Sr and Nd isotopic compositions of late Paleozoic Youngju and Andong granites in the northeastern Yeongnam Massif, Korea

JONG IK LEE, YONG-JOO JWA, CHUNG-HWA PARK, MI JUNG LEE, JACQUES MOUTTE and HIROO KAGAMI

1Polar Research Center, Korea Ocean Research and Development Institute, Ansan P.O. Box 29, Seoul 425-600, Korea
2Department of Geology, Gyeongsang National University, Jinju 660-701, Korea
3Department of Engineering Geology, Taejeon University, Taejeon 300-716, Korea
4Spin-Geochimie, Ecole des Mines, 158 Cours Fauriel 42023 Saint Etienne, France
5Institute for Study of the Earth's Interior, Okayama University, Misasa, Tottori 682-01, Japan

(Received October 7, 1997; Accepted November 18, 1998)

Rb-Sr whole-rock isochron ages and Sr and Nd isotopic ratios have been determined for Youngju and Andong granites in the northeastern Yeongnam Massif, Korea. Six samples of Youngju granites yield an isochron age of 267 ± 27 Ma with an initial Sr ratio of 0.71505 ± 0.00026. Seven samples of Andong granites give an isochron age of 361 ± 41 Ma and an initial Sr ratio of 0.70944 ± 0.00011. The isochron ages indicate that Youngju and Andong granites were emplaced in middle Permian and late Devonian of late Paleozoic, respectively. Calculated $\varepsilon_{Sr}$ (T) and $\varepsilon_{Nd}$ (T) values at 267 Ma for Youngju granites are 152.2-156.4 and -19.7--18.0, and those values at 361 Ma for Andong granites are 73.8-79.7 and -11.4--8.0. Model ages of Youngju and Andong granites are 2.4-3.3 Ga and 1.4-1.8 Ga, respectively, suggesting that the Youngju granitic magma was derived from highly LREE-enriched lower crust formed in Late Archean, whereas the Andong granitic magma from slightly LREE-enriched lower crust formed in Proterozoic. Initial $^{87}Sr/^{86}Sr$ ratios of the granites in Ogcheon Belt and Yeongnam Massif display a broad range, but have two peaks around 0.709 and 0.715 regardless of emplacement age. It is likely that these two kinds of sources which are isotopically different have widely existed in the lower crust of Ogcheon Belt and Yeongnam Massif.

INTRODUCTION

The Phanerozoic granites are widely distributed in the southern Korean Peninsula (Fig. 1). The intrusion ages of these granites, however, have long been controversial. Until early 1980's, the Korean Phanerozoic granites were mainly divided into two groups based on K-Ar mineral ages: Jurassic (Daebó) and Cretaceous (Bulgugsa) granites. The Bulgugsa granites are mostly distributed in the Cretaceous, nonmarine Kyongsang Basin, and subordinately in the Ogcheon Belt. Since late 1980's, late Paleozoic and Triassic ages of Daebó granites in the Ogcheon Belt, Kyonggi and Yeongnam Massifs, determined by Rb-Sr and U-Pb methods, have been reported by many authors (e.g., Choo, 1986; Choo and Kim, 1986; Choo and Chi, 1990; Jwa et al., 1990; Park et al., 1993; Turek and Kim, 1995; Kim and Turek, 1996; Cheong and Chang, 1997). The K-Ar mineral ages of Daebó granites showing Jurassic in age are thus considered to be cooling or deformation ages. The geochemical and isotopic results suggest that the Bulgugsa granites in the Kyongsang Basin were derived from igneous protoliths at lower crust or upper mantle, whereas the other granites outside
the Kyongsang Basin originated by partial melting from older crustal materials (Jin, 1980; Jwa et al., 1990; Kwon, 1991; Lee et al., 1995; Cheong and Chang, 1997).

In the northeastern Yeongnam Massif, two batholiths, Youngju and Andong granites, were emplaced on a large scale (Fig. 1). Youngju granites (YJGR) cropping out over 1,000 km², form one of the largest batholiths in the Yeongnam Massif. Andong granites (ADGR) crop out with about 500 km² surface extension to the southeast of Youngju granites. The two granites are mostly separated by a ductile shear zone trending northeastwards. Like many other granites in the Yeongnam Massif, Youngju and Andong granites are partly affected by ductile shear deformation (Otoh and Yanai, 1996).

