further supporting the validity and reliability of our new age determination.

The newly determined emplacement age of the Gimcheon granite gneiss is a little younger than the rare Permian granites (Lee et al., 2007; Yi et al., 2012; Cheong et al., 2013) but older than the widespread Triassic granitoids over the Korean peninsula (e.g., Ree et al., 2001; Sagong et al., 2005; Park et al., 2005, 2006; Cho et al., 2008; Williams et al., 2009; Seo et al., 2010; Kim, J. et al., 2011; Kim, S.W. et al., 2011; Kim, T. et al., 2011).

To characterize the tectonic setting of the central Yeongnam massif from Late Permian to Middle Triassic periods, it is necessary to review what happened in the Korean peninsula over the same period. Recently, numerous Triassic emplacements of granitic plutons have been reported throughout the Korean peninsula (Ree et al., 2001; Cheong et al., 2002; Sagong et al., 2005; Park et al., 2005, 2006; Wu et al., 2007; Cho et al., 2008; Peng et al., 2008; Choi et al., 2009; Williams et al., 2009; Seo et al., 2010; Kim et al., 2011; Cheong and Kim, 2012; Yi et al., 2012; Cheong et al., 2013). Usually they display crystallization ages from 250 Ma to 220 Ma. Unlike Triassic granitoids, only two Permian granitoids have been reported so far from the Korean peninsula. Lee et al. (2007) reported emplacement age of 273 ± 4 Ma for the granodiorite drill-core sample from the Heunghae-eup, north of Pohang. Yi et al. (2012) also determined Permian emplacement age of 257 ± 2 Ma from the Jangsari granite in southern Yeongdeok, about 20 km to the north from the Heunghae-eup. The Early Triassic Yeongdeok granite, emplaced at 248 ± 2 Ma (Yi et al., 2012), is located ca. 10 km to the north of the Permian Jangsanri granite. Newly reported age by Yi et al. (2012) agrees well with previously reported TIMS U-Pb zircon age of 252.2 ± 2.9 Ma (Kim et al., 2003) and TIMS U-Pb sphene age of 244.5 ± 2.3 Ma (Sagong et al., 2005) for this intrusion. These three Permian to Early Triassic plutons along the eastern coast of the Korean peninsula seem to have originated in the same tectonic environment, not only because these neighboring plutons show similar emplacement ages but also because the initial ε_{Nd} values of the Heunghae granite core and the Yeongdeok granodiorite are distinctly high similarly. Lee et al. (2007) reported positive initial ε_{Nd} value of 4.57 for the Heunghae granite core and Yi et al. (2012) reported similarly high values from 2.32 to 4.46 for the Yeongdeok granodiorite, implying significant addition of the depleted mantle derived materials to the generation of these granitoids. Such juvenile characteristics of the Yeongdeok granodiorite is also confirmed by significantly high Hf isotopic composition of the zircons (Cheong et al., 2013).

Wu et al. (2007) reported laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) U-Pb zircon ages for the granitic rocks from North Korea. Among the several Triassic granites, Buryong granodiorite of the Dumangang (Tumangang) massif displays the emplacement age of 246 ± 1 Ma. The northernmost Buryong granodiorite should have close genetic relationship with contemporary granitoids of northeastern China along the suture boundary with Siberia Craton to the north and may have been produced within the eastern extension of the Central Asian Orogenic Belt unlike the rest of the Korean peninsula. If we exclude the Buryong granodiorite, only a granodiorite core sample from the Heunghae-eup, the Jangsari granite and the Yeongdeok granodiorite have similar ages or older than the Gimcheon granite gneiss of this study. It is worth to mention that these Permian to Early Triassic granitic plutons are all located within the Yeongnam Massif, if we consider the basement of the Gyeongsang Basin as a part of the Yeongnam Massif. Even though the Middle to Late Triassic granitic plutons are known to be widely distributed over the Korean peninsula, Permian to Early Triassic granitoids have not been reported either from the Gyeonggi Massif or from the Okcheon Metamorphic Belt so far. Such a contrasting distribution of the granitic plutons of different emplacement ages suggests critical change in tectonic environment during this period.

