U-Pb zircon ages of Mesozoic plutons in the Damyang-Geochang area, Ryongnam massif, Korea

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The Damyang-Geochang area in the southwestern part of the Ryongnam massif, Korea, is composed of Precambrian gneisses that have been intruded by Triassic to Jurassic, felsic to mafic, batholiths and stocks. Since the Triassic this area has been affected by four orogenies. Eight K-Ar, Ar-Ar, and Rb-Sr ages have previously been reported for some of the rocks in the area, and the ages range from 159 to 228 Ma.

This study reports the first U-Pb zircon ages for the Korean peninsula. In the Damyang-Geochang area, Mesozoic plutonism appears to span the period from 219 Ma to 176 Ma. The first period of Mesozoic plutonism resulted in the emplacement of the (unnamed) foliated granite, the foliated gabbro, and the Daegang foliated granite, at 219–212 Ma. The second plutonic event occurred at 187–183 Ma, in which a foliated granodiorite and the Sunchang foliated granite were emplaced. In the third plutonic event the Namweon granitic batholith and an associated diorite stock, both non-foliated and post-tectonic, were emplaced at 177–176 Ma. Concordia plots indicate derivation of these plutonic rocks from a Precambrian protolith, 1.9–2.6 Ga in age. Pb isotopic compositions measured on feldspars have an upper crustal signature. A porphyroblastic gneiss from the Precambrian basement yields a zircon age of 1935 Ma.

GEOLOGICAL BACKGROUND

The Korean peninsula is situated between the North China platform and the Japanese volcanic arc, and sits on the northeast Asian plate which borders the active Pacific plate. The rocks of the Korean peninsula are Archean to Holocene and have been involved in several orogenies, from Precambrian to Cenozoic. These orogenies involved tectonic movement, metamorphism and igneous intrusion, and produced distinct geologic terrains. In south Korea there are five such structural provinces: Kyonggi massif, Ryongnam massif, Okchon fold belt, Kyongsang basin and Pohang basin (Fig. 1). The major tectonic periods of the Phanerozoic that affected the Korean peninsula are: 1) the Great Hiatus (Ordovician-Carboniferous), 2) the Songnim Disturbance (Triassic), 3) the Daebo Orogeny (Jurassic), 4) the Bulguksa Disturbance (Cretaceous), and 5) the Yonil Dis-

turbance (Tertiary-Quaternary). Most of the Mesozoic plutonic rocks of the Korean peninsula were emplaced during the Jurassic and Cretaceous orogenies and are commonly referred to as the Daebo granites and the Bulguksa granites, respectively.

The Damyang-Geochang area (Fig. 2) is in the southwest part of the Ryongnam massif which is comprised of an undivided Precambrian Gneiss Complex, metasedimentary rocks of unknown age, foliated gabbro, foliated granites, and the non-foliated Namweon granite and diorite. The regional foliation trends northeast-southwest, which is the same as in the Okchon fold belt zone (Kim and Kim, 1984; Hong and Lee, 1989; Kim *et al.*, 1991).

The Precambrian Gneiss Complex is a mixture of metasedimentary and metaigneous rocks. The metasedimentary series is made up of metapelite, banded gneiss, granitic gneiss, and crystalline

Fig. 1. Structural provinces of the Korean peninsula.

schist. The granitic gneisses include granoblastite, migmatitic gneiss, and porphyroblastic gneiss. These granitic gneisses can be further distinguished by the amount of granitic component introduced during the granitization and migmatization process (Lee, 1973, 1980). The metaigneous series includes a mafic plutonic complex, metagabbro, metadiorite, metaanorthosite, and felsic plutonic rocks that are now orthogneisses. The orthogneisses recognized are: hornblende gneiss, leucocratic biotite gneiss, and leucocratic granitic gneiss. There is, however, some controversy and lack of agreement on the para- and ortho-gneiss designation.

The Precambrian Gneiss Complex is intruded by Mesozoic mafic to felsic plutonic rocks. A mafic complex that intrudes the gneisses (Fig. 2) is composed of anorthosite, foliated gabbro, and diorite. The dominant rock is the foliated gabbro and it is medium- to coarse-grained, occasionally pegmatitic, with large euhedral hornblende and pyroxene crystals. The foliation conforms to the regional trend.

