Common occurrence of calcic plagioclase in granitoids from Mt. Kaizuki area, central Japan

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Calcic plagioclase with anorthite (An) content of up to 91% commonly occurs in coexistence with the sodic phase (An<40–50) in the Cretaceous Kaizuki-yama (Mt. Kaizuki) granitoid body that intrudes into the Mino belt of the Jurassic accretionary sediment complex in central Japan. The Kaizuki-yama granitoids are mainly composed of plagioclase, K-feldspar, quartz, and biotite with subordinate amounts of amphibole, ilmenite, and apatite. The sodic plagioclase grains show common igneous-type normal zoning with decreasing anorthite content toward the rim. In most cases, the calcic plagioclase occurs as a crystal core, which is discontinuously surrounded by a sodic mantle. The calcic parts rarely show fine and nebular texture with sodic domains; however, a thin calcic zone (100–150 µm in width) develops along the boundary between the nebular core and the sodic mantle. In the nebular core, calcic plagioclase sometimes rims the fine-grained calcite, prehnite, and zoisite/epidote (less than 10–20 µm in size). Most amphibole grains have ferropargasite/ferrohornblende compositions and are usually rimmed by secondary ferro-actinolite. Although the pressure/temperature conditions estimated based on amphibole-plagioclase equilibria vary widely between samples, they show systematic decreases in pressure with decreasing temperature from 0.5 GPa/800 °C to approximately 0.2 GPa/700 °C. Some anorthite-rich plagioclase grains may have been xenocrystic and/or antecrystic in origins, and others were crystallized from calcic part of locally heterogeneous magma. The incorporation of calcic plagioclase into the felsic magma and the locally calcic environment probably resulted from the assimilation of skarn and related calcareous rocks consisting of the wall rocks of the Kaizuki-yama body during magmatic intrusion and solidification.

Keywords: Anorthite, Granitoid, Assimilation, Amphibole-plagioclase geothermobarometry, Cretaceous

INTRODUCTION

Plagioclase is a common constituent mineral in igneous rocks, and its anorthite content systematically decreases with increasing SiO2 content and decreasing CaO/Na2O value in their whole-rock compositions (e.g., Deer et al., 2001). Thus, plagioclase in felsic igneous rocks generally exhibits a less calcic composition of An<40–50, where the endmember proportion is estimated by An = Ca/(Ca + Na + K + Ba) × 100. Calcic plagioclase has been, however, rarely reported to occur in granitoid, and several origins of calcic plagioclase have been proposed. Blundy and Shimizu (1991) systematically measured major and trace elements of plutonic plagioclase grains in hornblende-gabbro, diorite, and granitoid from the Val Fredda Complex in the southern Adamello Massif, Italy, and reported occurrences of calcic plagioclase (up to An87), including its presence in felsic rocks with SiO2 ≈ 72 wt%. They also demonstrated that the zoning patterns and concentrations of trace elements in plagioclase grains are similar to each other, irrespective of the host rock composition, concluding that (1) the plagioclase grains were all comagmatic in origin and (2) early-formed calcic plagioclase in basaltic magma was ‘recycled’ by the magma during fractionation and remained as a core of zoned plagioclase in more evolved magmas. Calcic plagioclase grains (up to An82) were reported to occur as a core of large plagioclase crystals in calc-alkaline granitoids from the Sázava intrusion, Central Bohemian Pluton, Czech
Republic (Janoušek et al., 2004). These calcic cores were interpreted to have crystallized from mafic magma prior to its injection into a high-level felsic magma chamber, suggesting that the magma mixing process played a role in the genesis of their host granitoids. Thus, the calcic plagioclase in granitoid rocks is generally considered to originate primarily from mafic rock (magma) and implies lines of evidence for the assimilation of mafic rocks into granitic rocks and/or mixing of mafic and felsic magmas in a magma chamber.

Calcic plagioclase up to An ninety-one commonly occurs in the granodiorite of the late Cretaceous Kaizuki-yama (Mt. Kaizuki) pluton in central Japan. The calcic plagioclase exists in two different modes: (1) patch core mantled by andesine and less calcic plagioclase and (2) fine-grained aggregates with prehnite and zoisite/epidote in less calcic and zoned plagioclase. This paper describes the petrological and mineralogical characteristics of the calcic plagioclase-bearing granitoids and the textural and compositional characteristics of the calcic plagioclase, and discusses their possible origins.

