Geochemical Variations in Eruptive Products of Sambe Volcano, Southwest Japan, Based on Correlations of Tephra Layers in Drill Cores from Lake Suigetsu

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Abstract

A tephra layer from Lake Suigetsu tentatively correlated with the Sambe–Koyahara tephra from Sambe volcano was correlated based on the geochemistry of a Sambe–Koyahara tephra sample obtained near the source volcano and the petrographic properties of samples of the Sambe–Koyahara and Daisen–Kamogaoka tephras. The petrographic and geochemical properties of the Suigetsu tephra suggest that it should be correlated with the Daisen–Kamogaoka tephra. The eruptive volume of the Daisen–Kamogaoka tephra was estimated to be small, and it could hardly reach Lake Suigetsu. However, considering the absence of no other Daisen tephra which could reach Lake Suigetsu, the elemental patterns of the Sambe–Koyahara sample and the Suigetsu samples correlated with the Sambe tephras indicate that the chemistry of the magma of Sambe volcano changed from non-adakitic to adakitic between stages II (Sambe–Koyahara) and IV (the Sambe–Ukinuno tephra), with the transitional adakitic Sambe–Ikeda tephra being erupted during stage III.

Key words: tephra, Daisen volcano, Sambe volcano, Lake Suigetsu, chemical composition

I. Introduction

Studies of tephra layers in core samples from Lake Suigetsu, Fukui Prefecture, Japan, have been strongly influenced by tephrochronological research on tephras in and around Japan, particularly those erupted from Daisen and Sambe (also known as Sanbesan) volcanoes in Chugoku district, Honshu Island, southwest Japan (Fig. 1). Albert et al. (2018) reported $^{14}$C ages of visible tephra layer samples obtained from core samples from Lake Suigetsu. The estimated $^{14}$C ages were calibrated using the International $^{14}$C Calibration (IntCal) dataset (Reimer et al., 2013), based on varved sediment core samples from Lake Suigetsu. Maruyama et al. (2019b, 2020a) presented the petrographic properties, and major- and trace-element concen-
trations and patterns of volcanic glass shards in Suigetsu tephra layers. Fig. 2 provides a summary of the correlations of the Suigetsu tephra layer samples between the studies of Albert et al. (2018, 2019) and Maruyama et al. (2019b, 2020a).

In general, the petrographic properties of the tephras from Daisen volcano are similar to those of the tephras from Sambe volcano (Maruyama et al., 2019b), and the elemental patterns of the volcanic glass shards from the Daisen tephras, which show adakitic characteristics (including depletion of yttrium, high Sr/Y ratios, and depletion of heavy rare earth elements (HREE); e.g., Defant et al., 1991; Martin et al., 2005), are similar to those of the younger Sambe tephras. In contrast, the older Sambe tephra samples show non-adakitic compositions (Maruyama et al., 2020a). Consequently, the Daisen tephra can be distinguished from the older Sambe tephras.

Two independent research groups have proposed the same volcanic source for the Suigetsu, Daisen, and Sambe tephras, although it remains difficult to correlate the tephras among these volcanoes (Fig. 2; Albert et al., 2018, 2019; Maruyama et al., 2019b, 2020a). However, layer B-20-07 is an exception (Fig. 2). Based on its petrographic properties and major- and trace-element concentrations of volcanic glass shards, Maruyama et al. (2019b, 2020a) tentatively correlated layer B-20-07 with the Koyahara ash fall deposit (e.g., Matsui and Inoue, 1971; Fukuoka, 2014), which was erupted from Sambe volcano. On the other hand, Albert et al. (2018) suggested that SG06-3974 (the same tephra layer as B-20-07) may be correlated with the Daisen–Kamogaoaka tephra, although Albert et al. (2018, 2019) could not definitively establish that this is the case. The Koyahara ash fall deposit (the Sambe–Koyahara tephra described by Maruyama et al., 2020a) was erupted during
the period between the Sambe–Unnan (~54 ka; Albert et al., 2018; Fig. 2) and Sambe–Ikeda (~46 ka; Albert et al., 2018; Fig. 2) tephras (Fukuoka, 2014; Fig. 3). Similarly, as shown in Fig. 2, the Daisen–Kamogaoka tephra was erupted between the Daisen–Kurayoshi (~60 ka) and Daisen–Sasaganaru (~30 ka) tephras (Albert et al., 2018). These may constrain the age of the Sambe–Koyahara or Daisen–Kamogaoka tephras to 50.9 ka for SG06-3974 (Fig. 2).