5.2. Discovery of Middle Triassic (ca. 230 Ma) "Young Gneiss"

The significantly young emplacement U-Pb age of the Gimcheon granite gneiss is quite surprising itself, because it has been considered as a part of the Precambrian basement of the Yeongnam massif as mentioned above and also because such an early Triassic granitic emplacement has not been known from Korea until quite recently. However, its metamorphic nature is even more intriguing, because no regional metamorphic event, not only during the Phanerozoic but also since Paleoproterozoic ~1.9 Ga, has been reported from this area so far. In other words, it is the first discovery of the Phanerozoic high-grade metamorphic rock within the Yeongnam massif.

Even though many Mesozoic granitoids of Korean peninsula reveal local promotion of foliation due to pervasive development of ductile shear zones during the Jurassic, clear evidences of strong regional metamorphism have not been reported from them yet. However, the Gimcheon granite gneiss displays sufficient textural evidences for the regional metamorphism, such as well-developed gneissic foliations composed of felsic and mafic layers (Figs. 2 and 3). Clearly developed flat overgrowth rims of the zircon grains from KC-12, having low Th/U ratios, also provide supporting evidences for the metamorphism as discussed earlier. Even migmatitic textures are not uncommon, indicating significantly high temperature condition of the metamorphism. However, the simple mineral assemblage of the Gimcheon granite gneiss, as granitic rocks in general, and rather high stability of such minerals up to quite high temperature seems to make it hard to produce distinct new mineral assemblage during the metamorphism. Therefore, it is quite difficult to estimate the temperature and pressure conditions of the metamorphism quantitatively.

The timing of metamorphism has not been very precisely and unambiguously determined yet, because we have not been able to analyze sufficient number of U-Pb isotopic compositions from the metamorphic overgrowth rims of the zircon grains. Nevertheless, we can put a young side limit of such Triassic regional metamorphism from the ages of younger Triassic granite bodies neighboring the Gimcheon granite gneiss. For example, Sangju granite, Hamyang porphyritic granite and Cheongsan porphyritic granite were emplaced during the short interval of 220–225 Ma (Turek and Kim, 1995; Cho, D.-L. et al., 2001b; Ree et al., 2001; Kim, C.-B. et al., 2003; Lee et al., 2006; Park et al., 2006) and are located less than 10 km to the north, less than 50 km to the southwest, and also less than 50 km to the north respectively from the nearest edge of the Gimcheon granite gneiss. These granites, however, do not reveal any trace of regional metamorphism. Therefore, we can safely constrain the youngest estimate for the metamorphism of Gimcheon granite gneiss from the oldest emplacement ages of such non-metamorphosed granites. If we restrict the geochronology data determined by SHRIMP U-Pb zircon and TIMS U-Pb titanite analyses for the Cheongsan, Hamyang and Sangju granites, emplacement of these granites can be best constrained to be 225.1 ± 2.1 Ma (Cho, D.-L. et al., 2001b), 225.4 ± 4.1 Ma (Park et al., 2006) and 226.1 ± 2.9 Ma (Lee et al., 2006) respectively. Therefore, we can safely set a young side limit of the regional metamorphism of the central Yeongnam massif to be ca. 225 Ma. Such age constraint agrees well with the concordia age of 231.3 ± 1.7 Ma calculated from the two youngest data points of Gimcheon granite gneiss KC96-10, which seem to form a separate cluster from the main data cluster yielding an age of 252.3 ± 2.9 Ma. Therefore, ca. 230 Ma seems to be a reasonable estimate for the metamorphism of the Gimcheon granite gneiss. U-Pb concordia age of KC-12 itself, i.e., 241.7 ± 1.2 Ma, can be considered as the old side limit. Consequently, we can safely constrain the possible timing of the regional metamorphism of the "young gneiss" to be in the range from 240 to 230 Ma.