GEOLGICAL SETTING

The Kaizuki-yama granitoid body is a member of the Cretaceous granitoid complexes distributed around Biwa-ko (Lake Biwa) in central Japan (Figs. 1a and 1b). Sawada et al., 1994). This body is one of the largest plutons among the Cretaceous granitoid complexes in existence and occurs as an elliptical and zoned pluton that extends approximately 14 km from north to south and 11.5 km from east to west in the Mino belt of the Jurassic accretionary complex (Fig. 1c: Saito and Sawada, 2000). Sedimentary rocks in the Mino belt around the Kaizuki-yama granitoid, which is now exposed at the land surface, represent the subsurface structure of the Kaizuki-yama body. They geologically and petrologically discussed the subsurface structure of the Kaizuki-yama body and proposed a cross-sectional diagram of the area implying a structural relationship between the Kaizuki-yama granitoids and the surrounding sedimentary sequences (Fig. 2). They suggested the possibility that the Mino sedimentary complexes thinly cover the Kaizuki-yama body on the north and east sides and thus, the main part of the granitoid, which is now exposed at the land surface, represents the marginal facies of a zoned pluton.

Figure 3 summarizes the radiometric ages of the igneous rocks of the Kaizuki-yama and surrounding area. Sawada et al. (1994) reported Rb-Sr whole-rock and mineral isochron ages for the granitoids of 94.1 ± 5.0 and 96.4 ± 4.8 Ma, respectively. Similar K-Ar ages of 94.6 ± 4.7-98.8 ± 4.9 and 95.9 ± 4.8 Ma were reported for biotite and muscovite, respectively (Saito and Sawada, 2000). Although the K-Ar ages of the dikes vary slightly, they are distinctly younger than those of the Kaizuki-yama granitoids; felsic dikes (quartz diorite porphyry and quartz diorite) generally show older K-Ar ages of 69.5 ± 3.5-81.4 ± 4.1 Ma than the basalt (68.5 ± 3.4-70.1 ± 3.5 Ma) and andesite (16.5 ± 0.8-56.2 ± 2.8 Ma) dykes (Kurimoto et al., 1999; Saito and Sawada, 2000).

PETROGRAPHY OF GRANITOIDs

Amphibole-bearing coarse-grained granite and granodiorite are main members of the Kaizuki-yama pluton and are composed of plagioclase, K-feldspar, quartz, and biotite with subordinate amounts of amphibole. Ilmenite, apatite, zircon, titanite, monazite, allanite, and tourmaline also occur as minor and accessory phases. Mineral assemblages of the thirteen samples studied are listed in Table 1 and their localities are shown in Figure 1c. Modal amounts of plagioclase, amphibole, and biotite of the am-
phibole granitoids gradually decrease from the marginal part of the body toward the coarse–grained porphyritic biotite granite that occupies the central part of the Kai–zuki–yama body (Sugii and Sawada, 1999). The coarse–grained porphyritic granite has a similar mineral assemblage to that of common coarse–grained granite and granodiorite, and characteristically contains a megacryst of $K$–feldspar (2–7 cm in length). Most biotite grains occur as inclusions in plagioclase and $K$–feldspar, and as isolated grains in the matrix. Amphibole grains usually occur as aggregate with biotite in the matrix (Fig. 4a) and, rarely, as inclusions in plagioclase (Figs. 4b and 4c). Plagioclase grains are euhedral to subhedral and some are
composed of calcic and sodic parts. K–feldspar grains usually include plagioclase and biotite grains. Epidote and zoisite were formed as alteration products after plagioclase. Muscovite granite is mainly composed of plagioclase, K–feldspar, quartz, and biotite with accessories of muscovite, ilmenite, apatite, monazite, and zircon.

ANALYTICAL PROCEDURES

The whole-rock major and trace element compositions were measured by X-ray fluorescence spectrometry (XRF) using a Shimadzu XRF-1800 spectrometer at Kwansei Gakuin University. The rhodium target X-ray tube was energized at a voltage of 40 kV and current of 70 mA for the major element analysis. The XRF analytical methods used in this study followed those reported by Morishita and Suzuki (1993) and Nakazaki et al. (2004). Major and trace element compositions of the granitoids newly analyzed in this study are listed in Table 2. Strontium isotopic compositions of whole-rock samples were determined by thermal ionization mass spectrometry. Samples were decomposed with a mixed HF-HNO3 acid, and strontium was separated from other matrix elements using a cation exchange resin with an HCl carrier. \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios were measured with a VG Sector 54–30 thermal ionization mass spectrometer in multidynamic analysis mode at Nagoya University. The mass fractionation during the Sr isotope measurement was corrected based on \(^{86}\text{Sr}/^{88}\text{Sr} = 0.1194\). The average \(^{87}\text{Sr}/^{86}\text{Sr}\) for the NIST-SRM987 standard during this study was 0.710258 ± 0.000023 (2σ, n = 8).