Despite a large volume in the Yeongnam Massif, the intrusion ages of Youngju and Andong granites have long been controversial because of insufficiency of reliable data. In this paper, we present Rb-Sr whole-rock isochron ages and Sr and Nd isotopic characteristics of Youngju and Andong granites in the northeastern Yeongnam
Massif, Korea. These results, integrated with previous geochemical and isotopic information, will provide insights into the genesis of the granitic magmatism in the Yeongnam Massif.

**GEOLOGICAL SETTING**

In the Ogcheon Belt and Yeongnam Massif, a number of granitic plutons ranging in age from Late Paleozoic to Late Cretaceous widely intruded the Precambrian crystalline basement (Fig. 1). Among them, the pre-Cretaceous plutons are mainly I-type, hornblende-bearing granodiorite, and commonly deformed by ductile shear movement (Park et al., 1990; Lee and Lee, 1991; Kim et al., 1993, 1994).

The Precambrian basement, Sobaegsan metamorphic complex, comprises a high mountain range in the northwestern part of the study area (Fig. 2). It consists dominantly of granitic gneiss, banded gneiss and augen gneiss, and subordinately of migmatitic gneiss, mica schist, amphibolite, black slate and marble. The Precambrian granites and early Paleozoic Chosun Supergroup crop out
in the northeastern and northwestern parts of the study area, respectively. The early Cretaceous terrestrial to terrigenous sedimentary rocks, Kyongsang Supergroup, are in contact with Andong and Imha granites in the southeastern part of the area, juxtaposed by unconformity or fault.

The dextral ductile shear zone, which is a part of Honam strike-slip duplex (Otoh and Yanai, 1996), trends northeast in the central part of the study area. Both Youngju and Andong granites are partly deformed by this movement. This shear zone has been interpreted to have formed during late Jurassic to earliest Cretaceous (Otoh and Yanai, 1996) or during middle Jurassic (Kim and Turek, 1996).

Youngju granites (YJGR) are nearly semicircular body, and widely emplaced into the Precambrian basement in the northwestern part. They are accompanied by a number of pegmatitic dikes ranging in thickness from a few centimeters to ten meters. Small stocks of fine- to medium-grained two-mica granite intruded along the margin of YJGR. The two-mica granites have sharp, crosscutting contacts with YJGR. However, geochemical properties of the two-mica granites suggest that they have been more differentiated, and probably remelted products of YJGR (Lee and Lee, 1991).

Andong granites (ADGR) intruded the basement, and are overlain by the Cretaceous sedimentary rocks along the eastern boundary of the body. They have been more deformed than YJGR, and small shear zones develop inside the body. Strong foliation is defined by the preferred alignment of mafic minerals. Age-unknown Imha granites of gabbroic to granitic compositions have different chemical compositions from ADGR (Lee, J. I., unpublished data).

ADGR is in contact with YJGR by NE-trending fault in the southwestern part of the study area. The foliations of deformed YJGR and ADGR, subparallel to the trend of shear zone, generally trend N30° to 80°E and dip 50° to 70°NW. Along the contacts between the two granites and Precambrian basement, migmatite zones of several tens of meters in thickness are commonly developed, implying a small-scale contamination along the margin of the granitic bodies.

On the basis of hornblende geobarometry of Hammarstrom and Zen (1986), total Al in hornblends of YJGR and ADGR (Lee and Lee, 1991; Cho and Kwon, 1994) indicates that the former was emplaced at deeper level of the crust: 6–8 kbar for YJGR and 4–5 kbar for ADGR.

**PETROGRAPHY AND GEOCHEMISTRY**

The petrographical and geochemical characteristics of YJGR and ADGR are briefly summarized in Table 1. Both YJGR and ADGR belong to tonalite-granodiorite-granite association, but have dominantly granodioritic composition (Fig. 3). The whole-rock magnetic susceptibility and the content of opaque minerals (Lee et al., 1998) in-

