Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio heterogeneity in Kamihara Tonalite, Ryoke belt, southwest Japan: Evidence from strontium isotopic analysis of apatite

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Strontium isotopic analysis was carried out on magmatic apatite in the Kamihara Tonalite obtained from the Cretaceous Ryoke belt, southwestern Japan. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions of euhedral apatite indicated that the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (SrI) in the tonalite varies from 0.70695 to 0.70790. This provides direct evidence of SrI heterogeneity in the Kamihara Tonalite. The SrI heterogeneity is inherited to Rb-Sr whole-rock age determination, and makes the age discrepancy between the Rb-Sr age and CHIME, K-Ar ages. By combining the results of the isotopic analysis, knowledge on the whole-rock chemistry, and field observations, it can be inferred that the SrI heterogeneity in the Kamihara Tonalite was caused by the assimilation of high SrI country metamorphic rocks of the Ryoke belt.

Keywords: Apatite, Sr isotope, Granite, Kamihara Tonalite, Ryoke belt

INTRODUCTION

The Cretaceous Ryoke metamorphic belt, southwest Japan, comprises high temperature low pressure metamorphic rocks and related granitoids. Numerous radiometric dating methods such as K-Ar and Rb-Sr mineral- and whole-rock isochron methods have been used to determine the age of granitoids of the Ryoke belt. However, the Rb-Sr whole-rock isochron ages are not always consistent with those determined by considering intrusive relations or by using other dating methods (e.g., Owada et al., 1995; Suzuki and Adachi, 1998) such as the K-Ar method, SHRIMP U-Pb method, and chemical Th-U-total Pb isochron method (CHIME) (e.g., Suzuki and Adachi, 1991). Several authors (e.g., Nakai and Suzuki, 1996; Suzuki and Adachi, 1998) have suggested a model according to which the discrepancy between the age determined by the whole-rock Rb-Sr method and that obtained using other methods is due to the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (SrI) heterogeneity of the Rb-Sr isotopic system; however, this model has not been verified on the basis of isotopic analysis. Recently, a new technique involving the use of strontium isotopes of apatite has been developed to investigate the SrI in the Rb-Sr isotopic system and the magmatic processes within the granitic plutons (Tsuboi and Suzuki, 2003; Tsuboi, 2005). Apatite commonly occurs as an accessory phase in a variety of igneous rocks. It contains a very small amount of Rb (usually less than 1 ppm: Creaser and Gray, 1992) and a large amount of Sr; the high Sr content is due to the substitution of Sr for Ca in apatite. This leads to a very low Rb/Sr ratio in most apatites. Therefore, the decay of $^{87}\text{Rb}$ to $^{87}\text{Sr}$ is negligible in apatite unless there are inclusions influencing the Rb/Sr ratio. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of apatite does not change during cooling or hydrothermal alteration, and in the absence of changes, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of apatite remains unchanged. In such cases, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of apatite could be a good indicator of the SrI of the sample. Tsuboi and Suzuki (2003) and Tsuboi (2005) confirmed the reliability of apatite as an indicator of the SrI ratio in comparison with the SrI derived from mineral isochrons. The measurement of the strontium isotopic composition of apatite that is free from inclusions and alterations is a time- and cost-efficient method to obtain high-precision SrI ratios in various igneous rocks.
Initial $^{87}$Sr/$^{86}$Sr ratio heterogeneity

The Kamihara Tonalite, which occurs in the eastern part of the Ryoke belt, is one of the chronologically problematic plutons. Whole-rock Rb-Sr isotope data obtained by the isotopic analysis of the Kamihara Tonalite are observed to be scattered in the $^{87}$Sr/$^{86}$Sr-$^{87}$Rb/$^{86}$Sr diagram. Hence, no meaningful isochron can be drawn (Kagami, 1973). In this study, the new technique involving the use of strontium isotopes of apatite has been applied to the Kamihara Tonalite to reveal the SrI heterogeneity in the pluton and understand the detailed magmatic processes of the pluton.