Chemical analyses of major constituent minerals were carried out using an electron probe microanalyzer (EPMA) with wavelength- and energy-dispersive X-ray spectrometer systems (JXA-8900R) at Nagoya University. The accelerating voltage and beam current were kept at 15 kV and 12 nA on the Faraday cup, respectively. A beam diameter of 5 µm was used for the analyses of biotite and feldspars, and 2–3 µm for the analyses of all other phases. The factors calculated by Kato (2005) were employed for the matrix correction. Amphibole compositions for the mineral descriptions are determined by employing the \(\text{Fe}^{3+}/\text{Fe}^{2+}\) estimates suggested by Holland and Blundy (1994). Selective analyses of amphibole compositions are listed in Table 4. Anorthite contents of plagioclase grains are given in Tables 1 and 4. Representative compositions of mica group minerals and other phases are listed in Supplementary Tables S1 and S2 (available online from https://doi.org/10.2465/jmps.190118), respectively. Endmember and mineral abbreviations follow those of Whitney and Evans (2010).

WHOLE-ROCK CHEMISTRY

The Kaizuki-yama granitoids show relatively broad SiO\(_2\) content (66.5–73.3 wt%) and modified alkali–lime index (MALI) values (3.5–6.0), and most of them belong to the calc–alkalic series described by Frost et al. (2001) (Fig. 5a). The aluminum-saturation index (ASI: e.g., Chappell and White, 1974; Zen, 1986) increases from 1.01 to 1.11 with increasing SiO\(_2\) content, suggesting wide variations in the whole-rock composition of the peraluminous group (Fig. 5b). The granitoid samples, for which plagioclase grains were studied in detail, tend to have less silicic compositions with SiO\(_2\) = 66.5–71.9 wt% and lower MALI (3.5–4.6) and ASI (1.04–1.13) values than other...
Kaizuki-yama granitoids. They, however, partly share similar compositional ranges to other granitoids reported in the literature and exhibit simple compositional trends on the MALI–SiO$_2$ and ASI–SiO$_2$ diagrams.

The measured $^{87}$Sr/$^{86}$Sr values of the Kaizuki-yama granitoids vary from 0.708566 to 0.709352 (Table 3). The calculated initial $^{87}$Sr/$^{86}$Sr values, assuming an Rb-Sr isochron age of 95 Ma (Sawada et al., 1994), are relatively low at 0.70676–0.70750 (0.70694 on average) and are consistent with the initial $^{87}$Sr/$^{86}$Sr values (0.70687–0.70704) of the Kaizuki-yama granitoids reported by Sawada et al. (1994).

### MINERALOGY

#### Plagioclase

Figure 6 shows variations of the anorthite content of plagioclase in the Kaizuki-yama granitoids. Most plagioclase grains exhibit igneous normal zoning with decreases...
ing anorthite content from the crystal core toward the rim, and have a compositional range of An<40–50 similar to that of common granitoids reported in literature (e.g., Ribbe, 1983; Deer et al., 2001). However, calcic compositions with An>60–70 are locally observed in some grains, with the maximum value reaching An91 (Fig. 6). A distinct compositional gap exists between the calcic and less calcic parts in most calcic plagioclase-bearing samples. Figures 7a–7c show X-ray maps of typical plagioclase grains that contain calcic parts. The calcic parts primarily occur in the plagioclase core (Figs. 7a and 8a). They rarely form in the nebular core with sodic plagioclase, but a thin calcic zone develops along the boundary between the core and mantle parts (Figs. 7b, 7c and 8b). The calcic plagioclase partly replaces irregular-shaped and fine-grained prehnite (Fig. 7d). The plagioclase sometimes includes amphibole, calcite, and tourmaline (Figs. 4 and 7).

**Amphibole**

Amphibole grains in the matrix were altered along cracks and cleavages, and around the rim to varying degrees, with compositions ranging from ferropargasite/ferrohornblende to ferro-actinolite, as shown in Figure 9. The aluminous parts of the grains, which probably represent primary and igneous compositions, also vary from sample to sample: Si = 7.20 atom per formula unit (apfu), Al = 0.98 apfu, and [A](Na + K) = 0.23 apfu (for O = 23) in HM03, and Si = 6.81 apfu, Al = 1.37 apfu, and [A](Na + K) = 0.39 apfu in R68350, where superscript [A] indicates the largest A-site. Amphibole grains rarely occur as inclusions in plagioclase (Figs. 4 and 7a). Although they were partly altered to a less aluminous phase, the surviving parts have a more aluminous composition than the matrix amphibole: e.g., Si = 6.41 apfu, Al = 1.94 apfu, and [A](Na + K) = 0.54 apfu in R68350 (Fig. 9a).