---

**Table 1. Summary of petrological and geochemical characteristics of Youngju and Andong granites**

<table>
<thead>
<tr>
<th></th>
<th>Youngju granites (YJGR)</th>
<th>Andong granites (ADGR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>tonalite-granodiorite-granite</td>
<td>tonalite-granodiorite-granite</td>
</tr>
<tr>
<td></td>
<td>mostly granodiorite</td>
<td>mostly granodiorite</td>
</tr>
<tr>
<td>Deformation</td>
<td>partly deformed</td>
<td>partly but more intensely deformed than YJGR</td>
</tr>
<tr>
<td>Emplacement depth</td>
<td>lower-middle crust (6–8 kbar)</td>
<td>upper-middle crust (4–5 kbar)</td>
</tr>
<tr>
<td>MIIII-series</td>
<td>II-series</td>
<td>Mt-series</td>
</tr>
<tr>
<td>Geochemistry</td>
<td>(similarity) metaluminous, calc-alkaline, I-type, volcanic arc granites</td>
<td>(difference) higher Fe, Mn, Mg, K, Rb, Th and Sc in YJGR lower Al, Na, P, Ti, Sr and Zr in YJGR higher K/Na, Rb/Sr and lower K/Rb ratios in YJGR</td>
</tr>
</tbody>
</table>

*Abbreviations: Mt = magnetite, II = ilmenite (data sources: Lee and Lee, 1991; Lee et al., 1998).*
Sr and Nd isotopes of Paleozoic granites, Korea

Fig. 3. Ternary diagram of modal quartz, plagioclase and alkali feldspar. The classification of plutonic rocks follows the recommendation of IUGS (1973) subcommission. Abbreviations: Qz = quartz, Pl = plagioclase, Af = alkali feldspar, To = tonalite, Gd = granodiorite, Gr = granite.

Fig. 4. CaO-Na₂O-K₂O (wt.%) ternary diagram of Youngju and Andong granites. Note that K₂O/Na₂O ratios are substantially higher in YJGR (data source: Lee et al., 1998).

dicate that YJGR belongs to ilmenite-series granites, whereas ADGR to magnetite-series granites of Ishihara (1977).

YJGR is mostly coarse-grained, slightly deformed and porphyritic. Porphyritic granodiorite containing alkali-feldspar phenocrysts commonly occurs in the southwestern part of the body. Partly deformed hornblende-biotite tonalite and granodiorite occur near the shear zone. Minor amounts of fine- to medium-grained biotite granite randomly occur in the northeastern part of the body. YJGR is mainly composed of plagioclase, quartz, alkali-feldspar, biotite and hornblende. Zircon, apatite, sphene, allanite and ilmenite occur as accessory minerals. Subhedral plagioclase commonly shows albite-Carlsbad twinning and oscillatory zoning. Anhedral quartz exhibits undulatory extinction and subgrain texture with serrated grain boundaries. Anhedral, interstitial alkali-feldspar is microcline and includes most of major and accessory minerals. Myrmekites are frequently observed in strongly deformed samples. Euhedral to subhedral hornblende occurs as discrete, prismatic crystals, whereas anhedral, elongate biotite as fine-grained aggregates. Discrete, euhedral sphene and euhedral allanite enclosed by epidote are commonly observed. Opaque minerals (<0.4 modal%) are mostly ilmenite.

ADGR mostly consists of medium- to coarse-grained, slightly to moderately deformed granodiorite. Minor amounts of tonalite and granite randomly occur in the body. ADGR includes plagioclase, quartz, alkali-feldspar, biotite and hornblende. Zircon, apatite, sphene, allanite, magnetite and ilmenite occur as accessory minerals. Subhedral plagioclase commonly shows albite-Carlsbad twinning and oscillatory zoning. Anhedral quartz shows undulatory extinction, and is completely recrystallized in the deformed rocks. Anhedral alkali-feldspar is microcline, and occurs as microperthite. Hornblende and biotite, less abundant than those of YJGR, commonly occur as aggregates of fine subhedral crystals. Subhedral to anhedral sphene contains many inclusions of fine-grained ilmenites. Secondary muscovite (or sericite) commonly replaces biotite and plagioclase in deformed rocks. Opaque minerals (about 0.6 modal%) consist primarily of magnetite together with minor ilmenite.