The foliated granites of the southwest

Ryongnam massif form a batholith, about 250 km long and 1 to 20 km wide, subparallel to the Okchon fold belt. The batholith is intrusive into the Precambrian Gneiss Complex along its west margin (Fig. 2) whereas the western contact of the batholith is covered by Cretaceous volcanic rocks which places a minimum age on this body. There are several varieties of the foliated granites identified. The more important ones are the Daegang foliated granite and granodiorite, Sunchang foliated granite and undivided foliated granitoids, and a two-mica foliated granite (Fig. 2). Major element chemical data show that the Sunchang, undivided, and two-mica foliated granites belong to the calc-alkalic series, whereas the Daegang foliated granite shows tholeiitic affinities. Trace elements, REE, and $(La/Lu)_{CN}$, Eu/Sm ratios for the above felsic plutonic rocks are, according to Kim and Kim (1988, 1990), Kim (1990), and Kim *et al.* (1990), characteristic of plutonism in a continental margin and volcanic arc setting. The foliation is attributed by Hong and Lee (1989) and Kim and Kim (1990) to ductile deformation at depth related to a dextral strike-

Fig. 2. Generalized geology of the Damyang-Geochang area, Korea, showing location of samples.

Table 1. Published and reported isotopic ages of plutonic rocks in the Damyang-Geochang area

Rock name	Area	Age* (Ma)	Initial ratio	Geologic period	Reference
Foliated granite	Vicinity of Hamyang	Ar-Ar Mu 179.2 ± 0.5		Jurassic	Kim (1986)
Daegang foliated granite	Southwestern part of Namwon	Rb-Sr WR 228 ± 5 0.7158 ± 0.001		Triassic	Choo and Kim (1986)
Foliated granodiorite	Western Jangsoo	K-Ar Hb 198 ± 9.9		Jurassic	Kim and Lee (1988)
Sunchang foliated granite	Vicinity of Osu	K-Ar Bt 159		Jurassic	Kim (1971)
Sunchang foliated granite	Northeastern part of Damyang	Rb-Sr WR 222 ± 5 0.7163 ± 0.0002		Triassic	Choo and Kim (1986)
Namwon granite	Western part of Namwon	K-Ar Hb 203 ± 10		Jurassic	Kim and Lee (1988)
Namwon granite	Western part of Namwon	Rb-Sr WR 211 ± 3 0.7186 ± 0.0004		Triassic	Choo and Kim (1986)
Diorite	Vicinity of Geochang	K-Ar Hb 179 ± 9		Jurassic	Kim <i>et al.</i> (1989)
Gneiss	Jirisan Gneiss Complex	Rb-Sr WR 2070 ± 70 0.7102 ± 0.0008 Rb-Sr WR 1950 ± 40 0.7100 ± 0.0010		Precambrian	Choo and Kim (1986)

*WR - Whole rock; Hb - Hornblende; Bt - Biotite; Mu - Muscovite.

Table 2. Analytical data for zircons from the Damyang-Geochang area, Korea

Sample detail ¹⁾			Concentration (ppm)			Atomic ratios				
Sample No.	Magnetism	Average grain size (µm)	Weight (mg)	U	Pb	²⁰⁴ Pb/ ²⁰⁶ Pb ⁽²⁾	²⁰⁸ Pb/ ²⁰⁶ Pb ⁽³⁾	²⁰⁷ Pb/ ²⁰⁶ Pb ⁽³⁾	²⁰⁷ Pb/ ²³⁵ U ⁽⁴⁾	²⁰⁶ Pb/ ²³⁸ U ⁽⁴⁾
Foliated granite (KH-4)										
A	m0, Hp	114	0.5	696	31.1	0.00305	0.20233	0.03955	0.3259	0.0387
B	m1, Hp, Op	114	1.1	1031	43.4	0.00064	0.10882	0.06818	0.3631	0.0413
C	m0, Ab	62	3.1	759	30.2	0.00062	0.16519	0.06423	0.2971	0.0373
D	m0	<48	0.7	662	25.7	0.00156	0.19575	0.06228	0.2579	0.0354
Foliated gabbro (KH-2)										
A	m0-m3, Hp	>70	2.3	286	13.6	0.00115	0.37910	0.10450	0.4575	0.0375
B	m0-m3, Hp	>70	1.6	249	12.1	0.00338	0.35130	0.14430	0.5483	0.0358
C	m0	62	1.3	350	15.0	0.00313	0.32626	0.08971	0.2638	0.0337
D	m0, Ab	114	4.4	259	11.5	0.00188	0.31342	0.08254	0.2946	0.0356
F	m0, Ab, Hp	114	4.3	400	17.0	0.00118	0.32333	0.06445	0.2436	0.0350
G	m0, Hp	114	4.6	369	13.0	0.00072	0.28075	0.05734	0.2140	0.0304