**Other minerals**

Biotite grains in the matrix are relatively homogeneous, with crystals in the matrix (Si = 2.76–2.82 apfu for O = 11 and XMg = 0.36–0.38 on average) similar to those enclosed by plagioclase (Si = 2.76–2.77 apfu and XMg =

### Table 2. Whole-rock compositions of the Kaizuki-yama granitoids from central Japan

| Sample | HM02 | HM04 | HM05 | HM06 | HM09 | R359 |
|--------|------|------|------|------|------|------|
| (wt%)  |      |      |      |      |      |      |
| SiO₂   | 71.94| 68.41| 67.71| 68.54| 69.97| 67.80|
| TiO₂   | 0.33 | 0.37 | 0.38 | 0.52 | 0.40 | 0.40 |
| Al₂O₃  | 15.47| 15.69| 16.02| 16.07| 15.48| 15.44|
| Fe₂O₃* | 2.65 | 3.18 | 3.26 | 4.12 | 3.38 | 3.34 |
| MnO    | 0.06 | 0.07 | 0.08 | 0.09 | 0.08 | 0.08 |
| MgO    | 0.79 | 0.96 | 0.98 | 1.35 | 1.02 | 0.98 |
| CaO    | 2.88 | 2.87 | 2.95 | 3.07 | 2.70 | 2.95 |
| Na₂O   | 3.32 | 3.42 | 3.51 | 3.46 | 3.37 | 3.47 |
| K₂O    | 3.63 | 3.93 | 4.07 | 3.06 | 3.95 | 3.74 |
| P₂O₅   | 0.11 | 0.12 | 0.13 | 0.18 | 0.13 | 0.13 |
| Total  | 101.18| 99.02| 99.09| 100.46| 100.48| 98.33 |

*Total iron as Fe₂O₃.
R359, R68359.

n.d., not detected.
Their TiO₂ and BaO contents are as high as 4.3 and 0.6 wt% in the matrix and 3.6 and 0.6 wt% in the plagioclase inclusion, respectively. Orthoclase content of K-feldspar ranges from Or₈₉ to Or₉₅ on average, and BaO content is as high as 0.9 wt%. Muscovite has a near endmember composition of Si = 3.08 apfu (for O = 11) and XNa = Na/(Na + K + Ca + Ba) = 0.05 on average, and BaO = 0.38 wt% at maximum. Most secondary clinozoisite–epidote grains are aluminous and their XFe³⁺ = Fe³⁺ / (Fe³⁺ + Al) value varies from 0.08 to 0.20. XFe³⁺ values of zoisite are less than 0.05.

**PRESSURE-TEMPERATURE ESTIMATES**

Equilibrium P–T conditions of the Kaizuki–yama granitoids were estimated by a combination of amphibole–plagioclase thermometry proposed by Holland and Blundy (1994) and empirical Al–in hornblende igneous geobarometers calibrated by Hammarstrom and Zen (1986), Hollister et al. (1987), Johnson and Rutherford (1989), Blundy and Holland (1990), Schmidt (1992), and Anderson and Smith (1995). Amphibole grains in the matrix were altered during subsolidus cooling to a varying degree, and thus, the most aluminous composition was employed for the P–T estimations. For plagioclase, average compositions of the relatively homogeneous part, with the exception of the calcic part and sodic outermost rim, were used for calculations. Standard deviations of anorthite content of the homogeneous parts are defined by the An₅₉ (1σ level) value in each sample (e.g., Fig. 6). Equilibrium conditions of aluminous amphibole included in plagioclase (sample R68350) are estimated using a dataset listing different plagioclase composition (An₅₉) around the amphibole inclusion.

The estimated equilibrium conditions using matrix amphiboles show a systematic decrease in pressure with decreasing temperature from approximately 0.5 GPa/800 °C to 0.2 GPa/700 °C (Fig. 10), and the estimated lower conditions are roughly coincident with the solidus conditions of granitoids reported by Piwinskii and Wyllick (1968). The amphibole grains included in the plagioclase of sample R68350 yield higher P-T conditions (0.56 GPa/810 °C) than those in the matrix (0.34 GPa/760 °C), and these P-T conditions share a similar P-T trend to the trends shown by the matrix datasets from other samples.

**DISCUSSION**

**Genesis of calcic plagioclase**

The similarity between the P-T trends estimated using matrix assemblages and the set of matrix and inclusion assemblages of sample R68350 (Fig. 10) implies that the P-T systematic behavior probably provides a record of the cooling history during the magma ascent. The samples that record high P-T conditions all contain calcic plagioclase, suggesting that the calcic part of the plagioclase had already existed at the early stage in the formation of the Kaizuki–yama granitoid pluton. In this case, the calcic part may have been trapped as xenocryst in the Kaizuki–yama felsic magma. However, the cingular calcic plagioclase sometimes occurs at intermediate positions of the zoned plagioclase as well as in the core part (Figs. 7b and 8b). This texture makes it difficult to assume that such calcic parts have xenocrystic and/or antecrystic origins (e.g., Davidson et al., 2007; Miller et al., 2007). Therefore, at least some calcic parts are igneous and their crystalization may have repeatedly progressed during the early stages of solidification of calcic part of locally heterogeneous magma.

