Assimilation and fractional crystallization of Sanukitic high-Mg andesite-derived magmas, Kyushu Island, southwest Japan: An example of the Cretaceous Shaku-dake diorite body

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The Cretaceous granitoid batholith is characterized by sporadically occurring small mafic bodies. Some of these mafic bodies show high-Mg diorite (HMD) compositions derived from a high-Mg andesite (HMA) magma. One of the mafic bodies, the Shaku-dake body, can be divide into two groups: Two-pyroxene diorite (TPD), diorite (Do), porphyritic fine-grained tonalite (PFT), and clinopyroxene granodiorite (CG) belong to the Group-1, but hornblende-biotite granodiorite (HBG) and fine-grained biotite granite (FBG) can be found in the Group-2. The Group-1 is influenced by the assimilation and fractional crystallization process during the ascent and emplacement of magma, whereas the Group-2 changes its whole-rock compositions via fractional crystallization. Discrimination diagrams of HMA indicate that the TPD shows geochemical signatures similar to those of the Sanukitic HMA, where the TPD is defined as Sanukitoid. On the other hand, the Do is plotted as the composition range of island arc calc-alkaline basalts and tholeiite. The Cretaceous magma activities in northern Kyushu were led by the highly thermal structure of the wedge mantle at that time, it was the primary heat source of the voluminous igneous activities during the Cretaceous in Southwest Japan and the Korean Peninsula.

Keywords: Cretaceous, High-Mg andesite/diorite, Sanukitoid, Assimilation and fractional crystallization (AFC), Fractional crystallization (FC)

INTRODUCTION

The granitoids cover approximately 30% surface area of the Japanese island (Takagi, 2004). Intense magma activities of the granitoids occurred during the Cretaceous (50–130 Ma; Takagi, 2004). The Cretaceous granitoid batholith occurs is exposed over an area of about 100 km from east to west and 50 km from north to south in northern Kyushu (Fig. 1), showing zircon U-Pb ages of 116–102 Ma (Adachi et al., 2012; Tiepolo et al., 2012). Small mafic bodies occur sporadically in the batholith. Some of these mafic bodies represent HMD compositions derived from HMA, and their petrogenesis has been discussed by several workers (Murakami, 1994; Kamei et al., 2004; Yuhara and Uto, 2007; Tiepolo et al., 2012; Eshima and Owada, 2018; Eshima et al., 2019). The coexistence of both mafic and felsic rocks has been reported from volcanic-plutonic sites of the active continental margin in the Cretaceous granitoid batholith of southwest Japan and the Cordillera Mountains in the North America (Tainosho et al., 1985; Tepper et al., 1993). In addition, the mafic magma of mantle origin is strongly involved in the origin of granitic magma as a parent magma and a heat source of crustal melting (Reid et al., 1983; Le Bel et al., 1985). Therefore, clarification of the behavior of the HMA-derived magma in the crust play an important role in examining the genetic relationship with granitoids.

The HMA magma is rich in Mg and has a high Mg/Fe ratio compared with ordinary andesite magma. Based on the melting experiments (Tatsumi, 1981, 1982; Hirose, 1997), the HMA magma is at equilibrium with Mg-rich mantle olivine and pyroxenes, suggesting that the HMA may be formed by the solidification of primary magma from the mantle. Based on this background, many geochemical discrimination diagrams for HMA have been proposed using mineral and whole-rock chemical compositions and isotopic compositions (e.g., Tatsumi and Ha-
However, detailed studies on magmatic processes with HMA composition such as differentiation, mixing, and assimilation, and on the relationships among other magmas are scarce. By clarifying this issue, we should understand the characteristics of the large-scale magmatic activity of the Cretaceous period.

In this study, we discuss the magmatic process of a newly finding HMA-derived rock, the Shaku-dake body (a high-Mg diorite body), as a member of the Cretaceous granitoid batholith in northern Kyushu.

**GEOLOGICAL OVERVIEW**

The Mt. Shaku-dake area located in the northeastern part of Kyushu, Southwest Japan, is underlain by the Wakino sub-group of the Kannon group and the Shaku-dake body, a member of the Kawaradake suite, that intrudes the Wakino sub-group (Fig. 2). The Wakino sub-group is composed of Cretaceous shallow marine deposits with well-stratified sequences of lower basal conglomerate, the middle coarse sandstone, and the upper sandstone/shale alternation (Nakae et al., 1998). The basal conglomerate locally includes limestone blocks as large gravels (10–60 cm). The limestone is derived from the Permian accretionary complex (Nakae et al., 1998). The bedding structures of the Wakino sub-group generally show E–W to N 70° E in strikes and 10–40° N or S in dips (Fig. 2). The Shaku-dake body consists mainly of two-pyroxene diorite (TPD) and hornblende-biotite granodiorite (HBG) as stocks with several kinds of dikes. Both TPD and HBG are ellipsoidal in shape on the west of Mt. Shaku-dake (Fig. 2) and...
caused contact metamorphism to the surrounding rocks of Wakino sub-group in the range of several hundred meters.

PETROGRAPHY OF THE SHAKU-DAKE BODY

The Shaku-dake body can be divided into two groups, Group-1 and Group-2, in terms of the presence of xenoliths. The Group-1 locally involves xenoliths at the margin of the bodies and contains ilmenite as an opaque mineral. On the other hand, the Group-2 rarely involves xenoliths and bears magnetite. Besides the TPD, Do, PFT, and CG belong to the Group-1, and HBG and FBG are classified in the Group-2.