Daegang foliated granite (FA-1)										
A	m1, Hp	188	1.1	949	36.6	0.00150	0.21438	0.06825	0.2474	0.0342
B	m1, Hp	114	0.3	1587	65.0	0.00209	0.22021	0.07463	0.2809	0.0360
C	m0, Hp	114	1.0	633	28.6	0.00342	0.31026	0.09424	0.2604	0.0355
D	m1, Ab, Hp	<76	0.6	1115	45.9	0.00163	0.22758	0.07288	0.2895	0.0361
E	m0	114	0.2	335	14.4	0.00434	0.22230	0.06159	0.3317	0.0391
F	m1, Ab, Hp	114	1.2	851	38.7	0.00402	0.31830	0.11010	0.2442	0.0342
Foliated granodiorite (FH-1)										
A	m0, Hp, Br	114	1.2	1352	87.0	0.00035	0.09016	0.06714	0.5703	0.0644
B	m1, Hp	114	1.9	311	11.6	0.00134	0.17969	0.07633	0.3185	0.0341
C	m1, Hp, Cl	188	2.8	423	13.4	0.00098	0.16758	0.05861	0.2063	0.0297
D	m0, Blk	114	5.6	529	16.6	0.00040	0.13229	0.05932	0.2350	0.0305
Sunchang foliated granite (FB-2)										
A	m0, Hp, Cl	114	0.5	1659	53.7	0.00214	0.13515	0.07720	0.2228	0.0301
B	m0, Hp, Br, Cr	114	1.0	1154	39.5	0.00110	0.08066	0.07409	0.2967	0.0340
C	m0	<48	0.1	1870	106.0	0.00465	0.21612	0.14416	0.6297	0.0455
D	m0, Ab	62	5.2	806	23.6	0.00043	0.08470	0.05962	0.2248	0.0297
F	m0, Hp, Op	62	8.6	790	21.9	0.00024	0.07976	0.05613	0.2096	0.0283
G	m0, Hp	114	1.9	669	20.7	0.00091	0.09130	0.06760	0.2533	0.0307
Namwon granite (HB-1)										
A	m0, Hp	188	1.6	468	21.2	0.00652	0.35459	0.14648	0.2534	0.0311
B	m0-m4, Ab, Hp	114	1.8	406	11.9	0.00600	0.15663	0.05881	0.2280	0.0281
D	m0, Hp	114	2.6	1095	39.1	0.00030	0.08014	0.06799	0.3276	0.0361
F	m0, Hp	114	3.2	539	17.9	0.00046	0.12344	0.06265	0.2675	0.0324
G	m0, Hp, Br	114	1.6	1156	35.1	0.00390	0.09458	0.05769	0.2357	0.0305
Diorite (KH-5)										
C	m1, Hp, Cl	114	3.2	119	4.6	0.00302	0.27953	0.08122	0.2335	0.0316
D	m0, Cl	62	0.8	157	7.9	0.00782	0.40324	0.13145	0.2684	0.0346
F	m0, Hp, Cl	114	1.8	120	3.9	0.00402	0.31667	0.08098	0.2098	0.0264
G	m0, Ab, Hp, Br	114	1.7	101	3.7	0.00336	0.23231	0.07364	0.2756	0.0317
H	m1, Hp, Cl	62	1.3	148	4.9	0.00303	0.27159	0.06321	0.2267	0.0283
I	m1, Hp, Cl	114	1.1	133	4.5	0.00254	0.30880	0.09094	0.3483	0.0278
J	m1, Hp, Cl	188	2.9	84	2.7	0.00271	0.28156	0.06704	0.2242	0.0273
K	m0, Ab, Hp	114	2.5	99	3.8	0.00307	0.30297	0.08166	0.2735	0.0311
L	m1, Ab, Hp	114	1.0	121	4.3	0.00741	0.39376	0.11249	0.2221	0.0253
Porphyroblastic gneiss (KJ-2)										
A	m1, Hp, Cl	188	1.8	559	117.9	0.00058	0.06729	0.12177	3.244	0.2046
B	m0, Ab, Br	114	4.0	339	108.0	0.00012	0.04801	0.11911	5.155	0.3169
C	m1, Cl	62	2.7	298	95.2	0.00008	0.04346	0.11801	5.192	0.3200
D	m0, Hp, Br	114	1.8	381	121.6	0.00013	0.04772	0.11945	5.178	0.3179
E	m0, Ab, Blk	<48	2.3	445	137.4	0.00007	0.04495	0.11805	5.005	0.3082
F	m1, Ab, Op	114	1.3	286	99.5	0.00185	0.10941	0.14159	5.146	0.3151
G	m0, Ab	62	1.4	257	80.0	0.00008	0.04352	0.11825	5.053	0.3112
H	m0, Br	62	2.3	262	80.5	0.00008	0.04088	0.11821	5.019	0.3079
I	m1, Ab	62	1.3	480	147.5	0.00042	0.04769	0.12304	4.922	0.3032

¹⁾Relative magnetic susceptibility of zircons is reported as m0 (nonmagnetic) to m4 (paramagnetic) and relates to the inclination of the Frantz isodynamic separator using maximum current of 2A. Ab, strongly abraded; Blk, bulk; Br, amber/pink/brown; Cl, clear; Cr, cracked; Hp, totally hand-picked; Op, opaque. Steves used were 225, 152, 76, 48 μ m.