Occurrence of calcic plagioclase in granitoids has generally been considered to present evidence of the mixing of felsic and mafic magmas, and has been proposed for some granitoid complexes, such as the Val Fredda.
### Table 4. Representative analyses of amphibole and anorthite content of plagioclase in the Kaizuki–yama granitoids from central Japan

| Sample Modes | HM01a Matrix | HM02 Matrix | HM03 Matrix | HM04 Matrix | HM05 Matrix | HM06 Matrix | HM09 Matrix |
|--------------|--------------|-------------|-------------|-------------|-------------|-------------|-------------|
| (wt%)        |              |             |             |             |             |             |             |
| SiO₂         | 45.44        | 43.05       | 47.23       | 46.83       | 43.18       | 46.20       | 46.52       |
| TiO₂         | 1.10         | 1.48        | 0.65        | 0.74        | 1.95        | 0.99        | 0.65        |
| Al₂O₃        | 7.40         | 9.25        | 5.44        | 5.57        | 7.94        | 7.19        | 5.64        |
| FeO*         | 20.66        | 20.64       | 21.86       | 20.82       | 24.44       | 20.29       | 21.03       |
| MnO          | 0.79         | 1.13        | 1.56        | 1.42        | 1.23        | 0.79        | 1.44        |
| MgO          | 8.71         | 7.53        | 8.74        | 8.67        | 5.36        | 8.95        | 8.60        |
| CaO          | 10.82        | 10.83       | 9.85        | 10.62       | 10.74       | 10.87       | 10.67       |
| Na₂O         | 1.26         | 1.45        | 1.09        | 0.92        | 1.33        | 1.16        | 1.02        |
| K₂O          | 0.76         | 0.94        | 0.43        | 0.43        | 0.93        | 0.75        | 0.49        |
| Total        | 96.94        | 96.30       | 96.85       | 96.16       | 97.10       | 97.19       | 96.06       |

** Formulae (O = 23)**

| Si  | 6.899 | 6.637 | 7.194 | 7.180 | 6.733 | 6.977 | 7.142 |
| Ti  | 0.126 | 0.172 | 0.074 | 0.085 | 0.229 | 0.112 | 0.075 |
| Al  | 1.324 | 1.681 | 0.977 | 1.006 | 1.459 | 1.280 | 1.020 |
| FeO* | 0.502 | 0.449 | 0.436 | 0.376 | 0.408 | 0.442 | 0.453 |
| Mg  | 2.122 | 2.212 | 2.349 | 2.294 | 2.779 | 2.121 | 2.247 |
| Mn  | 0.102 | 0.148 | 0.201 | 0.184 | 0.162 | 0.101 | 0.187 |
| Mg  | 1.971 | 1.730 | 1.984 | 1.981 | 2.246 | 2.015 | 1.968 |
| Ca  | 1.760 | 1.789 | 1.608 | 1.744 | 1.794 | 1.759 | 1.755 |
| Na  | 0.371 | 0.433 | 0.322 | 0.273 | 0.402 | 0.340 | 0.304 |
| K   | 0.147 | 0.185 | 0.084 | 0.111 | 0.185 | 0.144 | 0.096 |
| Total | 15.324 | 15.436 | 15.229 | 15.234 | 15.397 | 15.291 | 15.247 |
| X_{Mg} | 0.482 | 0.439 | 0.458 | 0.463 | 0.310 | 0.487 | 0.467 |
| An% | 36     | 50     | 38     | 36     | 37     | 38     | 37     |

| Sample Modes | R68112 Matrix | R68350 Matrix | R68350 Iclulsion | R68359 Matrix | R68364 Matrix | R68366 Matrix | R68367 Matrix |
|--------------|---------------|---------------|------------------|---------------|---------------|---------------|---------------|
| (wt%)        |               |               |                  |               |               |               |               |
| SiO₂         | 44.95         | 44.01         | 41.93            | 45.73         | 41.62         | 46.91         | 45.30         |
| TiO₂         | 1.16          | 1.44          | 2.18             | 1.02          | 2.06          | 0.75          | 0.88          |
| Al₂O₃        | 7.10          | 8.11          | 10.82            | 6.78          | 9.93          | 5.88          | 6.26          |
| FeO*         | 21.04         | 18.78         | 18.87            | 20.47         | 21.18         | 21.52         | 22.12         |
| MnO          | 1.04          | 0.74          | 0.72             | 1.43          | 1.01          | 1.35          | 1.33          |
| MgO          | 8.52          | 9.50          | 8.38             | 8.14          | 6.80          | 8.85          | 8.37          |
| CaO          | 10.83         | 11.34         | 11.24            | 10.84         | 10.99         | 10.63         | 10.42         |
| Na₂O         | 1.33          | 1.31          | 1.80             | 1.15          | 1.68          | 0.82          | 1.07          |
| K₂O          | 0.66          | 0.67          | 0.80             | 0.64          | 1.08          | 0.53          | 0.61          |
| Total        | 96.63         | 95.90         | 96.74            | 96.20         | 96.35         | 97.24         | 96.36         |