Occurrence and petrography of the Group-1

Two-pyroxene diorite (TPD). The TPD occurs as a stock with an area of \(1.9 \times 1.5 \text{ km}^2\) (Fig. 2). It is dark gray in color. Xenoliths of sandstone, shale, and limestone, probably derived from the Wakino sub-group, are rarely included in the TPD (Figs. 3a and 3b).

The TPD shows a hypautomorphic granular texture and is mainly composed of plagioclase, orthopyroxene, clinopyroxene, and biotite with trace amounts of quartz.
and K-feldspar. Zircon, titanite, ilmenite, and apatite are present as accessory minerals (Fig. 4a). Plagioclase shows subhedral–euhedral crystals that are 0.5–1.5 mm in size and possesses the albite twins and zoning structures. Orthopyroxene and clinopyroxene are also subhedral–euhedral in shape with a size of 0.5–1.5 mm and are locally surrounded by hornblende and biotite. Quartz and K-feldspar occur as interstitial minerals of the early-crystallized minerals. The sandstone/shale micro-xenoliths can be identified under the microscope (Fig. 4b).

**Dolerite (Do).** The Do dikes with less than 100 m in length and 0.4–3.0 m in width intrude the Wakino sub-group, TPD, and CG (Fig. 3c). It rarely includes the sandstone/shale and the limestone (Figs. 3d and 3e). The grain sizes are fine-grain, and clinopyroxene and orthopyroxene are visible as phenocrysts.

The Do shows fine-grained porphyritic texture under the microscope (Fig. 4c). Phenocrystic minerals are of plagioclase, orthopyroxene, clinopyroxene, and biotite. Clinopyroxene reaches up to 2.5 mm in size. Plagioclase shows dusty zoning. Ilmenite occurring in the groundmass is partly rimmed by very fine plagioclase, orthopyroxene, and clinopyroxene in the groundmass (Fig. 4c). Mafic minerals generally show 0.2–1.2 mm in size.

**Porphyritic fine-grained tonalite (PFT).** The PFT intrudes only into the Wakino sub-group and may form a composite dike with the Do (Fig. 3f). It shows pale gray color, fine-grain, and a porphyritic texture. The boundaries between the PFT and the Wakino sub-group are generally clear; however, they show wavy features in some locations (Fig. 3g). The PFT sometimes involve the sandstone/shale and the limestone as xenoliths (Fig. 3g).

The PFT shows porphyritic texture, and consists mainly of plagioclase, hornblende, biotite, and quartz as phenocrysts with 0.5–1.5 mm in size. Some of hornblende locally shows very large crystals, up to 15 mm. The groundmass contains fine-grained plagioclase, quartz, and a small amount of K-feldspar. Ilmenite, titanite, and apatite are present as accessory minerals (Fig. 4d).

**Clinopyroxene granodiorite (CG).** The CG occurs as dikes with 1.0–10 m width and shows massive and
fine- to medium-grained with gray in color. It intrudes the TPD, FBG, Do, and the Wakino sub-group and extends the network veins along the intrusive boundary with the TPD and FBG (Figs. 3h and 3i) The CG locally involves the sandstone/shale as xenoliths (Fig. 3j). The CG is hypautomorphic granular texture and consists mainly of plagioclase, clinopyroxene, biotite, quartz, and K-feldspar. Ilmenite, titanite, zircon, and apatite are present as accessory minerals (Fig. 4e). Plagioclase shows subhedral-euhedral crystals with a size of 0.1-2.7 mm. Biotite (0.4-1.2 mm) shows subhedral-anhedral crystals and often forms clots. Quartz and K-feldspar occur as interstitial crystals with a size of 0.2-1.8 mm and the former shows a wavy extension.

**GEOCHEMISTRY**

**Analytical procedure**

Mineral compositions were determined using JXA-8230 electron probe micro-analyzer (EMPA) at the Center for Instrumental Analyses, Yamaguchi University. Operating conditions for chemical analyses were an accelerating voltage of 15 kV, a specimen current of 20 nA, and a beam diameter of 1-5 μm. Wavelength-dispersion spectra were collected with LiF, PET, and TAP crystals to identify interfering elements and located the best wavelengths for background measurements. The ZAF method was used for data correction. Under the conditions described, analytical errors are ±2% for major elements as estimated from the reproducibility observed in multiple measurements.

Geochemical analysis, for determining major and trace elements, was performed via X-ray fluorescence (XRF) spectrometry at the Center for Instrumental Analyses, Yamaguchi University. All analyses were made on glass beads using an alkali flux comprising of lithium tetraborate. The analytical procedure described by Eshima and Owada (2018) was followed. Trace elements including rare earth elements (REEs) were determined with inductively coupled plasma mass spectrometry (ICP-MS) at Activation Laboratory Ltd., Canada. Samples are fused with sodium peroxide and undergo an acid dissolution. Samples are then analyzed by Agilent 7900 ICP-MS. Calibration is performed using five synthetic calibration standards (μg/ml hereafter referred to as ppm).