²⁾Measured ratio, fractionation corrected; ³⁾Blank corrected; ⁴⁾Blank and nonradiogenic Pb corrected.

slip fault.

The Namweon granite batholith (Fig. 2) is a coarse-grained, massive non-foliated body, intrusive into the gneiss complex and into the foliated granites. Four rock types are recognized: hornblende biotite granodiorite, porphyritic granite, biotite granite, and a two-mica granite. Chemical evidence, major and trace elements, and REE, indicates that this body is also calcalkalic and related to continental plate margin plutonism (Hong *et al.*, 1988; Kim and Kim, 1990). There are several scattered small stocks of diorite to gabbro that are regarded as related to the Namweon granite.

Isotopic age determinations by the Rb-Sr, K-Ar, and Ar-Ar methods for rocks in and adjacent to the Damyang-Geochang area have been published or reported by Choo and Kim (1986), Kim (1971, 1986), Kim and Lee (1988), Kim *et al.* (1989). These ages, some of which are preliminary, are summarized in Table 1. This study presents the first U-Pb zircon ages for the Korean peninsula, and also evaluates the systematics of this isotopic system as applied to a relatively young, yet complicated geologic terrain.

ANALYTICAL PROCEDURES

The zircon separations were done by standard methods using the Wilfley table, the Carpc and Frantz magnetic separators, and heavy liquids. All zircon fractions were upgraded by handpicking and by mild abrasion (Krogh, 1982). In addition some fractions were subsequently strongly abraded. They were cleaned by repeated ultrasound vibration in

50% nitric acid and ultrapure water. Plagioclase feldspars were separated from each of the Mesozoic samples. The zircon dissolution using HF and HNO₃ acids was done using the methods of Krogh (1973) and Parrish (1987). Similar procedure was used for the feldspar dissolution, for which samples size was 15–20 mg. U and Pb concentrations were determined on aliquots spiked with ²³⁵U and ²⁰⁸Pb tracers, while Pb isotopic composition was measured on unspiked aliquots. More details of the laboratory procedures can be found in Turek *et al.* (1992).

The isotopic ratios were measured on a 90° 25-cm solid-source single-collector mass spectrometer at University of Windsor (Table 2). Mass fractionation based on values obtained for National Bureau of Standards isotopic standards was determined and used as 0.10‰ per atomic mass unit. The analytical uncertainty for unspiked Pb run is 0.1% (2σ) for both the ²⁰⁷Pb/²⁰⁶Pb and ²⁰⁸Pb/²⁰⁶Pb and less than ±0.000010 (2σ) for ²⁰⁴Pb/²⁰⁶Pb depending on the ²⁰⁴Pb content. Laboratory blank was 80 or 15 pg Pb, depending on the size of the dissolution vessel used, having a composition of ²⁰⁶Pb/²⁰⁴Pb = 18.7, ²⁰⁷Pb/²⁰⁴Pb = 15.7, ²⁰⁸Pb/²⁰⁴Pb = 38.4. Common Pb correction was made using the isotopic composition of Pb as determined in the feldspars for each of the Mesozoic samples (Table 3) and by using the Stacey and Kramers (1975) values for the Precambrian sample. The data reduction followed the procedure of Ludwig (1982). The regression analyses were done using the computer program of Ludwig (1992). The input errors used were 1% (2σ) for the U/Pb ratios,

Table 3. Isotopic composition of lead in feldspars from the Damyang-Geochang area

Sample	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
KH-4 Foliated granite	17.696	15.611	38.291
KH-2 Foliated gabbro	18.836	15.989	39.490
FA-1 Daegang foliated granite	17.665	15.604	38.077
FH-1 Foliated granodiorite	18.034	15.799	39.223
FB-2 Sunchang foliated granite	18.911	16.234	40.044
HB-1 Namweon granite	17.915	15.665	38.783
KH-5 Diorite	18.409	16.058	40.596

and covariance correlation of 0.95. The Ludwig (1992) regression is taken as being within experimental error when the probability of fit is 15% or higher, in which case this yields a so-called Model 1 age. For a probability of less than 15% the Model 2 age, which recognizes an error greater than experimental, is accepted. The errors reported with the ages are 95% confidence limits. The decay constants used were those recommended by Steiger and Jäger (1977).

