Unusual cooling of the Middle Miocene Ichifusayama Granodiorite, Kyushu, Japan

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K-Ar and FT analyses were carried out on biotite, zircon and apatite from the Middle Miocene Ichifusayama Granodiorite pluton in Kyushu, Japan in order to reveal the cooling history. The core and rim of the pluton revealed K-Ar biotite ages of 13.39±13.36 and 13.31±13.54 Ma, FT zircon ages of 13.3±13.1 and 12.7±12.3 Ma, and FT apatite ages of 13.1±13.7 and 10.6±10.8 Ma respectively, suggesting that the core cooled, to 100 °C from 300 °C, faster than the rim, of which the cooling rate is ~ 100 °C/Ma. The track-length analyses also suggest extremely rapid cooling without a late stage annealing process. The faster cooling of the core in comparison with the rim is unusual. The difference in cooling velocity between the core and rim was possibly caused by an influence of paleotopography.

Keywords: Thermochronology, K-Ar dating, Fission-track dating, Paleotopography, Ichifusayama Granodiorite, Southwest Japan

INTRODUCTION

Emplacement of the Middle Miocene granitic rocks in the Outer Zone of Southwest Japan occurred at 14 ± 1 Ma (Shibata, 1978; Sumii, 2000) just after the opening of the Japan Sea with the clockwise rotation of Southwest Japan (e.g., Otofuji et al., 1985), and in association with formation of the Setouchi Volcanic Rocks characterized by the high magnesium andesite (e.g., Tatsumi, 2001). There are many studies on the origin and magmatism of the granitic rocks (e.g., Nakada and Takahashi, 1979; Shinjoe, 1997). There is, however, no previous study of their cooling history to give information on the intrusion and emplacement processes and the relationship between tectonic evolution and igneous activity in the Outer Zone of Southwest Japan.

The Ichifusayama Granodiorite (Saito et al., 1996) is a member of the Middle Miocene granitic rocks exposed in southern Kyushu (Fig. 1). This pluton intruded into the Cretaceous to Paleogene mélangé of the Shimanto Supergroup (Saito et al., 1996). It is a gently gradationally zoned pluton composed of fine- to coarse-grained biotite granodiorite with many mafic microgranular enclaves and xenoliths (Saito et al., 1996). After cessation of the Middle Miocene plutonism, igneous activity did not reoccur in the region (Saito et al., 1996). The Ichifusayama Granodiorite may therefore be expected to have a simple cooling history. In this study, we attempt to clarify its cooling history using a thermochronological method based on K-Ar and fission-track (FT) dating, and we discuss its relationship to the Miocene tectonic events in the Outer Zone of Southwest Japan.

SAMPLES AND ANALYTICAL PROCEDURES

Biotite K-Ar analyses with zircon and apatite FT dating were carried out on samples from four localities on the Ichifusayama Granodiorite (Fig. 1): two from the center (Ic-2 and -3), and two from the rim (Ic-1 and -4). All of the samples were collected at approximately the same altitude above sea level (1100-800 m). Rock types are shown in Table 1.

K-Ar dating

Rock samples were crushed and sieved to obtain the 60 (250 μm) to 120 mesh (125 μm) fractions. Biotite was separated using conventional heavy liquid and magnetic techniques. The potassium and argon analyses of biotite were carried out at the Hiruzen Institute for Geology and Chronology Co. Ltd. The analytical and age calculation methods were based on those described by Nagao et al.
For calculation of the K\textsuperscript{+}Ar age, $\lambda_e = 0.581 \times 10^{-10}$/yr, $\lambda_\beta = 4.962 \times 10^{-10}$/y and $^{40}\text{K}/K = 0.0001167$ (Steiger and Jäger, 1977) were used. The argon isotope analyses were replicated for all the samples to check the reproducibility of experiments. Average ages were calculated using the formula proposed by Tsukui et al. (1985).

Fission-track (FT) dating

Zircon and apatite samples were separated using conventional heavy liquid and magnetic techniques. FT dating was carried out at the Kyoto FT Co. Ltd. by the external detector method using the geometry factors of $0.5$ for $4\pi/2\pi$ (ED1, internal surface: Gleadow, 1981), following the procedures described by Danhara et al. (1991), Iwano and Danhara (1997), and Iwano and Danhara (1998). Track length was also analyzed at the same laboratory. FT ages were determined with the zeta calibration approach (Hurford and Green, 1983), using the zeta value of $352 \pm 3$ for zircon (Iwano and Danhara, 1997) and $299 \pm 4$ for apatite (Iwano and Danhara, 1998). The errors in zeta values are given to one sigma. FT lengths in this study were measured on horizontal confined fission tracks (Laslett et al., 1982) following the methods described by Iwano et al. (1996). As the samples were obtained from plutonic rock, the influence of the extra grains was ignored in the track length measurements. The number of measurement grains in a sample was therefore about 300, more than those for the age determination.