The Sr and Nd isotopic analyses were performed using the following procedures. Sr and Nd from the powdered whole-rock samples were extracted at the Yoshida Research and Education Building of Yamaguchi University following the methods of Kagami et al. (1987). Isotopic analyses were conducted via thermo-ionization mass spectrometry (TIMS, Finnigan MAT-262) at the Department of Earth and Environment Sciences, Shimane University. The detailed analytical procedure is described in Iizumi (1996). Measured $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd ratios were corrected to $^{86}$Sr/$^{88}$Sr = 0.119410 and $^{146}$Nd/$^{144}$Nd = 0.7219, respectively. The $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd ratios were normalized relative to reference values.
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The initial Sr and Nd isotope ratios were calculated using the decay constants $\lambda^{87}\text{Rb} = 1.42 \times 10^{-11}/\text{year}$ (Steiger and Jäger, 1977) and $\lambda^{147}\text{Sm} = 6.54 \times 10^{-12}/\text{year}$ (Lugmair and Marti, 1978). The epsilon values ($\varepsilon$) were calculated using the method of Depaolo and Wasserburg (1976a, 1976b). The detailed isotopic analytical procedures are reported in Miyazaki and Shuto (1998). Considering the results of recently published age data from the Kawarada suite that involves the HBG, the Sr and Nd isotopic ratios were corrected to 103 Ma because the average hornblende K–Ar age is $\approx$ 103 Ma ($105.3 \pm 3.2$ Ma and $100.9 \pm 2.9$ Ma; Eshima et al., 2019), furthermore, Uraninite Th–U–Pb chemical age shows 103.0 ± 1.8 Ma (Yokoyama et al. 2016). The clinopyroxene compositions of the TPD and the Do listed in Table S1 (available online from https://doi.org/10.2465/jmps.191209). The results of major and trace element analyses and Sr and Nd isotopic analyses are listed in Table S2 (available online from https://doi.org/10.2465/jmps.191209) and Table 1.

### Table 1. Results of Sr–Nd isotope analyses of the Shaku–dake body

| Type    | Rb (ppm) | $^{87}\text{Rb}^{86}\text{Sr}$ | $^{87}\text{Sr}^{86}\text{Sr}$ | Sr$_{103\text{Ma}}$ | Sm (ppm) | $^{147}\text{Sm}^{144}\text{Nd}$ | $^{143}\text{Nd}^{144}\text{Nd}$ | Nd$_{103\text{Ma}}$ |
|---------|----------|-------------------------------|-------------------------------|---------------------|----------|---------------------------------|---------------------------------|------------------|
| TPD     | 87       | 0.362                         | 0.705360                      | 0.704343            | 4.3      | 0.1238                          | 0.512565                        | 0.512572         |
| TPD     | 121      | 0.9669                        | 0.705936                      | 0.704521            | 2.02     | 0.1138                          | 0.512680                        | 0.512603         |
| TPD     | 91       | 0.7272                        | 0.705832                      | 0.704668            | 1.26     | 0.1179                          | 0.512676                        | 0.512596         |
| TPD     | 189      | 2.86                           | 0.707415                      | 0.704616            | 3.37     | 0.1197                          | 0.512664                        | 0.512566         |
| TPD     | 88       | 0.698                         | 0.705661                      | 0.704604            | 3.20     | 0.1212                          | 0.512690                        | 0.512608         |
| TPD     | 89       | 0.6829                        | 0.705460                      | 0.704660            | 1.16     | 0.1297                          | 0.512738                        | 0.512651         |
| TPD     | 79       | 0.6605                        | 0.705693                      | 0.704726            | 4.93     | 0.1285                          | 0.512680                        | 0.512593         |
| Do      | 50       | 0.5717                        | 0.705642                      | 0.704805            | 6.05     | 0.1565                          | 0.512726                        | 0.512620         |
| Do      | 61       | 0.3139                        | 0.704893                      | 0.704434            | 0.78     | 0.1167                          | 0.512688                        | 0.512580         |
| Do      | 51       | 0.3249                        | 0.705663                      | 0.705188            | 11.48    | 0.1200                          | 0.512681                        | 0.512600         |
| CG      | 131      | 1.0052                        | 0.706194                      | 0.704722            | 4.88     | 0.1209                          | 0.512639                        | 0.512557         |
| CG      | 164      | 1.4783                        | 0.706903                      | 0.704726            | 4.93     | 0.1260                          | 0.512640                        | 0.512569         |
| PFT     | 84       | 0.5638                        | 0.706125                      | 0.705299            | 13.07    | 0.1197                          | 0.512561                        | 0.512481         |
| PFT     | 95       | 0.5378                        | 0.706469                      | 0.705682            | 18.50    | 0.1203                          | 0.512576                        | 0.512495         |
| FBG     | 141      | 2.5340                        | 0.708462                      | 0.704753            | 5.32     | 1.038                           | 0.512607                        | 0.512543         |
| HBG     | 122      | 1.0826                        | 0.706312                      | 0.704728            | 4.95     | 1.036                           | 0.512641                        | 0.512561         |
| HBG     | 128      | 1.9145                        | 0.706333                      | 0.704585            | 2.92     | 1.036                           | 0.512640                        | 0.512563         |
| Waki    | 16       | 0.1607                        | 0.706021                      | 0.705786            | 19.97    | 0.1392                          | 0.512656                        | 0.512562         |
| Waki    | 69       | 0.4160                        | 0.710052                      | 0.709443            | 71.90    | 0.1189                          | 0.512126                        | 0.512046         |

| Nishio and al., 1991 |
|---------------------|
| Limestone           | 479     | 0.706800                     | -                         | -        | -                               | -                               | -                 |
| Limestone           | 430     | 0.707100                     | -                         | -        | -                               | -                               | -                 |
| Limestone           | 491     | 0.706800                     | -                         | -        | -                               | -                               | -                 |
| Limestone           | 230     | 0.707700                     | -                         | -        | -                               | -                               | -                 |