In any case, it is certain that the Gimcheon granite gneiss has experienced a high-grade regional metamorphism. Then why the Triassic regional metamorphism has not been discovered from the Mesozoic granites of the Korean peninsula so far? Because all the researchers have been unaware of the existence of the Phanerozoic granites older than such Triassic metamorphism, they naturally have regarded all the high-grade metamorphic rocks as Precambrian. Therefore, there is a possibility to discover still more Triassic metamorphic rocks throughout the Korean peninsula. The discovery of the Middle Triassic metamorphism within the Yeongnam massif bears important implications for the crustal evolution of the Korean peninsula. Therefore, it is necessary to study further to constrain the timing of such metamorphic event more precisely.

5.3. Lower Triassic Metamorphism of the Imjingang Belt and Northeastern Gyeonggi Massif

The emplacement age of the Gimcheon granite gneiss obtained by U-Pb age determination demonstrates that the Yeongnam massif was an active magmatic arc at ca. 250 Ma. Then, what was the tectonic environment of the rest of the Korean peninsula? Was it similar to the Yeongnam massif? Apparently there are many evidences that the Imjingang belt and the Gyeonggi massif were situated in tectonic environment quite different from the Yeongnam massif.

Cho, D.-L. et al. (2001a) obtained a timing of the peak metamorphism at 252.9 ± 1.9 Ma of the garnet-biotite paragneiss from Samgot Unit of the Imjingang belt, confirming previously suggested late Permian to early Triassic metamorphism of the Imjingang belt (Cho et al., 1995; Jeon and Kwon, 1999). Pressure-temperature (*P-T*) estimates from the amphibolites suggest a relatively high-pressure amphibolite-facies metamorphism (8–13 kbar and 630–790 °C). Very similar age of metamorphism was reported by Oh et al. (2006b) for the high-temperature spinel granulite and enclosing migmatitic gneiss of Inje area within northeastern Gyeonggi massif. They dated SHRIMP U-Pb ages from the metamorphic zircon overgrowths and obtained Permo-Triassic ages of 245 ± 10 and 248 ± 18 Ma for the spinel granulite and enclosing migmatitic gneiss respectively. Cho et al. (2007) also reported concurrent metamorphism from Gamaksan alkaline meta-granitoid (247 ± 14 Ma, CHIME zircon).

In summary, 245~253 Ma regional metamorphism is recognized from the Imjingang belt and its eastern extensional area within Gyeonggi massif. It is noteworthy that such regional metamorphism of the central Korean peninsula and the plutonic emplacement of the central Yeongnam massif, exemplified by the Gimcheon granite gneiss, occurred at the same period of time. It is not certain yet whether such metamorphism of the northeastern Gyeonggi massif and the Imjingan belt was a consequence of continental collision occurred within the Korean peninsula, as some workers have been suggested (e.g., Yin and Nie, 1993; Ree et al., 1996; Oh et al., 2006b, c), because there have been no conclusive evidences for the ultra-high pressure metamorphism so far. However, it is evident that quite different tectonic activities like granitic magma emplacement occurred within the Yeongnam massif several hundred kilometers away to the south.

5.4. Middle Triassic Metamorphism of the Gyeonggi Massif

In addition to the Lower Triassic metamorphism discussed earlier, there are several reports suggesting Middle Triassic metamorphism of the Gyeonggi massif. Oh et al. (2005) discovered the HP metamorphism of eclogite facies from the Honseong area, located at southwestern Gyeonggi massif. Kim et al. (2006) reported precise SHRIMP U-Pb zircon age (231.4 ± 3.3 Ma) for this Triassic HP eclogite facies metamorphism. Considering the precisions of the data, about 20 Ma difference between metamorphic events occurred in garnet granulite of Hongseng area and garnet-biotite paragneiss of Samgot Unit (252.9 ± 1.9 Ma; Cho, D.-L. et al., 2001a) is quite large and it would be more appropriate to consider them as separate events. Cho and Kim (2003) reported 236 ± 13 Ma lower intercept age for the granitic dyke from Pocheon area of western Gyeonggi massif, located close to the Imjingang belt. They interpreted this age as a consequence of regional metamorphism. Even though we cannot rule out the possibility that the granitic dyke from Pocheon area might be a product of the Lower Triassic anatexis during the high-grade metamorphism prevailed over the Imjingang belt and northern Gyeonggi massif considering the relatively large error of this age estimation, however, it seems to match the timing of the metamorphic event of the Hongseong area rather well.