RESULTS

In this study we report on U-Pb zircon ages for eight rock units, based on analyses of 49 zircon fractions. The location of the samples is shown in Fig. 2 with coordinates given in the Appendix. The zircon analytical data is given in Table 2 and shown as concordia plots in Figs. 3–10. The isotopic composition of the Pb determined for the feldspars in the seven rocks is given in Table 3 and shown as a Pb-Pb plot in Fig. 11. Table 4 gives the concordia ages.

Foliated granite (KH-4)

This foliated granite is of batholithic proportions, it intrudes the Precambrian Gneiss Complex,

and in turn is intruded by foliated and non-foliated igneous rocks. The separated zircons are euhedral, transparent, clear to milky, with minor fractures. Three clear fractions and a fourth hand-picked fraction that is milky and slightly fractured were analyzed. The three clear fractions define a discordia within experimental error (Fig. 3). The probability of fit is 99%. The excluded point, B, is the milky fraction, which has the highest U and Pb concentration and noticeably lower $^{208}\text{Pb}/^{206}\text{Pb}$ compared to fractions A, C, and D (Table 2). The concordia lower intercept is 219.2 ± 2.9 Ma with an upper intercept at 2237 ± 176 Ma. Hence the age for this rock is 219 ± 3 Ma.

Foliated gabbro (KH-2)

This small plug intrudes the Precambrian Gneiss Complex and the foliated granite. The zircons in this rock are anhedral but of excellent quality, and there are very few cloudy or fractured grains. Anhedral habit of zircons in a gabbro is somewhat unusual, consequently we confirmed their identity by X-ray. Analyses of six zircon fractions show a very large scatter on the concordia plot (Fig. 4). A line could be fitted to points C, D, and G, but the resulting age would be too young for observed structural field relations,

Table 4. Summary of zircon age determinations for the Damyang-Geochang area, Korea

Sample	Concordia intercepts (Ma)		Comments*	Age (Ma)
KH-4 Foliated granite	2237 ± 176	219.2 ± 2.9	Model 1, $P = 99\%$, MSWD = 0.0001, point B excluded	219 ± 3
KH-2 Foliated gabbro			Point F only, $^{207}\text{Pb}/^{206}\text{Pb}$ age	219 ± 3
FA-1 Daegang foliated granite	2025 ± 475	212.3 ± 8.2	All 6 points, Model 2, MSWD = 11	212 ± 8
FH-1 Foliated granodiorite	2595 ± 233	186.9 ± 2.6	Model 2, MSWD = 1.5, point A excluded	187 ± 3
FB-2 Sunchang foliated granite	2628 ± 245	183.5 ± 9.2	All 6 points, Model 2, MSWD = 42	
	2648 ± 179	182.6 ± 8.0	Model 2, $P = 48\%$, MSWD = 9.1, points B and F excluded	183 ± 8
HB-1 Namwean granite	1858 ± 80	176.0 ± 2.8	Model 1, $P = 48\%$, MSWD = 0.49, points A and B excluded	176 ± 3
KH-5 Diorite	1164 ± 127	176.7 ± 6.2	Model 1, points C and D only, seven points excluded	177 ± 6
KJ-2 Porphyroblastic gneiss	1934.8 ± 4.0	150 ± 27	Model 1, $P = 40\%$, MSWD = 1	1935 ± 4

Notes: Decay constants used: $\lambda^{238}\text{U} = 1.55125 \times 10^{-10} \text{ year}^{-1}$ and $\lambda^{235}\text{U} = 9.8485 \times 10^{-10} \text{ year}^{-1}$ (Steiger and Jäger, 1977). Error terms of concordia ages are 95% confidence limits.

*P is probability of fit; MSWD, mean square of weighted deviates, as defined by Ludwig (1992).

Fig. 3. Concordia diagram for KH-4, foliated granite. Point B is excluded from the regression.

Fig. 4. Concordia diagram for KH-2, foliated gabbro. Point F is concordant, age is 219 Ma.

moreover, such an interpretation would mean that the concordant data point F would have to be discarded. A regression of data points C, D, and G gives intercept ages, within experimental limits,

of 189.7 ± 2.4 and 1733 ± 95 Ma. However as point F is concordant, and also to conform to the local mapping we feel that 219 ± 3 Ma is the best estimate of the age for this rock.

Daegang foliated granite (FA-1)

The sample collected from this batholith is an alkali granite. It contains zircons, yellow to pale brown in colour. Six fractions were selected, five of these, A, B, C, D, F, were handpicked to be internally as homogenous as possible, the sixth fraction, E, is a bulk sample. Morphologically, the differences between the fractions are very slight, possibly fractions B and E are best quality, clearest and most euhedral, grains. The six points form a linear array with some scatter (Fig. 5), the data regression defines a lower intercept age of 212.3 ± 8.2 Ma, and an upper intercept age of 2025 ± 475 Ma. The discordia defined by fractions A, E, and F is within experimental error, has a probability of fit of 23%, and gives an age of 211.9 ± 1.9 Ma. However, we prefer to accept the more robust error estimate, hence, the age of this rock is 212 ± 8 Ma.