RESULTS AND DATA PRESENTATION

The results of the K-Ar and FT dating are summarized in Tables 1 and 2, respectively. The errors for all ages are shown to the one-sigma level. The K-Ar biotite ages for Ic\textsuperscript{1} and Ic\textsuperscript{4} on the rim of the pluton and for Ic\textsuperscript{2} and Ic\textsuperscript{3} in the core are: $13.54 \pm 0.22$ and $13.31 \pm 0.22$ Ma, and $13.39 \pm 0.22$ and $13.36 \pm 0.22$ Ma, respectively (Table 1). Zircon FT ages from the same locations are: $12.7 \pm 0.5$ Ma (Ic\textsuperscript{1}), $12.3 \pm 0.4$ Ma (Ic\textsuperscript{4}), $13.3 \pm 0.5$ Ma (Ic\textsuperscript{2}) and $13.1 \pm 0.5$ Ma (Ic\textsuperscript{3}), and apatite ages are: $10.8 \pm 0.5$ Ma (Ic\textsuperscript{1}), $10.6 \pm 0.7$ Ma (Ic\textsuperscript{4}), $13.7 \pm 0.6$ Ma (Ic\textsuperscript{2}), $13.1 \pm 0.5$ Ma (Ic\textsuperscript{3}) (Table 2). The 12 new ages are consistent with the results from previous work that indicated a K-Ar biotite age of $14 \pm 1$ Ma (Miller et al., 1962) and a zircon FT age of $12.0 \pm 0.5$ Ma (Miyachi, 1985).

In general, the nonaligning, spontaneous and induced track lengths are characterized by a narrow unimodal distribution with a mean confined FT length of $\sim 10.7 \mu$m and standard deviation of $\sim 0.8 \mu$m for zircon (Hasebe et al., 1994), and a mean confined FT length of about $15-16 \mu$m for apatite (Gleadow et al., 1986). The confined FT lengths for all samples are characterized by a narrow unimodal distribution with a mean length of $10-11 \mu$m (mode: $10-11 \mu$m) for zircon and a mean length of $14-15 \mu$m (mode: $14-16 \mu$m) for apatite (Fig. 2). These FT length data do not show evidence of noticeable shortening or annealing.

None of the apatite and zircon FT data from locations Ic\textsuperscript{3} and Ic\textsuperscript{4} passed the $\chi^2$-test at the 5% criterion (Galbrath, 1981). The ED1 (Gleadow, 1981) data are susceptible to variation in addition to Poisson variation in track counts (Danhara et al., 1991). The $\chi^2$-test indicates that sample failure could be attributed to contamination by a xenocryst, or variation in the uranium content of each grain or inner grain. In the context of these age data obtained from plutonic rocks, it is not considered that an inmix of tracked exotic material would survive the heat of granitic magma.

A failure to pass the $\chi^2$-test is often observed in ED1
Unusual cooling of the Middle Miocene Ichifusayama Granodiorite

Table 1. Sample description and K–Ar biotite dating results for the Ichifusayama Granodiorite