There are several other reports of metamorphic ages of the Gyeonggi massif, which supports the Middle Triassic metamorphism. Yi and Cho (2009) investigated SHRIMP U-Pb geochronology of monazite from the Hwacheon granulite complex. Among their data there are two spot analyses of symplectic allanite around monazite yielding ^{238}U-^{206}Pb ages of 232 and 229 Ma, respectively. Yi and Cho (2009) raised a possibility that such Triassic U-Pb allanite ages could be linked to the 223 Ma recrystallization of monazite near the ductile shear zone (Yi et al., 2008). Yi and Cho (2009) also suggested multiple episodes of crystallization-dissolution−recrystallization based on the observation of various textures and ages of monazite. Kim et al. (2006) reported SHRIMP U-Pb sphene age of 224 ± 14 Ma for the nearby Chuncheon amphibolite and interpreted the age as metamorphism. Kim et al. (2009) reported that the allanite in Neoarchean tonalitic gneisses, Daeijak Island, displays two metamorphic age clusters one ca. 228 Ma and the other ca. 214 Ma. Such metamorphic ages reported from Hwacheon, Chuncheon and Daeijak Island of the northern and western Gyeonggi massif belong to Middle to Upper Triassic period. Despite relatively large errors of these age determinations in general, the possibility of concurrent or successive Middle Triassic metamorphism over the large area of the Gyeonggi massif is highly suggested.

Considering just ages, the elcogite facies metamorphic event of the Hongseong area and possibly high-grade metamorphic events of quite large area of the Gyeonggi massif occurred contemporaneously with high-grade metamorphism of the Gimcheon granite gneiss within the central Yeongnam massif. So, it will be worthwhile to obtain better geochrnological constraints for such metamorphic events to test the possibility of separate metamorphic event later than ~250 Ma metamorphism occurred in the Imjingang belt and its eastern extension.

5.5. Middle Triassic Magmatism of the Korean Peninsula

It is very interesting that there were widely scattered concurrent plutonic emplacements over the Korean peninsula during the very short interval during the Middle Triassic. Furthermore, they belong to rather different kinds of rock types compared with the rest of the Mesozoic granitic plutons of the Korean peninsula in general. Kim, T. et al. (2011) reported SHRIMP U-Pb zircon ages of 234.0 ± 1.2Ma and 231.0 ± 1.3 Ma for the mangerite and gabbro in the Odaesan area, eastern Gyeonggi massif, respectively. Such ages are consistent with another SHRIMP age determination for the mangerite yielding 231.9 ± 1.1 Ma (Yi et al., 2009) and independent TIMS single zircon age determination of 228.7 ± 0.9 (Jeong et al., 2008).

Williams et al. (2009) determined a $^{206}Pb/^{238}U$ age of 231.1 ± 2.8 Ma from the Yangpyeong hornblende gabbro in central Gyeonggi massif. Very similar ages also can be found from the southwestern Gyeonggi massif. Seo et al. (2010) reported SHRIMP U-Pb age of 232 ± 3 Ma for the Gwangcheon intrusive orthopyroxene-bearing monzonite (mangerite) and 230 ± 3 Ma for a syenite enclave within the Haemi biotite granite that also has indistinguishable age of 233 ± 2 Ma (Choi et al., 2009). In addition to these plutonic rocks of the Gyeonggi massif, Macheon gabbro in the south-central Yeongnam massif also reveals quite similar age (Seo and Song, 2010).