Both YJGR and ADGR have similar chemical characteristics in terms of metaluminous, calc-alkaline and I-type granites. Relative to ADGR, YJGR, however, contains higher FeO, MnO, MgO,
K₂O, Rb, Th and Sc and lower Al₂O₃, Na₂O, P₂O₅, TiO₂, Sr and Zr. The two fractionation trends in the CaO-Na₂O-K₂O diagram (Fig. 4) are nearly parallel, changing from Na-rich field to K-rich field. However, Na₂O contents are substantially higher in ADGR, implying that ADGR magma originated from more sodic source material. The Rb/Sr ratios of YJGR slightly increase, but those of ADGR highly increase with increasing SiO₂ (Fig. 5(a)). The significant difference in the Rb/Sr ratios of relatively silica-poor rocks suggests more incompatible nature of YJGR magma. The Rb vs. Sr diagram (Fig. 5(b)) illustrates that the fractionation trends of the two granites are different, although some data of fractionated ADGR are overlap with those of YJGR. Considering the Rb and Sr partition coefficients of feldspar, particularly of plagioclase (Arth, 1976), it is likely that plagioclase was not an early-crystallizing phase but started to crystallize from the ADGR magma of intermediate composition. On the other hand, plagioclase seems to have crystallized continuously, but slightly, from the initial magma of YJGR. YJGR has lower K/Rb and higher Th/Y ratios (Fig. 6), also indicating that YJGR has been greatly enriched in incompatible elements during magmatic evolution. The tectonic discrimination diagrams of Pearce et al. (1984) illustrate that the two granites were formed in volcanic arc environment (Fig. 7).

Consequently, the petrographical and geochemical characteristics confirm different source materials for the two granites. The source material of YJGR may have had much enriched components, and have been evolved under reduced environment. The more detailed information on the whole-rock geochemistry of YJGR and ADGR can be referred from Lee et al. (1998).

![Fig. 5](image_url)  
(a) Rb/Sr ratio vs. SiO₂ (wt.%), and (b) Rb (ppm) vs. Sr (ppm) diagrams of Youngju and Andong granites (data source: Lee et al., 1998).

![Fig. 6](image_url)  
Th/Y vs. K/Rb plot for Youngju and Andong granites. It is notable that YJGR distinctly has lower K/Rb and higher Rb/Sr and Th/Y ratios than ADGR (data source: Lee et al., 1998).
Sr and Nd isotopes of Paleozoic granites, Korea

Fig. 7. Tectonic discrimination diagrams for VAG (volcanic arc granite), syn-CORG (syncollision granite), WPG (within plate granite) and ORG (ocean ridge granite) of Pearce et al. (1984), illustrating that YJGR and ADGR were formed in volcanic arc environment (data source: Lee et al., 1998).

ANALYTICAL PROCEDURES

To obtain reliable isochron ages and initial Sr and Nd isotopic ratios, significant emphasis was placed on sampling throughout the bodies. Care was taken to avoid altered samples during field survey and sample preparation. The sample locations for Sr and Nd isotopic analysis are shown in Fig. 2.

Rb and Sr concentrations were determined by an XRF (Philips PW1404), and Sm and Nd concentrations were measured by an ICP-AES (JY32VHR) at Spin-Geochimie, Ecole des Mines, St. Etienn, France. An error of 5% is estimated for Rb/Sr ratio of each sample, based on reproducibility of a standard sample (JG-1a) and internal cross-checking of several samples by the isotopic dilution method at the Institute for Study of the Earth’s Interior (ISEI), Okayama University. Sr and Nd isotopic ratios were determined by a Finnigan MAT-262 mass spectrometer at ISEI, Okayama University, following the procedure of Kagami et al. (1987, 1989).

Measured $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. Measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for NBS987 during this study was 0.710254 ± 0.000011 ($N = 3$). Measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for JNd-1 was 0.512117 ± 0.000011 ($N = 5$). Estimated error for Sr isotopic ratios was less than 0.01% ($1\sigma$) in each isochron. Rb-Sr isochron ages and initial Sr ratios were calculated by the equation of York (1966) and the following decay constant: $\lambda^{87}\text{Rb} = 1.42 \times 10^{-11} \text{yr}^{-1}$ (Steiger and Jäger, 1977).

Model ages ($T_{DM}$) with reference to the depleted mantle were calculated using the following parameters: $^{143}\text{Nd}/^{144}\text{Nd}_{DM(0)} = 0.513153$ ($\varepsilon_{\text{Nd}} = +10$), $^{147}\text{Sm}/^{144}\text{Nd}_{DM(0)} = 0.2136$ (Liew and McCulloch, 1985).