Establishing the correct correlation for layer B-20-07 is important, as it clarifies the eruptive histories of both Sambe and Daisen volcanoes. To achieve this, it is necessary to obtain and

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examine the petrographic and/or geochemical properties of the Sambe–Koyahara and Daisen–Kamogaoka tephras sampled near the source volcanoes.

In this paper, we reconsider in detail whether Suigetsu tephra layer B-20-07 (i.e., layer SG93-43) should be correlated with the Sambe–Koyahara (Maruyama et al., 2019b, 2020a) or Daisen–Kamogaoka (Albert et al., 2018) tephras. Based on this result, we present temporal variations in the geochemical properties of volcanic glasses in late Pleistocene tephras from Sambe volcano.

### II. Samples

The abbreviations for the Sambe tephras referred to in this study are based on Machida and Arai (2011) and Fukuoka (2014), except for the Sambe–Koyahara tephra (hereafter abbreviated as SKy). The SKy sample was obtained from an outcrop, described by Fukuoka (2014), at the Shigaku Observatory, Ohda City, Shimane Prefecture (Fig. 1) on August 12, 2010. The sample of the Daisen–Kamogaoka (DKm) tephra was obtained from an outcrop in Kamogaoka, Sekigane-cho Hori, Kurayoshi City, Tottori Prefecture (Fig. 1) on October 10, 1990. The stratigraphy of the Kamogaoka outcrop is almost identical to that of the upper and middle Daisen volcanic ash layer groups described by Okada and Tanimoto (1986). Electronic Appendices 1 and 2 show the schematic columnar section of the Daisen tephras based on figure 1 of Okada and Tanimoto (1986) and a photograph of Kamogaoka outcrop, respectively. The petrographic properties of the tephras of Kamogaoka outcrop are summarized in Electronic Appendices 3 and 4.

The petrography and geochemistry of the Suigetsu tephra samples discussed in this study were described by Maruyama et al. (2019b) and Maruyama et al. (2020a), respectively. The Suigetsu tephra samples starting with “SG93” were obtained from cores drilled in 1993 (Take-mura et al., 1994), and those starting with “A”, “B”, “C”, or “D” were obtained from cores drilled in 1993.
Table 1  Modal compositions of grains and heavy minerals of Sambe–Koyahara and Daisen–Kamogaoka tephras, and possibly-related Suigetsu tephra samples.

| Tephra sample | Modal grain composition (%) | Modal heavy mineral composition (%) |
|---------------|----------------------------|-------------------------------------|
| Tephra samples obtained near source volcanoes | | |
| Sambe–Koyahara (SKy) | 46.0 41.5 8.5 4.0 0.0 | 0.0 0.0 0.0 0.0 4.0 |
| Daisen–Kamogaoka (DKm) | 1.0 37.0 16.0 46.0 0.0 | 0.0 9.0 0.0 1.0 50.5 |
| Tephra samples obtained from Suigetsu core samples (Maruyama et al., 2019b) | | |
| SG93-43 (bored in 1993) | 4.0 36.0 6.0 54.0 0.0 | 0.0 2.5 0.0 1.0 56.0 |
| B-20-07 (bored in 2006) | 10.0 31.0 7.5 51.5 0.0 | 0.0 2.0 0.0 1.0 50.5 |

Notes: Two hundred grains were analyzed for the compositions of fragments and heavy minerals in each tephra sample. Layer SG93-43, from a core drilled in 1993, corresponds to layer B-20-07 obtained from core drilled in 2006 (Maruyama et al., 2019b, 2020a). Layers SG93-43 and B-20-07 correspond to SG06-3974 of Smith et al. (2013) and Albert et al. (2018, 2019). Gl = glass; Lm = light minerals; Hm = heavy minerals; Rf = rock fragments; Ol = olivine; Opx = orthopyroxene; Cpx = clinopyroxene; BAmp = brownish amphibole; GAmp = greenish amphibole; Opq = opaque minerals; Cum = cummingtonite; Zrn = zircon; Bt = biotite; Ap = apatite.