The suggested tectonic environments of these seemingly concurrent plutons are quite dissimilar. Mangerite is essentially a hypersthene-bearing monzonite and requires quite high temperature for its generation, which can be generally provided during the within-plate extension and/or underplating of mantle-derived high-temperature magma. Oh et al. (2006c) explained that the Odaesan mangerite was produced by partial melting of a basaltic source at temperatures higher than 1025 °C, agreeing that quite higher temperature was needed than normal arc-type granite generation. However, Oh et al. (2006c) claimed that the Odaesan mangerites differ from mangerites formed in a typical within-plate tectonic setting in their high Mg# and Sr concentrations and negative Nb and Ta anomalies and suggested that their LILE enrichment and negative Ti-Nb-Ta anomalies are probably inherited from a pre-collision subduction event.

Seo et al. (2010) explained that the mangerite-syenite intrusion and the syenite enclaves of the Gwangcheon area are post-collisional igneous rocks formed by the partial melting of an enriched lithospheric mantle and claimed that the heat for the melting was derived from asthenospheric upwelling following oceanic slab break-off. Meanwhile, Choi et al. (2009) suggested that the Haemi high Ba-Sr granite formed in a post-collisional tectonic environment and that a Mesozoic post-collisional lithospheric delamination model can account for the genesis of high Ba-Sr granite in the Haemi area. Williams et al. (2009) suggested that the Yangpyeong hornblende gabbro formed during periods of relaxation that separated the culminations of post-orogenic uplift/collapse in the transitions from orogenic to anorogenic events after the Early-Middle Triassic continent-continent collision between the North and South China blocks in South Korea. In spite of such diverse suggestions, indisputable mechanism for the generation of these contemporaneous Middle Triassic igneous bodies is yet to be confirmed.

Currently available geochronological data cannot distinguish between Middle Triassic metamorphism and magmatism of the Korean peninsula. Both events have been recognized from quite wide area over the Korean peninsula. How such high-pressure metamorphism of the southwestern Gyeonggi massif and Imjingang belt, ultra-high temperature metamorphism of the northeastern Gyeonggi massif, high-grade metamorphism of the Yeongnam massif, and widely scattered emplacements of rather high-temeperature plutons can occur within very short time interval, if not simultaneously? Providing a definite solution to this question is out of the scope of this paper. We just intend to raise a question for further investigations about this important matter related with the crustal evolution of the Korean peninsula.

5.6. Remarkably Similar Late Permian to Triassic Magmatism and Metamorphism of South China

Widespread magmatism during the period from the Late Permian to Middle Triassic is well known within South China (e.g., Wang et al., 2001, 2006, 2007a; Li et al., 2006; Li and Li, 2007). Li et al. (2006) suggested that the Indosinian Orogeny of South China was likely contemporaneous with the onset of continental arc magmatism, initiated at 267–262 Ma. Their age estimation was based on SHRIMP U-Pb zircon ages of typical calc-alkaline I-type granites from Hainan Island formed in continental arc environments, which coincide with a sudden change in sedimentary environments in South China during the Permian time. Wang, Q. et al. (2005) interpreted the small 254–242 Ma alkaline syenite plutons in western Fujian as having been emplaced in a backarc transtentional regime related to oblique subduction of the Pacific plate underneath South China. Recently, Li and Li (2007) also reported the presence of 249–217 Ma high-K calc-alkaline I-type granites in the inland area as well and summarized that the ages of thrusting, metamorphism, and synorogenic magmatism all show a similar trend of younging toward the cratonic interior. Li and Li (2007) suggested that the distance between the orogenic front and an inferred trench increased from ~500 km to ~1,200 km within the 250–200 Ma interval based on their flat-slab-subduction model.