| Type    | $\varepsilon$ | $\sigma(\varepsilon)$ |
|---------|----------------|-----------------------|
| TPD     | 1.30           | 1                      |
| TPD     | 1.90           | 14                     |
| TPD     | 1.77           | 13                     |
| TPD     | 1.19           | 14                     |
| TPD     | 1.99           | 14                     |
| TPD     | 2.83           | 12                     |
| TPD     | 1.71           | 13                     |
| Do      | 2.24           | 12                     |
| Do      | 1.46           | 14                     |
| Do      | 1.85           | 14                     |
| Do      | 1.01           | 13                     |
| CG      | 1.24           | 13                     |
| CG      | -0.49          | 13                     |
| PFT     | -0.21          | 13                     |
| FBG     | 0.73           | 13                     |
| HBG     | 1.07           | 13                     |
| HBG     | 1.13           | 13                     |
| Waki    | 1.11           | 12                     |
| Waki    | -8.97          | 14                     |

| Nishio and al., 1991 |
|---------------------|
| Limestone           | -        | -                     |
| Limestone           | -        | -                     |
| Limestone           | -        | -                     |
| Limestone           | -        | -                     |

Error values are 5 and 4 decimal places for Sr and Nd, respectively.
Abbreviations are shown in the abstract.

Major and trace elements of whole-rock

The variation diagrams of SiO$_2$ vs. major and trace elements for the TPD, HBG, CG, FBG, Do, and PFT are shown in Figure 5. The chemical compositions of these six intrusive rocks belong to a high-K series (Peccerillo and Taylor, 1976).
The SiO$_2$ contents of TPD range from 52.0 to 63.5 wt%, and Al$_2$O$_3$ and K$_2$O increase with increasing SiO$_2$. Some of TPD possess very high MgO contents (~ 7.4 wt%) and low FeO*/MgO ratios (~ 0.98). Cr and Ni decrease with increasing SiO$_2$, and some samples show very high concentrations of these elements (Cr, ~ 369 ppm; Ni, ~ 148 ppm). The SiO$_2$ contents of HBG range from 66.5 to 67.7 wt%, and Al$_2$O$_3$, K$_2$O, and Y increase with increasing SiO$_2$. MgO, Cr, and Ni decrease with increasing SiO$_2$. The SiO$_2$ contents of CG range from 60.5 to 65.2 wt%, and Al$_2$O$_3$, MgO, Cr, and Ni decrease with increasing SiO$_2$. The SiO$_2$ contents of Do range from 65.2 to 66.5 wt%, and Al$_2$O$_3$, MgO, Cr, Ni, K$_2$O, and Y increase with increasing SiO$_2$. In the FeO*/MgO–SiO$_2$ (wt%) diagram, the part of TPD and Do samples are plotted within the field of high-Mg andesite composition (Fig. 5g; Kamei et al., 2004). Two trends can be observed in the MgO–Fe$_2$O$_3$ (wt%) diagram: The Group–1 and Group–2 trends (Fig. 5h).

Sr and Nd isotopes

The initial Sr and Nd isotopic ratios termed as $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd, respectively. Figure 6a shows the $\varepsilon$Sr–$\varepsilon$Nd diagram for the studied samples. The Group–1 (Do, PFT, TPD, and CG) is plotted within the wide area in the epsilon diagram ($\varepsilon$Sr = $-0.51 \pm 18.50$ and $\varepsilon$Nd = $-0.49 \pm 2.83$), whereas the Group–2 (HBG and FBG) has the limited ($\varepsilon$Sr = $+2.92 \pm 5.32$ and $\varepsilon$Nd = $+0.73 \pm 1.13$) (Fig. 6a).

DISCUSSIONS

The Shaku-dake body is composed of six types of intru-
sive rocks (TPD, Do, CG, PFT, HBG, and FBG). Most of intrusive rocks such as TPD and HBG, TPD and FBG, CG and FBG, CG and Do show intrusive–intrusive relationship (Figs. 3c, 3i, 3k, and 3l). In addition, The PFT dike forms a composite dike with the Do (Fig. 3f). We therefore conclude that the six intrusive rocks from the Shaku–dake body contemporaneously intrude each other.

The Shaku–dake body is divided into two groups, the Group–1 and Group–2, and these show different trends in the variation diagrams including those of SrI and NdI values (Figs. 5 and 6b). The Group–1 rocks show two trends in the SiO$_2$ wt%–SrI and –NdI diagrams (Fig. 6b), while the Group–2 rocks show monotonous trends in some variation diagrams (Figs. 5 and 6b).

**Geochemical characteristics of Do and TPD**

The SiO$_2$ contents of TPD and Do range between 63.5 to 52.0 and 62.2 to 49.8 wt%, respectively. Some samples show relatively primitive compositions; Mg$\#$ [100*Mg/(Mg + total Fe)] = 64.5 to 68.9, FeO*/MgO = 0.80 to 0.98, Cr = 288 to 825 ppm, and Ni = 119 to 190 ppm (Fig. 5). In the FeO*/MgO–SiO$_2$ (wt%) diagram (Fig. 5g), some TPD samples are plotted in the compositional field of high–Mg andesite (HMA). In addition, the clinopyroxene compositions of TPD are similar to those of HMD (Fig. 7a). On the other hand, the SiO$_2$ contents of Do belong to basalt, and the clinopyroxene compositions of Do
show those of the fields in the Sub–alkaline gabbro and Sub–alkaline andesite–basalt (Fig. 7a). The SrI and NdI values of TPD and Do are different in the epsilon diagram (Fig. 6a); the Do possesses enriched SrI values rather than those of the TPD, but the NdI values of Do ($\varepsilon_{Nd} = +1.46 - +2.24$) range within the field of TPD ($\varepsilon_{Nd} = +1.30 - +2.83$). This suggests that the TPD is hardly produced via fractionation and assimilation of crustal materials with basaltic magma as opposed to the Do. Considering the mineral and whole-rock geochemistry including Sr and Nd isotopic compositions, it can be concluded that the TPD was originally derived from a HMA magma, whereas the parent magma of Do was basaltic.