in 2006 (Smith et al., 2013). The Sambe–Kisuki (SK) tephra sample was previously described by Maruyama et al. (2020a) and Suzuki et al. (2020). The SK sample was obtained from an outcrop in Kamihashinami, Sada-cho, Izumo City, Shimane Prefecture (Fig. 1). The overview of Kamihashinami outcrop has been described by Fukuoka (2014). The sample of the Sambe–Ukinuno (lower) (SUk (lower)) tephra defined by Maruyama et al. (2020b), which is commonly known as “Sambe–Ukinuno (SUk)” at present, has been previously described by Maruyama et al. (2020a). It was obtained from the type locality of this tephra (Fukuoka and Matsui, 2002) beside Lake Ukinuno-ike (Fig. 1). Unfortunately, the sample of the Makibara pyroclastic flow deposit (hereafter abbreviated as MkF), which can be regarded as a contemporaneous heterotopic facies of DKm (Yamamoto, 2017), was not available in this study.

III. Analytical procedures

The petrographic properties of the tephra samples including the modal compositions of the grain components and the heavy minerals and the shapes of the volcanic glasses were determined by using a polarizing microscopic observation method. Heavy minerals described in this study are minerals with relative densities greater than ~2.85, which is approximately equivalent to that of bromoform (CHBr₃) used as a heavy liquid. The heavy minerals in tephra samples are shown in Table 1. Light minerals, whose relative densities are lower than ~2.85, are mostly quartz and feldspar-group minerals. The refractive index values of volcanic glass shards from the tephra samples were determined using a refractive index measurement system (RIMS; Kyoto Fission-Track; Danhara et al., 1992).

Fifty-eight major and trace elements in volcanic glass shards from the SKy tephra sample were analyzed with a Thermo Fisher Scientific iCAP TQ quadrupole inductively coupled plasma–mass spectrometer (ICP–MS) coupled to a Light Conversion CARBIDE femtosecond laser ablation system at the University of Tokyo, Tokyo, Japan. Details of the analytical conditions and data processing for SKy and other samples discussed in this study are described by Maruyama et al. (2016, 2017, 2020a). Laser ablation-ICP-MS analysis of volcanic glass
Hierarchical cluster analysis of geochemical data for the Suigetsu tephra samples that are correlated with tephras from Daisen and Sambe volcanoes and those obtained near the source volcanoes was performed using the R software package (R Core Team, 2020). Additional details are described by Maruyama et al. (2019a).

IV. Results and Discussion

1) Re-examination of the correlation for the Suigetsu tephra layer correlated with the Sambe-Koyahara tephra

Albert et al. (2018) suggested that the Suigetsu tephra may have been derived from Daisen volcano, based on the major-element compositions of volcanic glass shards and the absence of eruptive activity at Sambe volcano around 50 ka. However, two tephras were erupted from Sambe volcano, the Sambe-Ohda (SOd) tephra and SKy, between the eruptions of SUn and SI (Fig. 3; Fukuoka, 2014). The volcanic glass shards from SKy are typically enriched in microlites, as are those in layer B-20-07 and the corresponding layer SG93-43 (Maruyama et al., 2019b). The glass shards of DKm have a dusty appearance because of the presence of microlites, and this similar characteristic makes a robust correlation of the tephras more difficult. Tables 1 and 2 compare the petrographic properties of SKy and DKm samples obtained near the source volcanoes with those of two Suigetsu tephra samples correlated with SKy (Maruyama et al., 2019b). Fig. 4 shows graphically the modal compositions of the grain components and the heavy minerals summarized in Table 1, and Fig. 5 shows the distributions of the refractive index values summarized in Table 2. The compositions of both Suigetsu tephra samples are similar to that of DKm. Volcanic glass shards make up 46% of the SKy sample, compared with < 10% of the DKm and Suigetsu tephra samples (Table 1; Fig. 4). As with DKm, the Suigetsu tephra samples contain small amounts of orthopyroxene (2-3% of the heavy minerals; Table 1). In contrast, SKy contains no orthopyroxene (Table 1; Fig. 4). The refractive index values of the volcanic glass shards in the SKy sample (1.490-1.495) are slightly lower than those in the DKm (1.496-1.500) and Suigetsu tephra samples (1.494-1.500) (Table 2; Fig. 5). Based on the petrographic properties, layers SG93-43 and B-20-07 can be correlated with DKm rather than SKy. As with DKm, the tephra layers found from the Kamogaoka outcrop such as DSP, DKP, DSs, and K-Ah (Electronic Appendices 1 and 2) contain small amounts of volcanic glass shards (< 13%; Electronic Appendix 3), probably because of secondary aqueous alterations.