** Formulae (O=23)**

| Si  | 6.873 | 6.726 | 6.401 | 7.012 | 6.475 | 7.114 | 6.960 |
| Ti  | 0.133 | 0.166 | 0.250 | 0.118 | 0.241 | 0.086 | 0.102 |
| Al  | 1.279 | 1.461 | 1.947 | 1.225 | 1.821 | 1.051 | 1.134 |
| FeO* | 0.532 | 0.496 | 0.373 | 0.437 | 0.358 | 0.446 | 0.621 |
| Mn  | 2.158 | 1.906 | 2.036 | 2.188 | 2.398 | 2.283 | 2.222 |
| Mg  | 0.135 | 0.096 | 0.093 | 0.186 | 0.133 | 0.173 | 0.173 |
| Ca  | 1.942 | 2.164 | 1.907 | 1.860 | 1.577 | 2.000 | 1.917 |
| Na  | 0.394 | 0.388 | 0.533 | 0.342 | 0.507 | 0.241 | 0.319 |
| K   | 0.129 | 0.131 | 0.156 | 0.125 | 0.214 | 0.103 | 0.120 |
| X_{Mg} | 0.474 | 0.532 | 0.484 | 0.459 | 0.397 | 0.467 | 0.463 |
| An% | 32    | 38    | 49    | 38    | 45    | 35    | 36    |

* Total iron as FeO.
** Calculated values based on criteria proposed by Holland and Blundy (1994).
† Anorthite content of plagioclase.
Complex, southern Adamello Massif, Italy (Blundy and Shimizu, 1991) and the Sázava intrusion, Central Bohemian Pluton, Czech Republic (Janoušek et al., 2004). However, injection of basaltic melt with a higher melting point into enormous amounts of granitic melt will certainly cause the quenching of the basaltic melt, and thus, the distinct differences in their melting points make it unlikely that they can mix homogenously. Additionally, any data implying the injection of mafic magma into the felsic magma have not been reported in the case of the Kaizuki–yama granitoids. Although the Kaizuki–yama granitoids usually contain dark enclaves that were derived from Mino sedimentary lithologies, any basaltic inclusions have not been observed (Saito and Sawada, 2000). Although Saito and Sawada (2000) reported dioritic inclusions, such intermediate rocks may not have been able to act as a source for the calcic plagioclase. Basaltic dikes widely intrude in the Kaizuki–yama granitoids and the surrounding sedimentary sequences. However, their K–Ar ages (68.5 ± 3.4–70.1 ± 3.5 Ma) are distinctly younger than those of the Kaizuki–yama granitoids (94.6 ± 4.7–98.8 ± 4.9 Ma), suggesting that basaltic magmatism clearly postdated the solidification of the granitoids (Saito and Sawada, 2000). Therefore, the mixing process between the mafic and felsic magmas which was proposed for the cases of other regions (e.g., Blundy and Shimizu, 1991; Janoušek et al., 2004), probably cannot be attributed to the presence of calcic plagioclase in the Kaizuki–yama granitoids.

Calcic plagioclase up to An90 commonly occurs in skarn and related rocks other than mafic rocks (e.g., Cempírek et al., 2008; Chang and Meinert, 2008; Idrus et al., 2009). Skarns have developed in the Mino sedimentary complexes around the Kaizuki–yama granitoids. Anor-
thite (An$_{87-100}$) occurs in clintonite-bearing skarn (S. Endo, personal communication, 2016). Scapolite (Me$_{51-53}$) was also reported in calcic–aluminous rock in dolomite–calcite marble (Banno et al., 2004). The calcic plagioclase in the skarn might have given origin to the xenocrystic and/or antecrystic grains. The locally calcic environment probably resulted from the assimilation of skarn and related calcareous rocks. The occurrence of calcic plagioclase grains in the Kaizuki–yama granitoids can potentially be explained by the incorporation and assimilation of such skarn materials into the granitoid magma.

**Assimilation of limestone and $^{87}$Sr/$^{86}$Sr value**

Saito and Sawada (2000) geologically and petrologically proposed the extensive distribution of marginal facies of the granitoids throughout the Kaizuki–yama pluton and especially in the northern half (Fig. 2). The similarity be-
between the Rb–Sr whole-rock and mineral isochron ages (94.1–96.4 Ma: Sawada et al., 1994) and K–Ar biotite and muscovite ages (94.6–98.8 Ma: Saito and Sawada, 2000) suggests relatively rapid cooling of the granitoids, as discussed by Saito and Sawada (2000). These facts support the idea of wide exposure of marginal facies in the Kaizuki–yama area.