The HMA magma is geochemically divided into several types (Kay, 1978; Shiraki et al., 1980; Jenner, 1981; Tatsumi and Ishizaka, 1982a; Tatsumi and Ishizaka, 1982b; Rogers et al., 1985; Saunders et al., 1987; Crawford et al., 1989; Stern and Hanson, 1991; Yogodzinski et al., 1995; Shimoda et al., 1998). Kamei et al. (2004) classified each HMA magma depending on various elements (Fig. 8). Figure 8 indicate that the TPD shows geochemical signatures similar to those of the Sanukitic HMA but do not resemble the Bajaitic and Boninitic HMA. In addition, the previously reported Cretaceous and Neogene HMA rocks from Southwest Japan are also classified into the Sanukitic HMA (Fig. 8; e.g., Murakami, 1994; Kamei et al., 2004; Eshima et al., 2019). On the other hand, the Do is plotted within the composition range of island arc calc–alkaline basalts and tholeiite in some discrimination diagrams (Figs. 7b and 7c). These results suggest that the magma activities of TPD and Do in the Shaku–dake body have similar characteristics to those of the sanukitoid and basalt from the Setouchi volcanic rocks during the Miocene in the Setouchi region, Japan (Tatsumi, 1982).

**Petrogenetic relationships among the intrusive rocks of the Shaku–dake body**

**Group-1 (Do, TPD, CG, and PFT).** The Group-1 is influenced by assimilation and fractional crystallization because of its field occurrence involving xenoliths and regularly changing Sr–Nd isotopic compositions with SiO2 contents (Figs. 3a, 3b, 3d, 3e, 3g, 3j and 6). Furthermore, the SiO2 (wt%)-SrI data for comparison were obtained from the following sources; andesite from the Kannon Group, Yamaguchi (Imaoka and Murakami, 1979; Imaoka et al., 1993), diorite from North Kyushu (Murakami, 1994; Kamei et al., 2004; Eshima et al., 2019). The Neogene HMA rocks in Kyushu also geochemically possess the Sanukitic HMA (Shiraki et al., 1991; Nagao et al., 1992; Kakubuchi et al., 1995; Shiraki et al., 1995).

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The partition coefficients are listed in Table S4 (available online from https://doi.org/10.2465/jmps.191209). The calculated compositions are shown in the spider diagram (Fig. 11) normalized to the C1 chondrite (Sun and McDonough, 1989). These results suggest that simple Rayleigh fractionation model without assimilation process cannot reproduce trace element compositions of the PFT and CG (Fig. 11).

In order to evaluate the importance of AFC processes with the Wakino sub-group (Sandstone/shale) and limestone for the evolution of the Shaku-dake body, we performed AFC calculations utilizing the equation (15b) in DePaolo (1981). For these calculations, the initial TPD and Do magmas were assumed to have SrI (103 Ma) and NdI (103 Ma) ratios of 0.7043 and 0.51265, 0.7044 and 0.51262, respectively, and Sr = 390 ppm, Nd = 19 ppm, and Sr = 562 ppm, Nd = 8.5 ppm, based on data for the least differentiated samples. The Wakino sub-group as assimilated material was assumed to have SrI (103 Ma) and NdI (103 Ma) values of 0.7094 and 0.51205, respectively, and Sr = 480 ppm, Nd = 24 ppm. The limestone as another assimilated material was estimated to have SrI values of 0.7077 and Sr = 479 ppm, respectively, that has the highest Sr values from the quoted data of Nishioka et al. (1991) to make the assimilation effect easily distinguishable. We addressed the assimilation process using Sr–Nd isotopic compositions for both subgroups. As previously mentioned, the rocks from each subgroup include different types of xenoliths. The TPD-CG and Do-PFT subgroups mainly involve the Wakino sub-group (sandstone/shale) and limestone as xenoliths (Figs. 3a, 3b, 3d, 3e, 3g, and 3j), respectively. Therefore, we examined assimilation and fractional crystallization (AFC) modeling using different contaminants. The AFC processes can duplicate the chemical variations for the TPD-CG and the Do-PFT subgroups (Fig. 12). According to the results of AFC calculation, the geochemical variations of the Group-1 are attributed by the differences of ‘r’ value that is assimilation/fractionation rate from 0.01 to 0.5 (Fig. 12).

**Group-2 (HBG and FBG).** The Group-2 (HBG and FBG) shows a clear trend that is different from that of the Group-1 in the MgO–Fe2O3 (wt%) diagram (Fig. 5). The HBG and the FBG are plotted within the same compositional range in the εSr–εNdI diagram (Fig. 6a).
Table 2. Results of mass balance calculation using the major elements for whole-rocks and minerals of the TPD-CG, Do-PFT and HBG-FBG