**GEOLOGICAL SETTING AND PETROGRAPHY OF THE KAMIHARA TONALITE**

The Kamihara Tonalite, which occurs in the eastern part of the Ryoke belt, is one of the chronologically problematic plutons. The Ryoke belt is composed of pelitic, psammitic, and siliceous schists and gneisses, and related granitic plutons. The Ryoke metamorphism is a typical high-temperature low-pressure, andalusite-sillimanite type event that occurred around 100 Ma (Nakajima, 1994; Suzuki and Adachi, 1998). The grade of metamorphism in this area increases from the northwest to the southeast, up to the sillimanite-orthoclase zone at the center of the mapped area, and decreases toward the MTL. The protoliths of the metamorphic rocks are mainly chert, shale, and sandstone of the Mino terrane (Paleozoic – Mesozoic; e.g., Mizutani et al., 1981; Wakita 1987; Adachi and Suzuki, 1992). The peak pressure and peak temperature of the Ryoke metamorphism are estimated to be approximately 5 kbar and 850 °C, respectively (Brown, 1998). The Kamihara Tonalite is the oldest series of granitoid intrusions in the Cretaceous Ryoke belt. Nakai and Suzuki (1996) reported CHIME monazite ages of 94.9 ± 4.9 and 94.5 ± 3.1 Ma. The Kamihara Tonalite intrudes into country metamorphic
rocks of the Ryoke metamorphic belt and forms interfinger-
ing relationships with the metamorphic rocks in the
northeastern part of the study area (Tenryu). The contact
between tonalite and the country metamorphic rock is
generally sharp, whereas the contact between tonalite and
the gneiss xenolith of the Ryoke metamorphic rocks
within few meters of the transitional zone is gradual (Ka-
gami, 1968). In contrast, the Kamihara Tonalite intrudes
as a stock form in the southwestern part of the study area
(Shimoyama). The Kamihara Tonalite is intruded by the
Kiyosaki Granodiorite, the Tenryukyo Granodiorite
(CHIME monazite ages: 89.7 to 92.2 Ma; Nakai and
Suzuki, 1996; Suzuki and Adachi, 1998), and the Busetsu
Granite (CHIME monazite ages: 75.0 to 78.5 Ma; Suzuki
et al., 1994) (Ryoke Research Group, 1972). The Kamih-
ara Tonalite in the Tenryu and Shimoyama areas consists
of medium-grained tonalite and is characterized by well
developed foliation. It commonly contains mafic enclaves,
and each enclave is elongated in harmony with the folia-
tion. In the Shimoyama area, the foliation forms a basin
structure along the oval shaped outer boundary of the plu-
ton (Fig. 1). The Kamihara Tonalite contains plagioclase,
quartz, biotite, hornblende, and K-feldspar with minor
amounts of apatite, ilmenite, and zircon. Plagioclase is
euhedral to subhedral. The anorthite content ranges from
An$_{34-44}$ in the Shimoyama area to An$_{42-46}$ in the Tenryu
area (Masumoto et al., 2007). Most of the quartz is anhe-
dral and shows wavy extinctions. K-feldspar, biotite, and
hornblende are subhedral to anhedral. Biotite composi-
tions in the Shimoyama area (Si = 2.8 pfu, Mg#$ = 0.45
to 0.50) and the Tenryu area (Si = 2.7 to 2.8 pfu, Mg#$ = 0.41
to 0.50) are similar (Masumoto et al., 2007). Hornblende
is actinolitic (average Si = 7.0 to 7.4 pfu) and does not
show zoning (Masumoto et al., 2007). Kutsukake (1993)
reported the occurrence of cummingtonite in parallel in-
tergrowth with or as small patches in hornblende. Apatite
is a common accessory mineral and occurs mainly as
inclusions in biotite and hornblende. It develops as prismatic
grains with a length of approximately 200 µm. The
detailed petrography of the Kamihara Tonalite has been
described by Kutsukake (1993).

**ANALYTICAL PROCEDURE**

Whole-rock chemical compositions of eight samples from
the Shimoyama area and six samples from the Tenryu
area (Fig. 1) were determined by X-ray fluorescence
(XRF) analysis using a Shimadzu SXF-1200 XRF spec-
trometer equipped with a 40 kV, 70 mA rhodium target
tube. This analysis was carried out at Nagoya University.
Glass beads were prepared by fusion of whole-rock sam-
ple with Li$_3$B$_2$O$_5$ alkali flux. The amounts of sample and
flux were 0.7 and 6.0 g for major-element analyses and
2.0 and 3.0 g for trace-element analyses, respectively.
Analytical uncertainties were estimated to be 1% for SiO$_2$
and Al$_2$O$_3$, 5% for the rest of the major elements, and 10%
for trace elements. Details and discussions of the analyti-
cal methods by XRF are given in Morishita and Suzuki
(1993) and Yamamoto and Morishita (1997). Samples
used in the Rb–Sr whole-rock and apatite analyses were
taken from 11 locations (Fig. 1). For apatite separation,
approximately 2 kg of each sample was crushed in a
stamp mill to obtain grains with sizes of around 250 µm.
Heavy minerals were separated by a standard procedure
using an isodynamic magnetic separator and heavy liq-
uids. All the apatite grains were manually selected after
observation under a binocular microscope in order to
ensure the selection of only euhedral grains and grains
without inclusions. Approximately 200 apatite grains
were collected from each sample. The apatite grains were
washed with ultra fine grade ethanol and distilled water in
an ultrasonic bath.