RESULTS

Analytical results, calculated $\varepsilon$-values and Nd model ages of YJGR and ADGR are listed in Table 2. Because YJGR and ADGR are mostly intermediate granodiorite compositions, their $^{87}\text{Rb}/^{86}\text{Sr}$ ratios have narrow ranges: 0.5~1.2 for YJGR and 0.1~0.9 for ADGR. Rb-Sr whole-rock isochrons and initial Sr ratios of YJGR and ADGR are shown in Fig. 8. Six samples of YJGR yield an isochron age of $267 \pm 27$ Ma with an initial Sr ratio of $0.71505 \pm 0.00026$ ($2\sigma$). Seven samples of ADGR give an isochron age of $361 \pm 41$ Ma and an initial Sr ratio of $0.70944 \pm 0.00011$ ($2\sigma$). The isochron ages indicate that YJGR and ADGR were emplaced in middle Permian and late Devonian, respectively. The two granites have comparatively
### Table 2. Rb-Sr and Sm-Nd isotopic data, calculated ε-values and model ages for Youngju and Andong granites

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Sample No.</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>(^{87}\text{Rb}/^{86}\text{Sr})</th>
<th>(^{87}\text{Sr}/^{86}\text{Sr})</th>
<th>Initial (^{87}\text{Sr}/^{86}\text{Sr})</th>
<th>(\varepsilon_{\text{Sr}}) (T)</th>
<th>Nd (ppm)</th>
<th>Sm (ppm)</th>
<th>(^{147}\text{Sm}/^{144}\text{Nd})</th>
<th>(^{143}\text{Nd}/^{144}\text{Nd})</th>
<th>(\varepsilon_{\text{Nd}}) (T)</th>
<th>(T_{\text{DM}}) (Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YJGR</td>
<td>1522</td>
<td>92.2</td>
<td>507</td>
<td>0.5263</td>
<td>0.717028 ± 10</td>
<td>0.71503</td>
<td>154.0</td>
<td>24.2</td>
<td>5.6</td>
<td>0.1399</td>
<td>0.511528 ± 13</td>
<td>-19.7</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>1506</td>
<td>100.4</td>
<td>474</td>
<td>0.6135</td>
<td>0.717401 ± 13</td>
<td>0.71507</td>
<td>154.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1507</td>
<td>122.7</td>
<td>440</td>
<td>0.8075</td>
<td>0.718262 ± 13</td>
<td>0.71520</td>
<td>156.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1511</td>
<td>123.7</td>
<td>302</td>
<td>1.1880</td>
<td>0.719413 ± 11</td>
<td>0.71491</td>
<td>152.2</td>
<td>32.8</td>
<td>6.1</td>
<td>0.1124</td>
<td>0.511569 ± 11</td>
<td>-18.0</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>3110</td>
<td>87.8</td>
<td>459</td>
<td>0.5544</td>
<td>0.717123 ± 13</td>
<td>0.71502</td>
<td>153.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1519</td>
<td>122.6</td>
<td>437</td>
<td>0.8133</td>
<td>0.718139 ± 16</td>
<td>0.71505</td>
<td>154.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADGR</td>
<td>1412</td>
<td>34.0</td>
<td>1012</td>
<td>0.0972</td>
<td>0.709970 ± 12</td>
<td>0.70947</td>
<td>76.6</td>
<td>38.7</td>
<td>5.7</td>
<td>0.0890</td>
<td>0.511975 ± 10</td>
<td>-8.0</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>1411</td>
<td>37.0</td>
<td>1025</td>
<td>0.1044</td>
<td>0.710038 ± 14</td>
<td>0.70950</td>
<td>77.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1414</td>
<td>42.4</td>
<td>954</td>
<td>0.1286</td>
<td>0.710134 ± 12</td>
<td>0.70947</td>
<td>76.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1406</td>
<td>131.5</td>
<td>432</td>
<td>0.8821</td>
<td>0.714212 ± 13</td>
<td>0.70969</td>
<td>79.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1417</td>
<td>49.0</td>
<td>976</td>
<td>0.1453</td>
<td>0.710170 ± 14</td>
<td>0.70942</td>
<td>76.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1503</td>
<td>71.3</td>
<td>514</td>
<td>0.4014</td>
<td>0.711327 ± 12</td>
<td>0.70927</td>
<td>73.8</td>
<td>22.7</td>
<td>3.9</td>
<td>0.1038</td>
<td>0.511834 ± 10</td>
<td>-11.4</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>1402</td>
<td>45.1</td>
<td>875</td>
<td>0.1491</td>
<td>0.710091 ± 13</td>
<td>0.70933</td>
<td>74.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Initial \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios were calculated at 267 Ma and 361 Ma for Youngju and Andong granites, respectively. \(\varepsilon_{\text{Sr}}\) (T) and \(\varepsilon_{\text{Nd}}\) (T) values were calculated using the following parameters: \(^{87}\text{Sr}/^{86}\text{Sr}_{UR(0)} = 0.7045\), \(^{87}\text{Rb}/^{86}\text{Sr}_{UR(0)} = 0.0827\), \(\lambda^{87}\text{Rb} = 1.42 \times 10^{-11}\) y\(^{-1}\), \(^{147}\text{Nd}/^{144}\text{Nd}_{CHUR(0)} = 0.512638\), \(^{147}\text{Sm}/^{144}\text{Nd}_{CHUR(0)} = 0.1966\), \(\lambda^{147}\text{Sm} = 6.54 \times 10^{-12}\) y\(^{-1}\). Model ages with reference to the depleted mantle (DM) were calculated by following parameters: \(^{143}\text{Nd}/^{144}\text{Nd}_{DM(0)} = 0.513153\), \(^{147}\text{Sm}/^{144}\text{Nd}_{DM(0)} = 0.2136\) (Lee and McCulloch, 1985).
high initial Sr ratios (>0.709), suggesting a minor contribution of relatively young mantle-derived materials to the granitic magmas, or reflecting an origin from a crustal source.