There are also reports on the Triassic metamorphism of the South China. Wang et al. (2001) reported 226–259 Ma tectonothermal events on the granitic gneisses of the Wugongshan massif in southeast China and interpreted that such dynamic event was related with intracontinental deformation and magmatic activity linked to Indosinian collision between South China and the North China blocks during Triassic time. Wang et al. (2007b) summarized that high-grade metamorphism in the South China block occurred during 246–252 Ma based on published SHRIMP zircon U-Pb data (Chen et al., 1998; Peng et al., 2004). For example, Peng et al. (2004) dated zircons from granulite xenoliths hosted by charnokite intrusion in the Shiwan Mountains (southeastern Guangxi) and suggested that magmatic crystallization age of the rim at ca. 248 Ma of the A-type charnokite, formed in the fast lift and exhumation partial melting in post-collision orogenic environment, marks the end of Indosinian orogeny. On the other hand, Wang et al. (2007b) also obtained a weighted mean $^{206}Pb/^{238}U$ age of 236.0 ± 3.1 Ma from the zircon of gneissic rocks in the Yunkai massif of South China Block and interpreted it as the metamorphic resetting age during the Indosinian tectonic event. According to them, most of the metaigneous rocks are actually the Caledonian anatectic granites possibly overprinted by Indosinian (~236 Ma) reactivation. Wang, Y. et al. (2005) constrained the timing of the major deformation event to the middle Triassic to early Jurassic (244–195 Ma) on the basis of $^{40}Ar/^{39}Ar$ geochronology and other geological observations for the Xuefengshan tectonic belt of the South China Block and suggested that the Xuefengshan belt may represent part of a huge structural fan between the Yangtze and Cathaysian blocks and can be interpreted as a product of the Indosinian intracontinental collision involving a weak zone.

In summary, there are many reports of both plutonic emplacement and regional metamorphism over a period from the late Permian to middle Triassic. Especially the timings of the metamorphism occurred within the South China block are quite similar to those of the Korean peninsula but somewhat earlier than the Dabie-Sulu continental collision belt, because UHP metamorphism of the Dabie-Sulu collision belt occurred at ca. 225 Ma (e.g., Liu et al., 2004. 2005; Zheng et al., 2006). In other words, there were metamorphic events within the South China block during the late Permian to middle Triassic prior to the well-known Triassic continental collision with the North China block.

6. CONCLUSION

We report the presence of "Young granite gneiss" that has been mistakenly regarded as a part of the Precambrian metamorphic basement. SHRIMP U-Pb zircon age investigation of the Gimcheon granite gneiss reveals an emplacement near the boundary Permian-Triassic boundary and following middle Triassic regional metamorphism, which requires reconsideration of some traditional perspectives. The discovery of Phanerozoic "Young" gneiss raises the possibility that there might be more middle Triassic high-grade metamorphic rocks around 230 Ma within the Youngnam massif.

It is also interesting that the Permian-Triassic boundary emplacement age of the Gimcheon granite gneiss is very similar to the ages of metamorphism for the Imjinagang belt and also northeastern Gyeonggi massif including Odaesan area. Similar ages of metamorphism also have been reported within the South China block. Obviously such ages predate the continental collision between North and South China blocks along the Dabie-Sulu belt. So far many workers have considered the late Pemian to early Triassic metamorphism of the Imjingang belt or northeastern Gyeoggi massif as possible indications of a continental collision event within the Korean peninsula. However, the occurrences of concurrent metamorphism within both the Korean peninsula and South China block prior to the Chinese continental collision event may not be fortuitous and it is necessary to evaluate the possibility of regional metamorphic events independent from the collisional events.

There are widely scattered middle Triassic metamorphic rocks throughout the Korean peninsula and also within the South China block. Among those, eclogite facies metamorphism of the Hongseong area was suggested as an evidence of the continental collision within the Korean peninsula. However, there is no evidence of ultra-high pressure metamorphism, such as diamond or coesite. There is a possibility that it may not be related with the continental collision event. It would be worthwhile to examine the possibility that lower to middle Triassic metamorphism of the Korean peninsula might be products of the intracontinental collisional events as suggested for the Xuefengshan tectonic belt of the South China Block (Wang, Y. et al., 2005).

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