After the apatite grains (approximately 1 mg) dis-
solved in HCl, Sr was separated from the major elements
by using a cation-exchange resin with an HCl carrier.
Whole–rock, biotite, hornblende, and felsic (mainly pla-
gioclase with small amounts of quartz and K-feldspar)
fractions of the samples were also used in the Sr isotope
analyses. These samples (200 mg) were decomposed
using a mixture of HF + HClO$_4$. The decomposed samples
were divided into two aliquots. One was used in the stron-
tium isotopic analysis and the other for isotope dilution.
Rb and Sr were separated from the major elements by
using the cation-exchange resin. The Rb and Sr contents
were determined using the isotope dilution method; a
quadrupole thermal ionization mass spectrometer (Finni-
gan MAT THQ) was used. The Sr isotopic compositions
were measured at Nagoya University using a thermal ion-
ization mass spectrometer (VG SECTOR 54-30) in the
multidynamic analysis mode (Table 2). The reproduc-
ibility of the Sr isotope ratios for the NBS 987 standard
during apatite analyses was $^{87}$Sr/$^{86}$Sr = 0.710250 ± 0.000024
(2σ, n = 14).

**RESULTS**

The whole-rock chemical compositions of the Kamihara
Tonalite are shown in Table 1. The silica content (SiO$_2$)
varies from 58.7 to 62.8 wt% for the samples obtained
from the Shimoyama area and from 57.8 to 67.7 wt%
for the samples obtained from the Tenryu area. Figure 2
shows Harker’s variation diagram for whole-rock data
obtained by this study, Morishita and Suzuki (1993),
Kutsukake (1993, 1970), and Kagami (1968). The Na$_2$O
Initial $^{87}$Sr/$^{86}$Sr ratio heterogeneity and Rb increase, while the TiO$_2$, Al$_2$O$_3$, FeO, MnO, MgO, CaO, and P$_2$O$_5$ contents decrease with increase in SiO$_2$. The K$_2$O content is relatively constant. It is found that there are no significant differences in the whole-rock chemical compositions between the Tenryu and Shimo-yama areas.

Whole-rock, plagioclase, hornblende, and biotite fractions from sample SH3 yield an isochron of 65.2 ± 2.7 Ma with Srl of 0.70794 ± 0.00008 (Fig. 3). This age is significantly less than the CHIME monazite age (approximately 95 Ma; Nakai and Suzuki, 1996), but is consistent with the reported K-Ar biotite age (67 Ma; Kawano and Ueda, 1966). The consistency between the $^{87}$Sr/$^{86}$Sr ratio of apatite (0.70782 ± 0.00003) and the Srl obtained from the mineral isochron of sample SH3 suggests that the Kamihara Tonalite preserves its $^{87}$Sr/$^{86}$Sr ratio since Rb-Sr system was closed. Similarly, the $^{87}$Sr/$^{86}$Sr ratios of apatite in the other ten samples (SH1, 2, 4, 5; TE1–6) are also consistent with the Srl of the whole-rock, which is corrected to 65 Ma (Table 2). The $^{87}$Sr/$^{86}$Sr ratio of apatite ranges from 0.70695 to 0.70787 in the Tenryu area and from 0.70782 to 0.70790 in the Shimoyama area, except for the sample SH5 (0.70731) obtained from the center of the pluton. Figure 1 shows the spatial distribution of the $^{87}$Sr/$^{86}$Sr ratio of apatite in the Kamihara Tonalite. The ratio varies extensively in the Tenryu area, but no systematic spatial variation is recognized. The $^{87}$Sr/$^{86}$Sr ratio of apatite in the Shimoyama area is relatively homogeneous.