| TPD–CG | Initial magma | Final magma | Subtract phases |
|--------|---------------|-------------|-----------------|
| Sample No. | 16102103 | 16110611 | 16102103 | 16102103 | 16102103 | 16102103 | 16102103 | 16102103 |
| SiO₂ (wt%) | 63.5 | 65.18 | 58.66 | 51.64 | 50.73 | 50.73 | 0.04 |
| TiO₂ | 0.83 | 0.64 | 0.03 | 0.31 | 0.17 | 0.17 | 49.80 |
| Al₂O₃ | 15.41 | 15.42 | 25.60 | 1.70 | 0.84 | 0.84 | 0.02 |
| FeO* | 5.2 | 4.3 | 0.18 | 8.82 | 26.22 | 26.22 | 46.28 |
| MgO | 0.08 | 0.08 | 0.01 | 0.26 | 0.75 | 0.75 | 1.66 |
| CaO | 2.81 | 2.36 | 0.01 | 14.19 | 18.43 | 18.43 | 0.08 |
| K₂O | 4.52 | 3.84 | 7.49 | 20.97 | 0.99 | 0.99 | 0.30 |
| Na₂O | 3.15 | 3.52 | 7.21 | 0.36 | 0.02 | 0.02 | 0.01 |
| P₂O₅ | 3.81 | 3.73 | 0.01 | 10.00 | 0.00 | 0.00 | 0.03 |
| Calculated result (%) | 88.01 | 6.07 | 2.71 | 2.71 | 2.25 | 0.97 |
| Degree of crystallization, 11.99% |
| Fractionated proportions (%) | 50.60 | 22.57 | 18.73 | 8.10 |
| Sum of squares, 0.113 |

| Do–PFT | Initial magma | Final magma | Subtract phases |
|--------|---------------|-------------|-----------------|
| Sample No. | 17031006 | 17031009 | 17031006 | 17031006 | 17031006 | 17031006 | 17031006 | 17031006 |
| SiO₂ (wt%) | 53.66 | 61.87 | 51.92 | 51.60 | 53.68 | 53.68 | 0.00 |
| TiO₂ | 1.03 | 0.63 | 0.08 | 0.46 | 0.27 | 0.27 | 51.90 |
| Al₂O₃ | 14.34 | 15.69 | 29.23 | 2.50 | 1.76 | 1.76 | 0.02 |
| FeO* | 8.42 | 6.92 | 0.61 | 7.21 | 13.27 | 13.27 | 42.60 |
| MnO | 0.13 | 0.12 | 0.04 | 0.20 | 0.29 | 0.29 | 3.60 |
| MgO | 8.03 | 2.23 | 0.13 | 16.28 | 27.71 | 27.71 | 0.13 |
| CaO | 7.78 | 5.67 | 12.62 | 19.67 | 1.58 | 1.58 | 0.28 |
| Na₂O | 2.85 | 3.11 | 4.14 | 0.31 | 0.02 | 0.02 | 0.00 |
| K₂O | 1.41 | 2.73 | 0.23 | 0.01 | 0.00 | 0.00 | 0.00 |
| P₂O₅ | 0.38 | 0.17 | 0.03 | 0.00 | 0.00 | 0.00 | 0.02 |
| Calculated result (%) | 62.23 | 21.70 | 11.30 | 3.44 | 0.36 |
| Degree of crystallization, 37.77% |
| Fractionated proportions (%) | 57.44 | 22.92 | 9.12 | 3.52 |
| Sum of squares, 0.297 |

| HBG–FBG | Initial magma | Final magma | Subtract phases |
|--------|---------------|-------------|-----------------|
| Sample No. | 16101403 | 16102108A | 16101403 | 16101403 | 16101403 | 16101403 |
| SiO₂ (wt%) | 66.88 | 72.36 | 59.97 | 48.50 | 0.02 |
| TiO₂ | 0.48 | 0.25 | 0.02 | 0.92 | 0.05 |
| Al₂O₃ | 15.51 | 14.23 | 24.60 | 4.87 | 0.04 |
| FeO* | 3.44 | 1.43 | 0.18 | 13.66 | 89.63 |
| MnO | 0.07 | 0.03 | 0.01 | 0.49 | 0.07 |
| MgO | 2.14 | 0.72 | 0.00 | 14.21 | 0.00 |
| CaO | 3.55 | 1.05 | 6.31 | 10.52 | 0.00 |
| Na₂O | 3.88 | 4.08 | 7.72 | 1.13 | 0.01 |
| K₂O | 2.94 | 4.52 | 0.27 | 0.42 | 0.00 |
| P₂O₅ | 0.14 | 0.09 | 0.01 | 0.01 | 0.01 |
| Calculated result (%) | 65.92 | 21.57 | 11.79 | 0.72 |
| Degree of crystallization, 13.62% |
| Fractionated proportions (%) | 63.28 | 34.59 | 2.12 |
| Sum of squares, 0.570 |

Abbreviations are shown in the abstract.
addition, the SiO₂ (wt%) – SrI and – NdI diagrams show fractional crystallization trends where the SrI (10³ Ma) and NdI (10³ Ma) values do not change with increasing SiO₂ contents (Fig. 6b). These data suggest that the FBG is formed by fractional crystallization from the HBG magma. The fractionated minerals are estimated by the Rb–Y (ppm) and Sr–Y (ppm) diagrams (Fig. 13a), and the proportion of fractionated minerals are obtained by the mass balance calculation using major elements (Table 2). The fractional crystallization model is adapted for the equation of Rayleigh fractionation model, and the results are shown in the spider diagram (Fig. 13b). In conclusion, the chemical variations in the Group-2 can be explained by fractional crystallization with the fractionated minerals of plagioclase, hornblende, and magnetite (Fig. 13).