| Tephra sample                  | Refractive index of volcanic glass (n) | Glass shape¹ |
|-------------------------------|----------------------------------------|--------------|
|                               | N⁰  | Range      | Mean      | Mode       |               |
| Tephra samples obtained near source volcanoes |      |            |            |            |               |
| Sambe-Koyahara (SKy)          | 60  | 1.4897-1.4953 | 1.4938   | 1.494 pm > im, irr |
| Daisen-Kamogaoka (DKm)        | 7   | 1.4959-1.5000 | 1.4986 -  | irr         |
| Tephra samples obtained from Suigetsu core samples (Maruyama et al., 2019b) |      |            |            |            |               |
| SG93-43 (bored in 1993)       | 60  | 1.4942-1.4987 | 1.4962 1.496 pm > irr |
| B-20-07 (bored in 2006)       | 50  | 1.4947-1.5000 | 1.4968 1.496 irr > pm |

¹ Number of measurements. The mode value for DKm was not obtained because of small number of analyzable glass shards.

² Classification of the shape of volcanic glass shards is based on Yoshikawa (1976): pm = pumice type, im = intermediate type, and irr = irregularly shaped type.
after deposition. Therefore, the modal ratio of the volcanic glass shards in the DKm sample from the Kamogaoka outcrop (1%: Table 1; Fig. 4) might be ~10% just after falling, considering those of layers SG93-43 and B-20-07. Nevertheless, DKm originally contained significantly smaller amount of the volcanic glass shards than SKy (46%; Table 1; Fig. 4).

Figure 6a shows the elemental patterns of volcanic glass shards from SKy and layer B-20-07 relative to crustal abundances. The major and trace-element concentrations of volcanic glass shards from SKy are listed in Table 3. The geochemistry of SKy is clearly distinguishable from that of layer B-20-07, and is similar to that of the older Sambe tephras (SUn and SK; Fig. 6a). SKy and the older Sambe tephras show non-adakitic characteristics. The adakitic pattern is characterized by a marked negative Y anomaly, a right-sloping pattern of light REE (LREE), and depletion of HREE (Maruyama et al., 2020a; Fig. 6b). The tephra layers correlated with the Daisen tephras also yield adakitic elemental patterns, and the elemental pattern of layer B-20-07 is similar to those of the Daisen tephras (Fig. 6b). The elemental pattern of layer B-20-07, especially that of heavy elements (La–U), is generally similar to those of the Daisen tephras in comparison with those of the Sambe tephras (Fig. 6). The LREE pattern of layer B-20-07 is clearly distinguishable from those of A-11-00 (SUk (upper)) and A-19-04 (SI), although those of these three tephra layers obviously show the adakitic characteristic (Fig. 6a).
Figure 7 shows a dendrogram of the Suigetsu tephra layers correlated with those from Sambe and Daisen volcanoes, as derived from cluster analysis of the geochemical data of volcanic glass shards (Maruyama et al., 2020a). The Euclidean distances between the samples are provided in Electronic Appendix 5. Layer B-20-07, tentatively correlated with SKy, belongs to the same branch as the samples correlated with tephras from Daisen volcano (Fig. 7). The cluster analysis suggests that layer B-20-07 can be regarded as a tephra from Daisen volcano rather than from Sambe volcano, as previously implied by figure 8 of Maruyama et al. (2020a).

The sample of DKm obtained from the Kamo-gaoka outcrop was not geochemically analyzed. Nevertheless, the petrographic and geochemical properties of the tephra samples apparently suggest that B-20-07 (i.e., SG06-3974) and SG93-43 from the Suigetsu core can be cor-

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related with DKm, as suggested by Albert et al. (2018). As shown in Fig. 6b, the geochemistry of layer B-20-07 suggests that the magma of Daisen volcano has retained these adakitic characteristics since the eruption of at least DHP or DMP.