Calculated $\varepsilon_{Sr}$ (T) and $\varepsilon_{Nd}$ (T) values at 267 Ma for YJGR are 152.2~156.4 and -19.7 to 18.0, respectively. Those values at 361 Ma for ADGR are 73.8~79.7 and -11.4 to -8.0, respectively. These calculated $\varepsilon_{Sr}$ (T) and $\varepsilon_{Nd}$ (T) values confirm that the sources of YJGR and ADGR are significantly different and YJGR contains a much highly evolved crustal component. Model ages ($T_{DM}$) with reference to the depleted mantle (Liew and McCulloch, 1985) for YJGR and ADGR are 2.37 to 3.33 Ga and 1.44 to 1.83 Ga, respectively, indicating that the sources of YJGR and ADGR have different crustal histories. The ultimate source of YJGR has longer history of crustal evolution than that of ADGR.

**DISCUSSION**

**Granitic magmatism in Ogecheon Belt and Yeongnam Massif**

It is now well accepted that the mineral ages of both K-Ar and Rb-Sr systems are not emplacement or crystallization ages of the granitic rocks but cooling ages depending on their blocking temperatures. The blocking temperatures of major minerals in the granitic system are generally lower than solidus temperature (Harrison and McDougall, 1982; Harrison et al., 1985). Furthermore, the mineral ages may be easily reset by later thermal effects or influx of fluids in highly deformed magmatic terrane. Highly variable mineral ages from the same pluton in the Yeongnam Massif, summarized by Kim et al. (1994), may reflect the blocking effect of each mineral system as well as deformation history related with fluid movement.

Magmatic zircon in granitic rocks can be used to date the time of emplacement by U-Pb method, because of its higher blocking temperature than the solidus temperature (Cliff, 1985). Turek and Kim (1995) and Kim and Turek (1996) have reported many U-Pb zircon ages of plutonic rocks in the southwestern Yeongnam Massif. Their results indicate that the plutonic activity occurred during Triassic to Jurassic periods with three apparent peaks; i.e., 205~230 Ma, 180~200 Ma and 170~180 Ma. However, no late Paleozoic ages have been reported for granitic rocks in the southwestern Yeongnam Massif.