Petrological evolution model of the Shaku-dake body

In this section, we discuss the magma process of the Shaku-dake body utilizing the observations, modeling,
and interpretations. The important considerations are listed as follows. (1) The intrusive rocks from the Shaku-dake body can be classified into two groups, the Group-1 (Do, TPD, CG, and PFT) and the Group-2 (HBG and FBG). The Group-1 is further subdivided into the TPD-CG and Do-PFT subgroups. Parental magmas for the TPD-CG and Do-PFT subgroups are interpreted as the sanukitic HMA and the Island arc calc-alkaline basalt, respectively (Fig. 7). (2) The Group-1 is influenced by the assimilation and fractional crystallization during the ascent and emplacement of magma, whereas the Group-2 changes its whole-rock composition through fractional crystallization (Figs. 12 and 13).

The petrological evolution model of the Shaku-dake body is shown in Figure 14. These parental magmas are assimilated by the sandstone/shale and limestone during upward movement of the crust to form the Group-1 rocks. On the other hand, the Group-2 magma is only affected by fractional crystallization during cooling without assimilation. The Cretaceous granitic magmas from north Kyushu were thought to formed by the partial melting of the mafic lower crust (Kagami et al., 1992; Owada et al., 1999; Tepold et al., 2012; Eshima et al., 2019). Similarly to this, the Group-2 magma would be produced by the partial melting of lower crust similar to the other Cretaceous granitoids in north Kyushu. In this scenario, the heat source for the crustal melting would be of the underplated mafic magmas derived from the wedge mantle such as the Sanukitic HMA magma and basaltic magma. The Cretaceous magma activities in the northern Kyushu were led by the highly thermal structure of the wedge mantle at that time. It is consistent with the ideas proposed by Iwamori (2000), Imaoka et al. (2014), Iida et al. (2015), and Kim et al. (2016), where the highly thermal structure of the wedge mantle was the major heat source of the voluminous igneous activities during the Cretaceous in Southwest Japan and the Korean Peninsula.

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Figure 13. (a) Rb-Y (ppm) and Sr-Y (ppm) diagrams of the Group-2 (HBG and FBG). Fractionated vectors were calculated by the Rayleigh fractionation model using partition coefficient after Arth (1976) and Rollinson (1993). (b) Results of fractional crystallization modeling for the Group-2 (HBG to FBG) are shown in the spider diagrams. Normalized values of C1 chondrite are after Sun and McDonough (1989). The Rayleigh fractionation model using partition coefficients are listed in Table S4 (available online from https://doi.org/10.2465/jmps.191209). Detailed explanations are described in the text.

Figure 14. The petrological evolution model of the Shaku-dake plutonic body. Various magmatic processes such as AFC and FC are also shown. Waki, wakino sub-group; Ls, limestone.
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SUPPLEMENTARY MATERIALS

Supplementary Tables S1–S4 are available online from https://doi.org/10.2465/jmps.191209.

REFERENCES

Adachi, T., Osanai, Y., Nakano, N. and Owada, M. (2012) LA-ICP-MS U–Pb zircon and Fe–EPMA U–Th–Pb monazite dating of pelitic granulites from the Mt. Ukidake area, Sefuri Mountains, northern Kyushu. Journal of the Geological Society of Japan, 118, 39–52.

Adam, J. and Green, T. (2006) Trace element partitioning between mica- and amphibole-bearing garnet thortveitite and hydrous basanitic melt: 1. Experimental results and the investigation of controls on partitioning behavior. Contributions to Mineralogy and Petrology, 152, 1–17.

Arth, J.G. (1976) Behavior of trace elements during magmatic processes: a summary of theoretical models and their applications. Journal of Research of the US Geological Survey, 4, 41–47.

Bacon, C.R. and Druitt, T.H. (1988) Compositional Evolution of the Zoned Calcalkaline Magma Chamber of Mount-Mazama, Crater Lake, Oregon. Contributions to Mineralogy and Petrology, 98, 224–256.

Cabanis, B. and Lecomte, M. (1989) Le diagramme La/10–Y/15-Nb/8: un outil pour la discrimination des series volcaniques et la mise evidence des processus de melange et/ou de contamination crustale. Comptes rendus de l’Academie des sciences. Serie 2, 309, 2023–2029 (in French).

Crawford, A.J., Falloon, T.J. and Green, D.H. (1989) Classification, petrogenesis and tectonic setting of boninites. In Boninite: Nature, Occurrence and Tectonic Significance. LGI Série 2, 309, 2023

Eshima, K. and Owada, M. (2018) Whole rock geochemistry of diorite and dikes from Mt. Shaku-dake area, Fukuoka, Kyushu. Journal of the Geological Society of Japan, 124, 857–862 (in Japanese with English abstract).

Eshima, K., Iida, K., Iwamori, H., Orihashi, Y., Park, T., et al. (2015) Tectonic reconstruction of batholith formation based on the spatiotemporal distribution of Cretaceous-Paleogene granitic rocks in southwestern Japan. Island Arc, 24, 205–220.

Izumi, S. (1996) Sr and Nd isotopic analyses, using a thermal ionization mass spectrometer MAT262. Geoscience Report Shimane University, 15, 153–159 (in Japanese with English abstract).

Imaoka, T. and Murakami, N. (1979) Petrochemistry of late Mesozoic to early Tertiary volcanic rocks in West Chugoku, Southwest Japan. The memoirs of the Geological Society of Japan, 17, 259–271 (in Japanese with English abstract).

Imaoka, T., Nakajima, K. and Itaya, T. (1993) K–Ar ages of hornblends in andesite and dacite from the Cretaceous Kannon Group, southwest Japan. Journal of Mineralogy, Petrology and Economic Geology, 88, 265–271 (in Japanese with English abstract).