Foliated granodiorite (FH-1)

This coarse-grained, foliated granodiorite also intrudes the Precambrian Gneiss Complex. The zircons in this rock are a heterogeneous population, transparent, but range from clear, milky, to

light brown. Fraction A is comprised of cracked, light brown grains, and on the concordia plot, Fig. 6, it is an outlier. Compositionally, this fraction is high in U and Pb and has the lowest $^{208}\text{Pb}/^{206}\text{Pb}$ (Table 2). The other three fractions are clear; fraction B is gem quality, fraction C has some fractures and inclusions, and fraction D is a bulk sample of the clear grains. The three points yield a discordia line which intercepts the concordia at 186.9 ± 2.6 Ma and at 2595 ± 233 Ma. This is a Model 2 age with a probability of fit of 7.2%, which is a slightly larger error than experimental, however, point C is within error of concordia, and thus 187 ± 3 Ma is taken as the age of this rock.

Sunchang foliated granite (FB-2)

This is a coarse-grained granodiorite that intrudes the Precambrian Gneiss Complex and the metasedimentary rocks. The zircons separated are amber-brown, milky to clear, euhedral to subhedral. Fraction A grains are clear, elongate and of gem quality, while fraction B is amber and fractured, and the others are clear to milky. The six fractions scatter on the concordia plot, Fig. 7. The regression of all six data points gives a lower

Fig. 5. Concordia diagram for FA-1, Daegang foliated granite. Regression line is fitted to all points.

Fig. 6. Concordia diagram for FH-1, foliated granodiorite. Point A is excluded from the regression.

Fig. 7. Concordia diagram for FB-2, Sunchang foliated granite. Points B and F are excluded from the regression.

concordia intercept of 184 ± 9 Ma, but, a better fit is obtained by excluding fractions B and F, which are poorer quality, cracked and opaque grains. In this case the Model 1 regression inter-

cepts are 182.6 ± 8.0 Ma and 2648 ± 179 Ma. Hence, 183 ± 8 Ma is regarded as best estimate of the age of this rock.

Namweon granite (HB-1)

This is a non-foliated, fine-grained granite, which carries zircons that are brown, milky to clear, mostly euhedral, with some fracturing and some magnetite inclusions. The concordia plot (Fig. 8) shows that fractions G, F, and D are collinear yielding a lower concordia intercept age of 176 ± 2.8 Ma and an upper intercept of 1856 ± 80 Ma. Points A and B, which have the lowest U and Pb concentrations, fall below the discordia. Point A zircons are of large grain size and fraction B zircons are strongly abraded but magnetic. Thus 176 ± 3 Ma is the assigned age for this body.

Diorite (KH-5)

This diorite stock near the town of Geochang is a medium to coarse grained, non-foliated body. It contains zircons of very good quality, clear or slightly milky, mostly euhedral, with very few cracks and no fractures, but most grains contain magnetite inclusions. A total of nine fractions was analyzed, and as seen on the concordia plot, Fig. 9, the data have a large scatter. The oldest age that can be defined is by a discordia through points, C and D, which are clear grains with mag-

netite inclusions. However, the remaining seven fractions are not appreciably different; they are populations of clear to milky, euhedral to subhedral, with or without magnetite inclusions. In an attempt to create a concordant data point by very strong abrasion, we hand-picked and abraded fractions K and L with the expectation that K, L, C, and D data would be collinear, but instead K and L points are among those showing the greatest Pb loss. The discordia through the data points C and D gives concordia intercepts of 176.7 ± 6.2 Ma and 1164 ± 127 Ma, and thus our interpreted age for this stock is 177 ± 6 Ma.

Porphyroblastic gneiss (KJ-2)

A coarse grained porphyroblastic gneiss was collected from the Precambrian Gneiss Complex. It contains a very heterogeneous population of zircons. They range from colourless, through different shades of pink to brown, and they are euhedral, elongate to stubby. Because of this heterogeneity and also to obtain a spread of points on the discordia line nine fractions were analyzed (Fig. 10). Fraction A zircons which are the best quality grains, crystal clear, euhedral and elon-

Fig. 8. Concordia diagram for HB-1, Namweon granite. Points A and B are excluded from the regression.

Fig. 9. Concordia diagram for KH-5 diorite. The regression line shown is for points C and D only.