However, it is a hasty conclusion, because DKm reached only 30 km eastward (i.e., toward Lake Suigetsu) (Okada and Ishiga, 2000; Suto et al., 2007; Fig. 1). Lake Suigetsu is ~210 km to the east of Daisen volcano. Yamamoto (2017) estimated the total volume of DKm to be 0.035 km³ DRE (dense rock equivalent). On the other hand, the total eruption volume of MkF was estimated to be more than five times larger than that of DKm (0.19 km³ DRE; Yamamoto, 2017). However, the distribution of MkF is limited in the west side of Daisen volcano (Tsukui, 1984; Yamamoto, 2017; Fig. 1). Therefore, both DKm and MkF could hardly reach Lake Suigetsu.

Albert et al. (2018) reported that the thickness of SG06-3974 (i.e., layer B-20-07) in the SG06 core sample was only 0.03 cm. This observation suggests that very tiny amount of DKm on the west wind could reach Lake Suigetsu, although it is still difficult to make a definitive correlation for B-20-07 and SG93-43. At any rate, as implied by Albert et al. (2018, 2019), B-20-07 and SG93-43 can be correlated with the Daisen tephra (possibly corresponding to DKm) based on the petrographic and chemical properties rather than the Sambe tephra. Considering that no other Daisen tephra which erupted during the same eruptive activity as DKm/MkF and more widely distributed toward the west of Daisen volcano has been found, it may be safe to say that the IntCal13 ¹⁴C age of SG06-3974 (i.e., B-20-07 and SG93-43) of 50.9 ± 0.4 ka (Fig. 2; Albert et al., 2018) is tentatively assigned to DKm and MkF. This ¹⁴C age is consistent with the fission-track (FT) age of DKm (50 ± 13 ka; Ishida et al., 1984; Okada and Ishiga, 2000). Katoh et al. (2007) estimated the ¹³C age of DKm to be slightly younger (41,632 ± 203 cal BP).

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Table 3  Mean major- and trace-element abundances of volcanic glass shards from the Sambe–Koyahara tephra sample.

| major components (wt.%) | mean | 1σ | trace elements (µg/g) | mean | 1σ | mean | 1σ |
|-------------------------|------|----|----------------------|------|----|------|----|
| SiO₂                    | 76.9 | 1.4| Li                   | 44   | 18 | Zr   | 29.8| 5.5 | Tb   | 0.17| 0.14|
| TiO₂                    | 0.079| 0.092| Be                 | 2.8  | 2.6 | Nb   | 19.1| 3.6 | Dy   | 1.39| 0.66|
| Al₂O₃                   | 13.19| 0.94| B                  | 85   | 52 | Mo   | 5.5  | 6.9 | Ho   | 0.25| 0.16|
| FeO                     | 0.424| 0.088| P                 | 187  | 294 | Ag   | 0.17| 0.29 | Er   | 0.94| 0.40|
| MnO                     | 0.010| 0.019| Sc                | 19   | 17 | Cd   | 2.0  | 2.5 | Tm   | 0.15| 0.14|
| MgO                     | 0.097| 0.019| V                 | 3.9  | 4.8 | In   | 0.13| 0.26 | Yb   | 0.76| 0.77|
| CaO                     | 0.69 | 0.52| Cr                | 7.6  | 9.2 | Sn   | 1.6  | 1.6 | Lu   | 0.10| 0.10|
| Na₂O                    | 3.38 | 0.58| Co               | 0.8  | 1.0 | Sb   | 1.8  | 1.1 | Hf   | 1.57| 0.88|
| K₂O                     | 5.04 | 0.81| Ni               | 1.6  | 3.1 | Cs   | 10.6| 1.6 | Ta   | 1.73| 0.27|
| Cu                      | 8.0  | 8.2| Ba                | 645  | 148 | W    | 1.44| 0.74|
| Zn                      | 52   | 97 | La                | 4.92 | 0.93| Tl   | 0.59| 0.59|
| Ga                      | 16.8 | 4.7| Ce                | 8.5  | 1.3 | Pb   | 15.7| 3.5 |
| Ge                      | 4.5  | 5.4| Pr                | 1.34 | 0.43| Bi   | 0.34| 0.20|
| As                      | 13.0 | 9.2| Nd                | 3.8  | 1.4 | Th   | 6.1 | 1.3 |
| Rb                      | 135  | 36 | Sm                | 0.77 | 0.91| U    | 4.8 | 1.2 |
| Sr                      | 59   | 12 | Eu                | 0.20 | 0.14|
| Y                       | 9.1  | 1.6| Gd                | 1.04 | 0.93|