Rb-Sr whole rock ages is still one of most widely used isotopic methods inferring emplacement ages of granitic rocks, because their blocking temperature is thought to be similar to the solidus temperature (Harrison et al., 1979). Park et al. (1993) determined two Permian ages for the
granitic rocks in the Kimcheon-Geochang area, central Yeongnam Massif (Fig. 1), by the Rb-Sr whole rock (with some minerals) method. Cheong and Chang (1997) investigated Sr, Nd and Pb isotope systematics of the granitic rocks in the central Ogcheon Belt, and reported one late Permian granitic rock (Fig. 1); the Rb-Sr whole rock isochron age of Baegnok granodiorite is 256 ± 16 Ma with initial Sr ratio of about 0.709. The early Permian isochron age (267 ± 27 Ma) of YJGR is similar to those of the granitic rocks in the central Ogcheon Belt and Yeongnam Massif. However, the late Devonian age (361 ± 41 Ma) of ADGR is considerably older than the isochron ages previously determined for the other granitic rocks. The late Paleozoic (mainly Permian) granitic magmatism is thus considered to have extensively occurred in the central and northeastern Ogcheon Belt and Yeongnam Massif. From the data available for this discussion, it is likely that late Paleozoic magmatism did not occur in the southwestern Ogcheon Belt and Yeongnam Massif.

Source materials

The petrological and geochemical properties of YJGR and ADGR (Lee et al., 1998) suggest that their parental magmas would have been of tonalitic composition, and the source materials should be more mafic than this composition. Although the potential source materials in continental arc environment have a wide range in the lower crust, the most plausible protoliths for the generation of a large volume, metaluminous, I-type tonalite magma are considered to be mafic igneous rocks or their metamorphic equivalents (Chappell and Stephens, 1988; Rutter and Wyllie, 1988). High initial Sr ratios of YJGR and ADGR (>0.709) indicate that old crustal materials have been involved in the generation of the granitic magmas. The evolved, old mafic lower crust is thus considered to have produced the primary magmas of YJGR and ADGR.

Sr and Nd isotopic data, however, confirm that the source materials of YJGR and ADGR have significantly different crustal histories. Higher εSr (T) and lower εNd (T) values of YJGR indicate a highly enriched nature at the time of magma generation. Different candidates for the source materials can be evaluated by comparing the present data with those from other granites in Korea. The initial 87Sr/86Sr ratios of the granites in Ogcheon Belt and Yeongnam Massif display a broad range, but have two peaks around 0.709 and 0.715, regardless of their emplacement ages (Fig. 9), suggesting that at least two isotopically different sources have existed in the lower crust. Initial 87Sr/86Sr ratios of YJGR and ADGR are well correlated with those of the two sources.

Fig. 9. Frequency histogram of initial 87Sr/86Sr ratios of the granites in Ogcheon Belt and Yeongnam Massif. The ratios show a broad range, with two peaks around 0.709 and 0.715, regardless of emplacement ages (data sources: Choo, 1986; Choo and Kim, 1985, 1986; Kim et al., 1989; Choo and Chi, 1990; Park et al., 1993; Shin and Kagami, 1996; Cheong and Chang, 1997; Jwa et al., unpublished data; this study).
The Precambrian basements in Ogcheon Belt and Yeongnam Massif are Proterozoic in age. Although the existence of Archean basements has not been reported, the crustal residence ages ($T_{DM}$) by Lan et al. (1995) indicate their possible presence in Ogcheon Belt and Yeongnam Massif. The Sm-Nd isotopic data on Precambrian orthogneisses from Sobaegsan Massif, northeastern part of Yeongnam Massif, suggest two possible different sources of the basement: one is late Archean (2.6 Ga), LREE-enriched source and the other is Proterozoic (1.7 Ga) source (Lee et al., 1992). The Nd isotopic evolution diagram for Precambrian orthogneisses from Sobaegsan Massif, central Japan and northeast China reveals the existence of early Archean depleted mantle in east Asia, and suggests a nearly common or similar source for these Precambrian gneisses (the line A in Fig. 10). It is noted that $\varepsilon_{Nd}$ (T) values of YJGR and ADGR are plotted close to the line A and B, respectively. These lines of evidence, combined with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the granites in Ogcheon Belt and Yeongnam Massif (Fig. 9), strongly suggest that the YJGR magma was derived from highly LREE-enriched lower crust probably formed in late Archean, whereas the ADGR magma from slightly LREE-enriched lower crust formed in Proterozoic.
Acknowledgments—We wish to thank Prof. S. Otoh of Toyama Univ. for his stimulating discussion during field survey. We are deeply indebted to Dr. M. Yuhara and Miss Y. Kawamoto of ISEI, Okayama Univ. and Mr. S. Y. Chae of Taejeon Univ. for their kind assistance in isotopic analyses. We thank two anonymous reviewers for their constructive reviews of the manuscript.

REFERENCES