Fig. 10. Concordia diagram for KJ-2 Precambrian porphyroblastic gneiss.

gate, turned out to be 44% discordant. The other eight fractions were selected on a variety of colour and shape criteria and are 9–14% discordant. The regression of all nine data points is well within

experimental error and gives concordia intercepts of 1934.8 ± 4.0 Ma and 150 ± 27 Ma. Hence, the age of this member of the Precambrian Gneiss Complex is 1935 ± 4 Ma.

DISCUSSION

Some zircons separated from the seven Mesozoic plutonic rocks from the Damyang-Geochang area in this study have experienced recent Pb loss. Analytical results indicate emplacement of these plutonic rocks between 176 Ma to 219 Ma, and that they are derived from Precambrian, 1.9–2.6 Ga, protolith. In addition this study establishes the existence of 1.9 Ga basement in this area.

There are inherent problems in evaluating U-Pb data that plot at the lower end of the concordia diagram. Recrystallized zircons commonly contain some of the original older component and generally plot along a discordia line. However, systematics of Pb loss (or U gain) can cause data points to plot below the discordia. Points that plot above the discordia may be derived from a different, younger, protolith or have experienced a different loss of Pb having been pre-conditioned in response to an older episodic Pb loss. Data points that plot below the discordia are most likely showing recent Pb loss, though other causes, such as loss of Rn will have the same effect. In this study we observe both effects, some data points plot above and some below the discordia, but most of the data points are collinear and define geologically meaningful ages.

The U-Pb zircon ages indicate three sets of Mesozoic ages; some of the foliated plutons was emplaced at 219–212 Ma, a second set of foliated plutons came in at 187–183 Ma, a third set of plutons that are non-foliated formed at 177–176 Ma. Published and reported ages for these and similar rocks in the area by K-Ar and Rb-Sr are from 159 to 228 Ma (Table 1).

The foliated granite, KH-4, that we date at 219 Ma, has a metamorphic Ar-Ar age of 179 Ma (Kim, 1986). The Daegang foliated granite, FA-1, dated here at 212 Ma, has a Rb-Sr isochron age of 228 Ma (Choo and Kim, 1986), which we regard as reasonable agreement.

The second set of foliated granitic rocks we bracket at 187–183 Ma. The foliated granodiorite, FH-1, has a U-Pb age of 187 Ma, and a hornblende K-Ar age of 198 Ma (Kim and Lee, 1988).

The Sunchang foliated granite, FB-2, has a U-Pb age of 183 Ma, which is resolvably different than the Rb-Sr isochron age of 222 Ma reported by Choo and Kim (1986). The Rb-Sr isochron age is based on 11 data points, but the disposition of the points on the isochron is such that one point, having the lowest ^{86}Sr content, 4.4 ppm, and highest present day $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7506, controls the slope of the isochron. The other 10 points have low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, 0.7189 to 0.7262, and plot close to the origin. We are not able to reevaluate statistically this isochron data as the Rb and Sr concentrations reported are rounded off to one decimal place; however by visual inspection it appears that a younger isochron could be constructed if the one enriched sample is excluded. This excluded point may lie on a parallel isochron, having same age but higher initial ratio; as these rocks are recycled material variability in initial ratios is likely.

The non-foliated Namweon granite, HB-1, has a U-Pb age of 176 Ma, and the non-foliated diorite, KH-5, has an estimated age of 177 Ma. The hornblende K-Ar ages for the Namweon granite and the diorite are 203 ± 10 and 179 ± 9 Ma (Kim and Lee, 1988; Kim *et al.*, 1988), respectively. A Rb-Sr isochron age for the Namweon granite is 211 ± 3 Ma (Choo and Kim, 1986), which is significantly different from the U-Pb age obtained here. The isochron age is based on 4 points, the disposition of the points is such that additional data points could rotate the isochron to a younger age comparable to the 176 Ma U-Pb age.

The Precambrian porphyroblastic gneiss, KJ-2, gives a U-Pb zircon age of 1935 Ma. This compares with Rb-Sr isochron ages obtained for two units in the Granitic Gneiss Complex of 2070 and 1950 Ma by Choo and Kim (1986).

The systematics of the U-Pb, Rb-Sr, K-Ar systems, together with analytical and decay constant uncertainties, will produce differences in ages; particularly so, in a geologically complex area, such as this. In addition to the ages obtained here the upper intercepts of the concordia plots indicate derivation from a Precambrian protolith. These intercepts are 1.2–2.6 Ga, or 1.9–2.6 Ga if

Fig. 11. Pb-Pb plot for feldspars. The reference curve is the Stacey and Kramers (1975) Pb isotope evolution curve.

the data for the diorite sample KH-5 is disregarded because that upper intercept is based on only two data points. For the Mesozoic plutons we have measured the Pb isotopic compositions of feldspars (Table 3) in order to correct the zircon data for inherited Pb. All seven data points plot above the Stacey and Kramers (1975) Pb evolution curve (Fig. 11) and have an old crustal (i.e. radiogenic) signature. The feldspar lead isotope data together with the concordia upper intercept ages of 1.9–

2.6 Ga indicate that the Mesozoic plutonic rocks in this part of the Ryongnam massif were derived from a Proterozoic to Archean crust.