Note: A total number of the analysis points is 37 on 17 volcanic glass shards.
This revised correlation simplifies the temporal variations in the geochemistry of the Sambe tephras when compared with the correlation proposed by Maruyama et al. (2020a), who suggested that the magma changed from non-adakitic to adakitic, with an intervening transitional period. During stages I and II (Fig. 3), the compositions of the melts of Sambe volcano were non-adakitic, as shown by the elemental patterns of SK, SU, and SKy (Fig. 6a). By stage III, the composition of the melt was partly adakitic, as shown by the composition of SI (Fig. 6a). SI shows characteristics of both non-adakitic (slightly enriched HREE; i.e., SK, SU, and SKy) and adakitic (right-sloping LREE pattern and negative Y anomaly; SUk (lower) and SUk (upper)) tephras, and can be considered a transitional adakitic tephra as suggested by Maruyama et al. (2020a). Since stage IV, the compositions of the Sambe tephras have had adakitic characteristics, similar to those of the Daisen tephras (Fig. 6). During the Holocene (stages V–VIII; Fig. 3; Fukuoka, 2014), the magma might preserve the adakitic composition, based on the geochemical data of the Suigetsu samples, which are correlated with younger Sambe tephras (Maruyama et al., 2020a). The eruption style of Sambe volcano might be largely unrelated to magma composition, although it has changed over time (Fig. 7).
3). However, the process responsible for the change in geochemistry of the magma might also have influenced the change in eruption style (from Plinian to Vulcanian) through stages III–V (Fig. 3).

2) Correlations of young Suigetsu–Sambe tephra layers

The correlations between tephra layers in the uppermost part of the Suigetsu core remain controversial (Fig. 2). The youngest two tephra layers (D-03-05 and A-04-13) have adakitic compositions (Maruyama et al., 2020a), and the group of younger Sambe tephras is distinct from the group of Daisen tephras in the dendrogram (branch F in Fig. 7). Maruyama et al. (2019b, 2020a) correlated layers D-03-05 and A-04-13 with one of the unnamed youngest Sambe tephras (stage VIII; Fig. 3) and Sambe–Oohirayama (SOh; stage VII; Fig. 3), respectively, based on petrography and geochemistry. However, these tephra layers have also been correlated with SOh (or the Taiheizan Pyroclastic Deposit; Fukuoka, 2014) and the Shigaku Pyroclastic Flow (Fukuoka and Matsui, 2002), respectively, by Albert et al. (2018) based on a comparison of major-element compositions of volcanic glass shards (Fig. 2). The volcanic glass shards of these tephra layers have been incompletely hydrated or have almost completely escaped hydration after deposition, though some glass shards have been completely hydrated (Maruyama et al., 2019b). This observation may be sufficient to correlate these tephra samples with very young Sambe tephras. However, it is possible that layers D-03-05 and A-04-13 are correlated with SOh (as proposed by Albert et al., 2018) and a stage VI Sambe tephra (Fig. 3), such as the Tsunoi ash fall (as suggested by Maruyama et al., 2020a), respectively.

Correlations of volcanic glass shards based on major- and trace-element concentrations may be difficult among the younger Sambe tephras because of their overall similarity in composition. Moreover, the geochemical similarity between the Daisen and the younger Sambe volcanic glass shards needs to be carefully considered. Both show the adakitic characteristics, and the elemental patterns of them are similar to each other (Fig. 6). The LREE pattern of SUk (lower) is more similar to that of Suigetsu layer B-20-07 presumably derived from Daisen volcano than that of SUk (upper) which erupted just after SUk (lower) (Fig. 6a). In the result of the cluster analysis, SUk (lower) belongs to branch I along with the Daisen tephras (DMs and DKP), not branch F to which the other younger Sambe tephras including SUk (upper) (i.e., layer A-11-00) belong (Fig. 7). These results suggest that even the sample of SUk (lower) obtained from the type locality may be treated as a tephra from Daisen, if it is correlated based on only the geochemistry of volcanic glass shards. Correlating the younger Sambe tephras should be done carefully, also considering petrographic properties and stratigraphic information comprehensively.