### DISCUSSION AND CONCLUSIONS

Apatite, which forms euhedral grains, in the Kamihara Tonalite, is regarded as a primary mineral because it has a prismatic shape and is commonly observed in biotite and hornblende. Thus, apatite preserves the Srl of the host magma. The extensive variation in the $^{87}$Sr/$^{86}$Sr ratio suggests that the Srl heterogeneity occurred during the crystallization of the magma in the Tenryu area. Due to the Srl heterogeneity in the pluton, the Rb-Sr whole-rock ages of 110-265 Ma for the Kamihara Tonalite and Tenryukyo Granodiorite reported by Kagami (1973) are considered to be errorchron ages. The Srl heterogeneity of the Rb-Sr system is ascribed to the original heterogeneity of the magma and/or the assimilation of country rocks into an evolving magma (e.g., Schärer et al., 1984). Figure 4 shows plots of the $^{87}$Sr/$^{86}$Sr ratio of apatite against the Rb/Sr ratio of the host whole-rock in the Kamihara Tonalite together with the plot of the Srl of the whole-rock of the

### Table 1. Whole-rock chemical compositions of the Kamihara Tonalite

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>SH1</th>
<th>SH2</th>
<th>SH3</th>
<th>SH4</th>
<th>SH5</th>
<th>SH6</th>
<th>SH7</th>
<th>SH8</th>
<th>TE1</th>
<th>TE2</th>
<th>TE3</th>
<th>TE4</th>
<th>TE5</th>
<th>TE6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$ (wt%)</td>
<td>58.7</td>
<td>60.7</td>
<td>60.6</td>
<td>60.9</td>
<td>62.8</td>
<td>62.1</td>
<td>61.7</td>
<td>58.6</td>
<td>67.7</td>
<td>59.5</td>
<td>57.8</td>
<td>61.4</td>
<td>62.0</td>
<td></td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.78</td>
<td>0.75</td>
<td>0.89</td>
<td>0.79</td>
<td>0.78</td>
<td>0.72</td>
<td>0.78</td>
<td>0.77</td>
<td>0.86</td>
<td>0.85</td>
<td>0.83</td>
<td>0.92</td>
<td>0.79</td>
<td>0.67</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>15.6</td>
<td>16.3</td>
<td>16.4</td>
<td>16.9</td>
<td>15.8</td>
<td>15.8</td>
<td>16.2</td>
<td>16.8</td>
<td>15.7</td>
<td>15.7</td>
<td>16.9</td>
<td>17.2</td>
<td>17.1</td>
<td>16.1</td>
</tr>
<tr>
<td>FeO$^*$</td>
<td>7.16</td>
<td>5.42</td>
<td>6.42</td>
<td>5.63</td>
<td>5.81</td>
<td>5.14</td>
<td>5.75</td>
<td>5.54</td>
<td>6.69</td>
<td>4.03</td>
<td>6.09</td>
<td>6.70</td>
<td>5.28</td>
<td>5.09</td>
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<tr>
<td>MnO</td>
<td>0.16</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.14</td>
<td>0.09</td>
<td>0.12</td>
<td>0.13</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>MgO</td>
<td>4.58</td>
<td>3.23</td>
<td>3.84</td>
<td>3.17</td>
<td>3.29</td>
<td>3.43</td>
<td>3.37</td>
<td>3.04</td>
<td>4.01</td>
<td>1.09</td>
<td>2.57</td>
<td>3.93</td>
<td>3.19</td>
<td>3.20</td>
</tr>
<tr>
<td>CaO</td>
<td>6.05</td>
<td>5.13</td>
<td>5.75</td>
<td>5.30</td>
<td>5.35</td>
<td>4.78</td>
<td>5.06</td>
<td>5.06</td>
<td>6.18</td>
<td>3.34</td>
<td>5.77</td>
<td>6.40</td>
<td>4.92</td>
<td>5.32</td>
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<tr>
<td>Na$_2$O</td>
<td>2.87</td>
<td>3.03</td>
<td>3.04</td>
<td>2.94</td>
<td>3.06</td>
<td>2.85</td>
<td>2.96</td>
<td>3.06</td>
<td>3.04</td>
<td>3.86</td>
<td>3.32</td>
<td>3.10</td>
<td>3.10</td>
<td>3.04</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>2.05</td>
<td>2.12</td>
<td>2.16</td>
<td>2.24</td>
<td>2.31</td>
<td>2.88</td>
<td>2.50</td>
<td>2.48</td>
<td>1.76</td>
<td>1.76</td>
<td>1.81</td>
<td>1.81</td>
<td>2.16</td>
<td>1.96</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.14</td>
<td>0.15</td>
<td>0.19</td>
<td>0.17</td>
<td>0.17</td>
<td>0.13</td>
<td>0.15</td>
<td>0.15</td>
<td>0.16</td>
<td>0.22</td>
<td>0.19</td>
<td>0.15</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>98.1</td>
<td>98.2</td>
<td>99.7</td>
<td>97.9</td>
<td>98.3</td>
<td>98.6</td>
<td>98.6</td>
<td>98.1</td>
<td>98.2</td>
<td>98.1</td>
<td>97.1</td>
<td>98.2</td>
<td>98.2</td>
<td>97.6</td>
</tr>
</tbody>
</table>