The granitoid samples containing calcic plagioclase particularly occur in the marginal part and northern half of the Kaizuki–yama pluton (Fig. 1), and most exhibit a porphyritic texture (Figs. 4 and 7). Calcite grains are commonly included in plagioclase containing calcic domains (Figs. 7a and 7d). These facts imply the possibility that (1) most of the calcic plagioclase-bearing granitoids belong to the marginal facies of the pluton and (2) assimilation of skarn and related calcareous rocks from the wall rocks could have caused the formation of the calcic plagioclase.

Limestones and their contact metamorphosed equivalents frequently occur in the Mino sedimentary complex.
around the Kaizuki-yama granitoids. Although there is no Sr-isotopic data for these calcareous rocks, limestones with low $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.70681–0.70723 (average 0.70692 $\pm$ 0.00010, n = 26) were reported from the Akasaka area (latitude 136°34′ E, latitude, 35°24′ N) by Kani et al. (2013), which is located 13–14 km southeast from the margin of the Kaizuki-yama granitoid body (cf. Fig. 1a). Sawada et al. (1994) compared the initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of the Kaizuki-yama granitoids and those of other Cretaceous granitoid plutons around Lake Biwa and concluded that the Kaizuki-yama granitoids with the lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.70687 and 0.70704) probably have different magma geneses than the other Cretaceous granitoids with higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.70914–0.70989. The assimilation of limestones with low initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (estimated for $t$ = 95 Ma) (0.7156 $\pm$ 0.0029–0.7219 $\pm$ 0.0039: Shibata and Mizutani, 1980, 1982).

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SUPPLEMENTARY MATERIALS

Supplementary Tables S1, and S2 are available online from https://doi.org/10.2465/jmps.190118.

REFERENCES

Anderson, J.L. and Smith, D.R. (1995) The effect of temperature and $f_{O2}$ on the Al-in-hornblende geobarometer. American Mineralogist, 80, 549-559.

Banno, Y., Miyawaki, R., Matsubara, S., Makino, K., Bunno, M., Yamada, S. and Kaniya, T. (2004) Magnesiosadanaigaita, a new member of the amphibole group from Kasuga-mura, Gifu Prefecture, central Japan. European Journal of Mineralogy, 16, 177-183.

Blundy, J.D. and Holland, T.J.B. (1990) Calcic amphibole equilibria and a new amphibole plagioclase geothermometer. Contributions to Mineralogy and Petrology, 104, 208-224.

Blundy, J.D. and Shimizu, N. (1991) Trace-element evidence for plagioclase recycling in calc-alkaline magmas. Earth and Planetary Science Letters, 102, 178-197.

Cempiřík, J., Houzar, S. and Novák, M. (2008) Complexly zoned niobian titanite from hedenbergite skarn at Pisek, Czech Republic, constrained by substitutions $\text{Al(Nb,Ta)Ti}_{2+}$, $\text{AlF(OH)}$ (TiO)$_2$ and SnTi$_2$. Mineralogical Magazine, 72, 1293-1305.

Chang, Z.S. and Meinert, L.D. (2008) The Empire Cu-Zn Mine, Idaho: Exploration Implications of Unusual Skarn Features Related to High Fluorine Activity. Economic Geology, 103, 909-938.

Chappell, B.W. and White, A.J.R. (1974) Two contrasting granite types. Pacific Geology, 8, 173-174.

Davidson, J.P., Morgan, D.J., Chafliert, B.L.A., Harlou, R. and Hora, J.M. (2007) Microsampling and isotopic analysis of igneous rocks: Implications for the study of magmatic systems. Annual Review of Earth and Planetary Sciences, 35, 273–311.

Deer, W.A., Howie, R.A. and Zussman, J. (2001) Rock-forming Minerals. 4A, Framework Silicates Feldspars. pp. 972, The Geological Society, London.

Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J. and Frost, C.D. (2001) A geochemical classification for granitic rocks. Journal of Petrology, 42, 2033-2048.

Hammarstrom, J.M. and Zen, E.-a. (1986) Aluminium in hornblende: An empirical igneous geobarometer. American Mineralogist, 71, 1297-1313.

Holland, T.J.B. and Blundy, J. (1994) Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry. Contributions to Mineralogy and Petrology, 116, 433-447.
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Hollister, L.S., Grissom, G.C., Peters, E.K., Stowell, H.H. and Sisson, V.B. (1987) Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons. American Mineralogist, 72, 231-239.

Idrus, A., Kolb, J., Meyer, F.M., Arif, J., Setyandhaka, D. and Kepli, S. (2009) A Preliminary Study on Skarn-Related Calc-silicate Rocks Associated with the Batu Hijau Porphyry Copper-Gold Deposit, Sumbawa Island, Indonesia. Resource Geology, 59, 295-306.

Janoušek, V., Braithwaite, C.J.R., Bowes, D.R. and Gerdes, A. (2004) Magma mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Sazava intrusion, Central Bohemian Pluton, Czech Republic. Lithos, 78, 67-99.