Imaoka, T., Nakashima, K., Kamei, A., Itaya, T., et al. (2014) Episodic magmatism at 105 Ma in the Kinki district, SW Japan: Petrogenesis of Nb-rich lamprophyres and adakites, and geodynamic implications. Lithos, 184–187, 105–131.

Iwamori, H. (2000) Thermal effects of ridge subduction and implications for the age relative to the batholiths and paired metamorphic belts. Earth and Planetary Science Letters, 181, 131–44.

Jennier, G.A. (1981) Geochemistry of high-Mg andesites from Cape Vogel, Papua New Guinea. Chemical Geology, 33, 307–332.

Kagami, H., Iwata, M., Sano, S. and Honma, H. (1987) Sr and Nd isotopic compositions and Rb, Sr, Sm and Nd concentrations of standard samples. Technical Report, Institute for Study of the Earth’s Interior, Okayama University, Ser 4, 1–16.

Kagami, H., Yokose, H. and Honma, H. (1989) 87Sr/86Sr and 143Nd/144Nd ratios of GSI rock reference samples; JB-1a, JA-1 and JG-1a. Geochemical Journal, 23, 209–214.

Kagami, H., Iizumi, S., Tainosho, Y. and Owada, M. (1992) Spatial variations of Sr and Nd isotope ratios of Cretaceous-Paleogene granitoid rocks, Southwest Japan Arc. Contributions to Mineralogy and Petrology, 112, 165–177.

Kakubuchi, S., Kido, M. and Hikosan Collaborative Research Group. (1995) High-magnesian andesites from the northwestern margin of the Pleistocene Kuju-Beppu Tectonic Basin, northern Kyushu, Japan. The memoirs of the Geological Society of Japan, 44, 125–138 (in Japanese with English abstract).

Kamei, A., Owada, M., Nagao, T. and Shiraiki, K. (2004) High-Mg diorite derived from sanukitic HMA magmas, Kyushu Island, southwest Japan arc: evidence from clinopyroxene and whole rock compositions. Lithos, 75, 359–371.

Karayama, Y. (1985) Geological classification of granitic rocks in northern Kyushu Island. Proc. Nishinōhō Branch Journal of the Japan Society of Engineering Geology, 6, 2–12 (in Japanese with English abstract).

Kay, R.W. (1978) Aleutian magnesian andesites: melts from subducted Pacific ocean crust. Journal of Volcanology and Geothermal Research, 4, 117–132.

Kim, S.W., Kwon, S., Park, S.-T., Lee, C., et al. (2016) SHRIMP U–Pb dating and geochemistry of the Cretaceous plutonic rocks in the Korean Peninsula: a new tectonic model of the Cretaceous Korean Peninsula. Lithos, 262, 88–106.
desite. Earth and Planetary Science Letters, 54, 357–365.
Tatsumi, Y. (1982) Origin of high-magnesian andesites in the Setouchi volcanic belt, southwest Japan: II. Melting phase relations at high pressures. Earth and Planetary Science Letters, 60, 305–317.
Tatsumi, Y. and Ishizaka, K. (1982a) Origin of high-magnesian andesites in the Setouchi volcanic belt, southwest Japan: I. Petrographical and chemical characteristics. Earth and Planetary Science Letters, 60, 293–304.
Tatsumi, Y. and Ishizaka, K. (1982b) Magnesian andesite and basalt from Shodo-Shima island, southwest Japan, and their bearing on the genesis of calc-alkaline andesites. Lithos, 15, 161–172.
Tatsumi, Y. and Hanyu, T. (2003) Geochemical modeling of dehydration and partial melting of subducting lithosphere: Towards a comprehensive understanding of high-Mg andesite formation in the Setouchi volcanic belt, SW Japan. Geochemistry, Geophysics, Geosystems, 4, 1081, doi: 10.1029/2003GC000530.
Tepper, J.H., Nelson, B.K., Bergantz, G.W. and Irving, A.J. (1993) Petrology of the Chilliwack batholith, north Cascades, Washington: generation of calc-alkaline granitoids by melting of mafic lower crust with variable water fugacity. Contributions to Mineralogy and Petrology, 113, 333–351.
Tiepolo, M., Langone, A., Morishita, T. and Yuhara, M. (2012) On the recycling of amphibole-rich ultramafic intrusive rocks in the arc crust: Evidence from Shikanoshima Island (Kyushu, Japan). Journal of Petrology, 53, 1255–1285.
Yogodzinski, G.M., Kay, R.W., Volynets, O.N., Koloskov, A.V. and Kay, S.M. (1995) Magnesian andesite in the western Aleutian Komandorsky region: implications for slab melting and processes in the mantle wedge. Bulletin of the Geological Society of America, 107, 505–519.
Yokoyama, K., Shigeoka, M., Otomo, Y., Tokuno, K. and Tsutsumi, Y. (2016) Uraninite and Thorite ages of around 400 granitoids in the Japanese Islands. Memoirs of the National Museum of Nature and Science, 51, 1–24.
Yuhara, M. and Uto, C. (2007) Relationship between the Shikanoshima Granodiorite and Shikanoshima basic rocks at the Shikanoshima Island, northern Kyushu, Southwest Japan: coexistence of high Mg dioritic magma and granodioritic magma. Journal of the Geological Society of Japan, 113, 519–531 (in Japanese with English abstract).
Zack, T. and Brumm, R. (1998) Ilmenite/liquid partition coefficients of 26 trace elements determined through ilmenite/clino-pyroxene partitioning in garnet pyroxene. In 7th International Kimberlite Conference (Gurney, J.J., Gurney, J.L., Pascoe, M.D. and Richardson, S.H. Eds). Red Roof Design, Cape Town, 986–988.

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