SUMMARY AND CONCLUSION

The Mesozoic plutonic rocks of the Ryongnam massif in the Damyang-Geochang area were emplaced between 176–219 Ma (Table 4). Our data indicate three plutonic episodes: 219–212 Ma

and 187–183 Ma, when the foliated granitic to gabbroic rocks were emplaced, and a third period 177–176 Ma which was the time of emplacement of post-tectonic non-foliated plutonic felsic to mafic stocks. The ages reported for the foliated plutonic rocks conform to the field observations that these rocks did not form at the same time. Thus the 219–212 Ma plutons would be the result of plutonism associated with the Triassic Songnim Disturbance. The 187–183 Ma plutons belong to the Jurassic Daebou Orogeny, and the non-foliated plutons, ca. 177 Ma, must represent the waning stages of the Daebou Orogeny. The Cretaceous Bulguksa granites are absent in this area. The existence of non-foliated Daebou granites indicates that this region escaped the Bulguksa Disturbance. The zircon ages also indicate derivation from a Precambrian protolith of 1.9–2.6 Ga. The feldspar Pb isotopic data has a crustal signature. A gneiss from the Precambrian basement here has a U-Pb zircon age of 1935 ± 4 Ma.

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APPENDIX: SAMPLE DESCRIPTION AND LOCATION

Foliated granite (KH-4)

This is a coarse grained rock composed of: quartz (29%), plagioclase (38%), K-feldspar (21%), biotite (7%), and accessory minerals, titanite (1%), apatite, zircon, allanite, opaques, and a small amounts of secondary minerals, chlorite (2%), sericite, epidote (1%), and calcite. Latitude 35°37' 00" N, longitude 127°46' 40" E.

Foliated gabbro (KH-2)

This is a coarse grained rock composed of quartz (2%), plagioclase (78%), pyroxene (6%), hornblende (9%), biotite (3%), and accessory minerals: zoisite, zircon, apatite, opaques, and small amount of secondary minerals: sericite, chlorite and calcite. Latitude 35°40' 00" N, longitude 127°41' 30" E.

Daegang foliated granite (FA-1)

Composition of this pluton is granite to alkali granite. Sample is a coarse-grained alkali granite composed of quartz (37%), alkali feldspar (46%), plagioclase (10%), biotite (3%), reibeckite (2%), accessory opaques, apatite, allanite, zircon, and a small amount of secondary chlorite and sericite. Latitude 35°19' 00" N, longitude 127°15' 00" E.

Foliated granodiorite (FH-1)

A coarse-grained rock with phenocrysts of hornblende. Composition is: quartz (20%), plagioclase (50%), K-feldspar (9%), hornblende (3%), biotite (14%). Rest is titanite (1%), apatite, allanite, zircon, and secondary epidote (2%), sericite, chlorite, and calcite. Latitude 35°35' 00" N, longitude 127°27' 00" E.

Sunchang foliated granite (FB-2)

Composition is granite to granodiorite. Sample is a coarse-grained granodiorite made-up of quartz (28%), plagioclase (40%), K-feldspar (19%), biotite (5%), opaques, titanite (1%), zircon, apatite, allanite, and secondary epidote (2%), chlorite (3%), and sericite. Latitude 35°27' 00" N, longitude 127°14' 00" E.

Namweon granite (HB-1)

This is a granodiorite to granite pluton. Sample is a fine-grained granite composed of quartz (25%), plagioclase (42%), K-feldspar (22%), biotite (6%), hornblende (2%), accessory opaques (1%), titanite, zircon, apatite, allanite, and secondary myrmekite, chlorite, and sericite. Latitude 35°27'00" N, longitude 127°28' 50" E.

Diorite (KH-5)

This medium to coarse grained rock is composed of quartz (7%), plagioclase (64%), K-feldspar (5%), hornblende (9%), biotite (11%), accessory apatite, zoisite, allanite, opaques, and a small amount of secondary sericite, chlorite (1%), epidote (1%), and calcite. Latitude 35°37' 30" N, longitude 127°50' 00" E.

Porphyroblastic gneiss (KJ-2)

This is a massive coarsegrained rock with 5-12 cm porphyroblasts. It is composed of quartz, plagioclase, microcline, biotite, muscovite. Accessory minerals are apatite, zircon, opaques, and garnet. Secondary minerals are chlorite, sericite, and epidote. Latitude 35°23' 46" N, longitude 127°36' 14" E.