Johnson, M.C. and Rutherford, M.J. (1989) Experimental calibration of the aluminium-in-hornblende geobarometer with application to Long Valley caldera (California) volcanic rocks. Geology, 17, 837-841.

Kani, T., Hisanabe, C. and Isozaki, Y. (2013) The Capitanian (Permian) minimum of 87Sr/86Sr ratio in the mid-Panthalassan paleo-atoll carbonates and its demise by the deglaciation and continental doming. Gondwana Research, 24, 212-221.

Kato, T. (2005) New accurate Bence-Albee α-factors for oxides and silicates calculated from the PAP correction procedure. Geostandards and Geoanalytical Research, 29, 83-94.

Kurimoto, C., Naito, K., Sugiyama, Y. and Nakae, S. (1999) Geology of the Tsuruga district. With Geological Sheet Map at 1; 50000. pp. 73, Geological Survey of Japan, AIST (in Japanese with English abstract).

Leake, B.E., Woolley, A.R., Arps, C.E.S., Birch, W.D., Gilbert, M.C., Grice, J.D., Hawthorne, F.C., Kato, A., Kisch, H.J., Krivovichev, V.G., Linthout, K., Laird, J., Mandarino, J.A., Maresch, W.V., Nickel, E.H., Rock, N.M.S., Schumacher, J.C., Smith, D.C., Stephenson, N.C.N., Ungaretti, L., Whittaker, E.J.W. and Guo, Y.Z. (1997) Nomenclature of amphiboles: Report of the subcommittee on amphiboles of the International Mineralogical Association, commission on new minerals and mineral names. American Mineralogist, 82, 1019-1037.

Miller, J.S., Matz sel, J.E.P., Miller, C.F., Burgess, S.D. and Miller, R.B. (2007) Zircon growth and recycling during the assembly of large, composite arc plutons. Journal of Volcanology and Geothermal Research, 167, 282-299.

Morishita, T. and Suzuki, K. (1993) XRF analyses of the Mitsuhashi granite in the Shitara area, Aichi Prefecture. Bulletin of Nagoya University Furukawa Museum, No. 9, 77-90 (in Japanese with English abstract).

Nakazaki, M., Tsu bromi, M., Kanagawa, K., Kato, T. and Suzuki, K. (2004) Quantitative chemical analysis of rocks with X-ray fluorescence analyzer XRF-1800. Bulletin of Nagoya University Museum, 20, 79-91.

Piwinski, A.J. and Wyllie, P.J. (1968) Experimental studies of igneous rock series: a zoned pluton in the Wallowa Batholith, Oregon. Journal of Geology, 76, 205-234.

Ribbe, P.H. (1983) Reviews in Mineralogy. 2, Feldspar Mineralogy (2nd edition). pp. 362, Mineralogical Society of America, Chelsea, MI.

Saito, M. and Sawada, Y. (2000) Geology of the Yokoyama district. With Geological Sheet Map at 1:50000. pp. 126, Geological Survey of Japan, AIST (in Japanese with English abstract).

Sawada, Y., Kagami, H., Matsumoto, I., Sugii, K., Nakano, S. and Collaborative Research Group for the Granites around Lake Biwa. (1994) A Cretaceous granite ring complex and the Koto Cauldron around the southern part of Lake Biwa, Southwest Japan. Journal of Geological Society of Japan, 100, 217-233 (in Japanese with English abstract).

Schmidt, M.W. (1992) Amphibole composition in tonalite as a function of pressure: an experimental calibration of the Al-in-hornblende barometer. Contributions to Mineralogy and Petrology, 110, 304-310.

Shibata, K. and Mizutani, S. (1980) Isotopic ages of silicous shale from Hida-Kanayama, Central Japan. Geochemical Journal, 14, 235-241.

Shibata, K. and Mizutani, S. (1982) Isotopic ages of Jurassic silicous shale and Triassic bedded chert in Unuma, Central Japan. Geochemical Journal, 16, 213-223.

Sugii, K. and Sawada, Y. (1999) Late Cretaceous Kaizukiyama granite, northeast of Lake Biwa, Southwest Japan. Geoscience Report of Shumane University, 18, 69-84 (in Japanese with English abstract).

Suzuki, K. (1977) Local equilibrium during the contact metamorphism of silicous dolomites in Kasuga-mura, Gifu-ken, Japan. Contributions to Mineralogy and Petrology, 61, 79-89.

Suzuki, K. and Shiraki, K. (1980) Chromite-bearing 'spessartites from Kasuga-mura, Japan, and their bearing on possible mantle origin andesite. Contributions to Mineralogy and Petrology, 71, 313-322.

Whitney, D.L. and Evans, B.W. (2010) Abbreviations for names of rock-forming minerals. American Mineralogist, 95, 185-187.

Zen, E.-a. (1986) Aluminium enrichment in silicate melts by fractional crystallization: some mineralogic and petrographic constraints. Journal of Petrology, 27, 1095-1117.

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