* Not detected.

$^*$ Total iron as FeO.

i, determined by isotope dilution method.

and Rb increase, while the TiO$_2$, Al$_2$O$_3$, FeO, MnO, MgO, CaO, and P$_2$O$_5$ contents decrease with increase in SiO$_2$. The K$_2$O content is relatively constant. It is found that there are no significant differences in the whole-rock chemical compositions between the Tenryu and Shimo-yama areas.

Whole-rock, plagioclase, hornblende, and biotite fractions from sample SH3 yield an isochron of 65.2 ± 2.7 Ma with Srl of 0.70794 ± 0.00008 (Fig. 3). This age is significantly less than the CHIME monazite age (approximately 95 Ma; Nakai and Suzuki, 1996), but is consistent with the reported K-Ar biotite age (67 Ma; Kawano and Ueda, 1966). The consistency between the $^{87}$Sr/$^{86}$Sr ratio of apatite (0.70782 ± 0.00003) and the Srl obtained from the mineral isochron of sample SH3 suggests that the Kamihara Tonalite preserves its $^{87}$Sr/$^{86}$Sr ratio since Rb-Sr system was closed. Similarly, the $^{87}$Sr/$^{86}$Sr ratios of apatite in the other ten samples (SH1, 2, 4, 5; TE1–6) are also consistent with the Srl of the whole-rock, which is corrected to 65 Ma (Table 2). The $^{87}$Sr/$^{86}$Sr ratio of apatite ranges from 0.70695 to 0.70787 in the Tenryu area and from 0.70782 to 0.70790 in the Shimoyama area, except for the sample SH5 (0.70731) obtained from the center of the pluton. Figure 1 shows the spatial distribution of the $^{87}$Sr/$^{86}$Sr ratio of apatite in the Kamihara Tonalite. The ratio varies extensively in the Tenryu area, but no systematic spatial variation is recognized. The $^{87}$Sr/$^{86}$Sr ratio of apatite in the Shimoyama area is relatively homogeneous.

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Kamihara Tonalite. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of pelitic and psammitic rocks in the Ryoke metamorphic belt (Kagami, 1973; Yuhara, 1994; Yuhara and Kagami, 1995) are also plotted. All whole-rock data are corrected to 65 Ma. In the Tenryu area, the SrI increases with the Rb/Sr ratio toward to the Ryoke metamorphic rocks. The simple mixing line connecting the two end-member compositions roughly indicates the observed SrI variation in the Kamihara Tonalite (Fig. 4). This suggests that the mixing of the magma and wall metamorphosed sedimentary rocks
occurred simultaneously. The whole-rock chemical composition diagram also indicates the assimilation of the Ryoke metamorphic rocks since the plots of the Kamihara Tonalite and the Ryoke metamorphic rocks are similar (Fig. 2). The SrI heterogeneity of the Kamihara Tonalite is mainly due to the wall-rock assimilation. The mixing of the original magma to various extents with the country metamorphic rocks can produce rocks with intermediate chemical and isotopic compositions. The SrI reported by Kagami (1973) for the Tenryu area are systematically higher (0.7081–0.7118) than those of the samples obtained from other locations in the Tenryu area in this study (0.7069–0.7079) (Fig. 4). The whole-rock chemical compositions of the samples that were used by Kagami (1973) have relatively higher SiO₂ and are similar to the country metamorphic rocks (Fig. 2). This implies that the rocks studied by Kagami (1973) were assimilated into the country metamorphic rocks to a greater extent.