<table>
<thead>
<tr>
<th>Locality*</th>
<th>Lithofacies</th>
<th>Sampling Site</th>
<th>Potassium</th>
<th>Rad. $^{40}\text{Ar}$</th>
<th>K–Ar age (± 1σ)</th>
<th>Av. Age (± 1σ)</th>
<th>Non-rad. $^{40}\text{Ar}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Sample name)</td>
<td></td>
<td>Latitude**</td>
<td>Longitude**</td>
<td>Altitude</td>
<td>(wt.%)</td>
<td>(10$^{-6}$ STP/g)</td>
<td>(Ma)</td>
</tr>
<tr>
<td>Ic-1</td>
<td>Fine-medium grained biotite granodiorite</td>
<td>32° 22’ 27” N, 131° 2’ 13” E</td>
<td>800 m</td>
<td>7.230 ± 0.145</td>
<td>380.8 ± 4.4</td>
<td>13.52 ± 0.31</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>381.4 ± 4.4</td>
<td>13.55 ± 0.31</td>
<td>13.54 ± 0.22</td>
</tr>
<tr>
<td>Ic-2</td>
<td>Medium-grained biotite granodiorite</td>
<td>32° 20’ 39” N, 131° 3’ 8” E</td>
<td>900 m</td>
<td>7.319 ± 0.146</td>
<td>381.6 ± 4.3</td>
<td>13.39 ± 0.31</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>381.6 ± 4.3</td>
<td>13.39 ± 0.31</td>
<td>13.39 ± 0.22</td>
</tr>
<tr>
<td>Ic-3</td>
<td>Medium-grained biotite granodiorite</td>
<td>32° 20’ 53” N, 131° 5’ 12” E</td>
<td>980 m</td>
<td>7.612 ± 0.152</td>
<td>396.6 ± 4.5</td>
<td>13.38 ± 0.31</td>
<td>11.0</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>395.3 ± 4.5</td>
<td>13.33 ± 0.31</td>
<td>13.36 ± 0.22</td>
</tr>
<tr>
<td>Ic-4</td>
<td>Coarse-grained biotite granodiorite</td>
<td>32° 20’ 40” N, 131° 6’ 28” E</td>
<td>1090 m</td>
<td>7.449 ± 0.149</td>
<td>385.2 ± 4.2</td>
<td>13.28 ± 0.30</td>
<td>9.0</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>386.4 ± 4.2</td>
<td>13.32 ± 0.30</td>
<td>13.31 ± 0.22</td>
</tr>
</tbody>
</table>

* See Figure 1.
** Based on the WGS84 Datum.

Table 2. FT zircon and apatite dating results for the Ichifusayama Granodiorite

<table>
<thead>
<tr>
<th>Sample name</th>
<th>No. of Spontaneous</th>
<th>Induced</th>
<th>$P(\chi^2)$</th>
<th>Dosimeter</th>
<th>r</th>
<th>U-content</th>
<th>Age (± 1σ)</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zircon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ic-1</td>
<td>30</td>
<td>1.87</td>
<td>1.169</td>
<td>2.17</td>
<td>1.1936</td>
<td>0.16</td>
<td>8.392</td>
<td>2578</td>
</tr>
<tr>
<td>Ic-2</td>
<td>30</td>
<td>1.94</td>
<td>1.544</td>
<td>2.15</td>
<td>1.1716</td>
<td>0.28</td>
<td>8.399</td>
<td>2580</td>
</tr>
<tr>
<td>Ic-3</td>
<td>30</td>
<td>2.02</td>
<td>1.974</td>
<td>2.28</td>
<td>2.2255</td>
<td>&lt;0.1</td>
<td>8.407</td>
<td>2583</td>
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<tr>
<td>Ic-4</td>
<td>30</td>
<td>1.90</td>
<td>2.270</td>
<td>2.29</td>
<td>2.734</td>
<td>1</td>
<td>8.414</td>
<td>2585</td>
</tr>
<tr>
<td>Apatite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ic-1</td>
<td>30</td>
<td>0.569</td>
<td>0.791</td>
<td>3.60</td>
<td>5.009</td>
<td>&lt;0.1</td>
<td>45.89</td>
<td>2203</td>
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<tr>
<td>Ic-2</td>
<td>30</td>
<td>0.617</td>
<td>0.961</td>
<td>3.12</td>
<td>4.857</td>
<td>&lt;0.1</td>
<td>46.52</td>
<td>2233</td>
</tr>
<tr>
<td>Ic-3</td>
<td>30</td>
<td>0.552</td>
<td>1.106</td>
<td>2.96</td>
<td>5.922</td>
<td>&lt;0.1</td>
<td>47.14</td>
<td>2263</td>
</tr>
<tr>
<td>Ic-4</td>
<td>30</td>
<td>0.177</td>
<td>0.350</td>
<td>1.19</td>
<td>2.359</td>
<td>&lt;0.1</td>
<td>47.76</td>
<td>2293</td>
</tr>
</tbody>
</table>

* $\rho$ and N are the density and the total number of fission tracks counted, respectively.
** Analyses were made by the external detector method using geometry factors of 0.5 for 4π/2π (ED1, internal surface: Gleadow, 1981). Ages were calculated using a dosimeter glass NBS SRM612 and age calibration factors zeta (ED1) = 352 ± 3 (Zircon; Iwano and Danhara, 1997), zeta (ED1) = 299 ± 4 (Apatite; Iwano and Danhara, 1998). Errors for zeta values are given at one sigma. Zircon samples were irradiated using a TRIGA MARK II nuclear reactor at Rikkyo University, Japan and apatite samples were irradiated using a TRIGA nuclear reactor at Oregon State University, USA.
*** $P(\chi^2)$ is the probability of obtaining the $\chi^2$ value for n degrees of freedom (where n = number of crystals – 1).
**** r is the correlation coefficient between $\rho_s$ and $\rho_i$. 