Classification of the Daisen tephras during the period after deposition of AT (e.g., Tsukui, 1984; Okada and Ishiga, 2000; Machida and Arai, 2011; Yamamoto, 2017) also remains complicated and controversial. Albert et al. (2018) correlated the Suigetsu tephra SG06-2504 with the Daisen–Masumizuhara pumice as newly defined by Yamamoto (2017), whereas Maruyama et al. (2019b, 2020a) correlated SG06-2504 (i.e., layer A-13-07) with DMs (Machida and Arai, 2011), or more specifically, with the Daisen–Kusadanihara pumice (e.g., Tsukui, 1984). Daisen–Masumizuhara and –Kusadanihara are both regarded as volcanic products of the activity of the Misen lava dome. However, in recent studies (e.g., Yamamoto, 2017), the tephra of Daisen–Kusadanihara was considered unrelated to volcanic products of the Misen lava dome.

V. Conclusions

The geochemistry of volcanic glass shards in sample SKy and the petrographic properties of SKy and DKm provide insight into the eruptive activities of Sambe volcano and temporal variations in the composition of its magma. The results of this study support the correlation for SG06-3974 (i.e., layer B-20-07) done by Albert
et al. (2018, 2019). It is still difficult to definitively correlate the Suigetsu tephra layer B-20-07 with DKm because of a very small amount of the eruption volume. However, the $^{14}$C age of layer B-20-07 can be assigned tentatively as the age of DKm, considering the result of the correlation based on the petrographic and chemical properties, the thinness of layer B-20-07 in the core sample, and the absence of other significant Daisen tephras in the same eruptive activity.

In addition to the re-correlation for layer B-20-07, this study modified the chemical variations of the magma of Sambe volcano previously suggested by Maruyama et al. (2020a). Those based on this study are as follows (Fig. 6a): it changed from non-adakitic to adakitic between stages II (SKy) and IV (SUk), with the eruption of the transitional adakitic SI tephra (stage III). This study proposed more reasonable geochemistry of the magma of Sambe volcano in comparison with that proposed by Maruyama et al. (2020a). Moreover, it suggested that the magma of Daisen volcano preserved the adakitic geochemistry through the late Pleistocene.

It is more challenging to correlate the younger Sambe/Daisen tephras, given their similar petrographic and geochemical properties. Outstanding issues regarding correlations between Daisen and Sambe tephras and their classification will be the focus of future work.

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Notes

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水月湖コア試料に含まれるテフラ層の対比から推定される
三瓶火山噴出物の化学的変動

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三瓶火山から噴出した三瓶小屋原テフラに対比された水月湖コア中のテフラ層に関して、給源火山近傍で採取された三瓶小屋原テフラおよび大山鴨ヶ丘テフラ試料の岩石学的特性と、三瓶小屋原テフラの中は火山ガラスの化学組成に基づき対比を行った。水月湖コア試料の岩石学的・化学的特性は、このテフラ試料が大山鴨ヶ丘テフラに対比されることを示唆するものであった。大山鴨ヶ丘テフラは噴出量が僅かで、水月湖まで達することができたかどうかは疑問である。そのような問題はあるものの、同時期に噴出した他の大山テフラは発見されておらず、また先行研究で示されたこの水月湖テフラの層厚が非常に薄いことを考慮すると、このテフラ試料がごく僅かながら水月湖まで到達することができた大山鴨ヶ丘テフラである可能性がある。給源火山近傍で採取された三瓶小屋原テフラ試料と、三瓶火山を給源とするテフラに対比された水月湖コア試料の火山ガラスの元素濃度パターンから、三瓶火山のマグマの化学組成が、ステージII（三瓶小屋原テフラ）とステージIV（三瓶浮布テフラ）の間に、ステージIIIの遷移的アダカイト質（三瓶池田テフラ）を経由して非アダカイト質からアダカイト質へと変化したことが示唆された。

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