A two-component simple model is used for studying the mixing of the granitic magma and country metamorphic rocks in the Kamihara Tonalite (Fig. 5). The ⁸⁷Sr/⁸⁶Sr ratio of the original magma as a low-ratio end-member is assumed to be 0.7069 with a Sr content of 390 ppm (sample TE3). The mean SrI (0.7174) with a Sr content of 170 ppm is used for the end-member compositions of the country metamorphic rocks. In this model, the original magma and the wall metamorphic rocks were estimated to be mixed in the ratio 8:2 for the Shimoyama area and 3:7 for the Tenryu area. The effect of assimilation is more significant in the Tenryu area. This is supported by field

Table 2. Rb and Sr values obtained from the analysis of the Kamihara Tonalite

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>⁸⁷Rb/⁸⁶Sr</th>
<th>⁸⁷Sr/⁸⁶Sr (2σ)</th>
<th>⁸⁷Sr/⁸⁶Sr (65Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH1</td>
<td>Whole-rock</td>
<td>77.0</td>
<td>290</td>
<td>0.769</td>
<td>0.708460 (16)</td>
<td>0.707750</td>
</tr>
<tr>
<td></td>
<td>Apatite</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SH2</td>
<td>Whole-rock</td>
<td>85.0</td>
<td>323</td>
<td>0.761</td>
<td>0.708440 (14)</td>
<td>0.707737</td>
</tr>
<tr>
<td></td>
<td>Apatite</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SH3</td>
<td>Biotite</td>
<td>328</td>
<td>17.3</td>
<td>55.1</td>
<td>0.758544 (15)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hornblende</td>
<td>6.1</td>
<td>29.1</td>
<td>0.607</td>
<td>0.708853 (20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Whole-rock</td>
<td>68.2</td>
<td>361</td>
<td>0.547</td>
<td>0.708272 (16)</td>
<td>0.707767</td>
</tr>
<tr>
<td></td>
<td>Felsic</td>
<td>4.6</td>
<td>424</td>
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<td>88.2</td>
<td>325</td>
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<td>393</td>
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<td>68.1</td>
<td>367</td>
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<td>89.6</td>
<td>315</td>
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Not analyzed.
* The errors in the final digits are shown.
observations. These observations have uncovered the fact that the Kamihara Tonalite intrudes into the country metamorphic rocks of the Ryoke belt in the Tenryu area and forms interfingering relationships with the metamorphic rocks and gradual contacts. The SrI values in the Shimoyama area are relatively uniform within the pluton, although its chemical compositions widely vary. Thus, the whole-rock chemical variations in the Kamihara Tonalite in the Shimoyama area can be explained by fractional crystallization. Assuming the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the original magma to be as low as the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of sample TE3 obtained from the Tenryu area, it can be inferred that the Kamihara Tonalite in the Shimoyama area was emplaced after the assimilation of wallrocks to an extent of 20% and subsequent complete homogenization. These emplacements occurred under a pressure ranging from 0.15 to 0.44 GPa (Masumoto et al., 2007).

Tsuboi and Suzuki (2003) determined the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of magmatic apatite in a single-zoned pluton of the Habu Granodiorite in the western part of the Ryoke belt. The Sr isotopic compositions of euhedral apatite coupled with those determined through mineral isochrons and whole-rock data indicate that the SrI values of the samples vary from 0.7054 to 0.7074. They concluded that the SrI heterogeneity was caused by the heterogeneity of the magma source materials. Tsuboi (2005) determined the spatial distribution of SrI (0.7093–0.7107) within the Inagawa Granite batholith of the eastern Ryoke belt by using the apatite technique. The heterogeneity was caused by the mixing between mafic and felsic magmas. By comparing the previous studies with this study, we conclude that the SrI heterogeneity in the granitic pluton in the Ryoke belt is caused by the following factors: (1) the heterogeneity of the source magma (e.g., Tsuboi and Suzuki, 2003), (2) magma-magma mixing (e.g., Tsuboi, 2005), and (3) assimilation of the country metamorphic rocks (this study). Such SrI heterogeneity would lead to the erroneous estimation of the Rb-Sr whole-rock age in granitic plutons.

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REFERENCES


Geological Survey of Japan (1972) Geological map of the Toyohashi area (scale 1:200,000).


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Initial 87Sr/86Sr ratio heterogeneity

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