The reliability of the ages obtained is, however, considered to be high because the number of grains measured was more than sufficient (> 25 grains: Green, 1981).

The fission–track lengths in all of the samples are, furthermore, not reduced, and the ages obtained are concordant with ages determined by other methods and materials. It therefore seems that the sampled material cooled uniformly through the closure temperatures of the K–Ar biotite system (300 ± 50 °C: Dodson and McClelland-Brow, 1985), the FT zircon system (230–330 °C: Tagami and Shimada, 1996), and the FT apatite system (70–130 °C: Gleadow et al., 1983).
The relationship between the ages obtained and the closure temperatures is shown in Figure 3. This indicates that the biotite K-Ar ages are the same but the apatite ages show a significant difference between the core (lc-2 and lc-3) and rim (lc-1 and lc-4) samples. The rim is younger than the core, suggesting that the core and rim had different cooling histories. The rim cooled down to 100 °C from 300 °C with a cooling rate of ~ 100 °C/Ma (80-130 °C/Ma). This cooling rate is of the same order and in the same temperature range as those of the Takidani Granodiorite (Bando et al., 2003), which was emplaced and exposed in the Quaternary (Harayama, 1992).

An issue arises because the core part of the Ichifusayama Granodiorite cooled down more rapidly than the rim over a period of ~ 13 Ma (Fig. 3). In the cooling of a simple plutonic body, the central part of the pluton can be expected to cool more slowly than the periphery; therefore the apatite FT age of the central part should be younger than that of the rim because the center theoretically cools through the closure temperature for apatite later. There are two possibilities to explain the unusual cooling pattern in this study. The first interpretation is that there was rejuvenation of the ages by some thermal event after cooling of the pluton. However, evidence of postintrusion thermal events, such as igneous activity or hydrothermal alteration, has not been recognized in and around the pluton (Saito et al., 1996). In addition, a shortening of the FT track lengths is not observed in any of the samples (Fig. 2) and, therefore, this possibility is ruled out.

The second interpretation is that the central part of the pluton approached ground surface earlier than the rim. If so, the central part would cool down more rapidly than the rim. The underground temperature profile on the low-temperature shallow crust is changed by the influence of topography (House et al., 1998). These authors showed that the subsurface temperature at < ~ 100 °C at ~ 1 km depth can be remarkably changed by the influence of an incised topography. Moreover, they showed that the apa-
Unusual cooling of the Middle Miocene Ichifusayama Granodiorite

T. Oikawa, K. Umeda, S. Kanazawa and T. Matsuzaki

The U-Th/He age (closed temperature: ~ 70 °C) is remarkably changed by influence of paleotopography. We thus suggest the possibility that the difference in the apatite FT ages in the Ichifusayama Granodiorite was caused by influence of the paleotopography. In the Middle Miocene (~ 13 Ma), there may have existed a NE-trending deep valley crossing above the core of the pluton such that the central part of the pluton was closer to the ground surface than the rim.

Based on obtained apatite FT ages of 7.1± 2.3, 7.6± 4.1, 8.8± 6.5 and 13.3± 3.7 Ma, ± 2σ level, Hasebe and Tagami (2001) showed that the temperature of the Shimanto Supergroup in the eastern part of Southern Kyushu decreased to ~ 100 °C at approximately 10 Ma when the Southwest Japan block obducted onto the subducting Philippine Sea Plate. Miyachi (1985) showed that the zircon FT ages from the four granitic bodies of Osumi, Takakumayama, Ichifusayama, and Shibi in the Outer Zone of Southwest Japan in Kyushu are ~ 12 Ma, indicating that the four plutons cooled down to the closure temperature (230–280 °C) at virtually the same time. The obduction of the Southwest Japan block may have led to the rapid exhumation of the Shimanto Supergroup and its igneous intrusive rocks resulting in responsive erosion and rapid dissection that incised a deep NE-trending valley crossing the core part of the Ichifusayama Granodiorite.

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