Examination of the Relationship between the Ukinuno and Sakate Tephras from Sambe Volcano, Southwest Japan

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Abstract

The Sakate tephra beds in the Chugoku and Kinki districts of Japan have been correlated with the Sambe–Ukinuno (SUk) widespread marker tephras, which were erupted from Sambe volcano (ca. 20 ka). Based on geological surveys of proximal outcrops, the SUk has been divided into three tephras: the lowermost Ukinuno pumice fall deposit (Uk-pfa; normally regarded as the SUk tephra), the Midorigaoka pyroclastic flow deposit (Md-fl), and the uppermost Ukinuno ash fall deposit (Uk-fa). The Sakate tephra has been associated with the Md-fl. Moreover, previous studies have suggested that the refractive index of amphibole in the Md-fl (i.e., Sakate) samples is similar to that in the Uk-pfa samples, whereas those of the volcanic glass shards in the Md-fl samples are lower than those of the Uk-pfa samples. The petrographic properties of Uk-fa suggest that Uk-fa and Md-fl could be treated as a single tephra. However, the SiO₂ contents of the Uk-pfa volcanic glasses are slightly higher than those of Md-fl. The FeO contents of the Uk-pfa volcanic glasses are higher than those of Md-fl. This suggests that the difference in the refractive index values of the volcanic glasses is due to the FeO contents rather than the SiO₂ contents. A total of 58 elements distinguish the Md-fl volcanic glasses from Uk-pfa, particularly the light rare earth elements, although the trace element patterns are generally similar. This difference may result from fractional crystallization and/or varying magma inputs. In previous studies, the tephras correlated with the Md-fl/Uk-fa (i.e., Sakate) tephras were found to be widely distributed in the Chugoku and Kinki districts. However, those correlated with Uk-pfa were found in the southern Kinki district and immediately offshore, and at the eastern end of Shikoku Island. Uk-pfa and Md-fl/Uk-fa were erupted during the same eruptive sequence, but are clearly distinguishable from each other. The Uk-pfa and Md-fl/Uk-fa tephras can be more simply redefined as the SUk (lower) and (upper) tephras, respectively.

Key words : Sambe–Ukinuno tephra, Sakate tephra, volcanic glass shards, refractive index, chemical composition, tephra fall area

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I. Introduction

The Sambe–Ukinuno (SUk) tephra is one of the marker tephras erupted from Sambe volcano (also known as Sanbesan Volcano) in Shimane Prefecture, Chugoku, Japan (Fig. 1). The SUk tephra was erupted and deposited between two representative marker tephras from the calderas of Kyushu Island (e.g., Machida and Arai, 2011; Fig. 1), which are the Aira–Tn (AT; 30,078 ± 96 cal BP; Albert et al., 2019) and Kikai–Akahoya (K-Ah; 7,253 ± 46 cal BP; Albert et al., 2019) tephras. Therefore, the SUk tephra is an important marker tephra in the Chugoku and Kinki districts.

The Sakate volcanic ash layer was first found in Nara Prefecture in the Kinki district (Chugoku and Kinki districts. SUk tephra is an important marker tephra in the Sakate tephras. Therefore, the SUk tephra is an important marker tephra in the Chugoku and Kinki districts.

The Sakate volcanic ash layer was first found in Nara Prefecture in the Kinki district (Fig. 1) (Azuma et al., 1983; Yoshikawa et al., 1986), and has been regarded as a correlative of the SUk tephra (e.g., Katoh et al., 2007; Machida and Arai, 2011). Sambe volcano has been regarded to be the source volcano of the SUk and Sakate tephras, because of their characteristic mineralogies, such as the absence of pyroxene (Miura and Hayashi, 1991; Maruyama et al., 2019).

Recently, correlations of visible tephra layers in drill core samples from Lake Suigetsu (Fig. 1) have been conducted (e.g., Smith et al., 2013; Albert et al., 2018, 2019; Maruyama et al., 2019, 2020). The age of the Sakate tephra was estimated based on the tephra layer identified in the Suigetsu core samples. Albert et al. (2018) reported a 14C age calibrated using the IntCal13 (International Radiocarbon Calibration, 2013) dataset (Reimer et al., 2013), based on a varved sediment core from Lake Suigetsu. The IntCal13 age was estimated to be 19,551 ± 80 cal BP (Albert et al., 2018). This is currently regarded as the age of the SUk tephra.

However, there are some uncertainties regarding the SUk and Sakate tephras. Katoh et al. (2007) suggested that the petrographic properties, including the refractive index of amphibole, of some tephra layer samples obtained from Ohnuma Moor, ~180 km east of Sambe volcano (Fig. 1), are similar to those of the SUk tephra. However, the refractive index values of the volcanic glass shards differ. As such, Katoh et al. (2007) concluded that the tephra layers from Ohnuma Moor could be correlated with the upper unit of the SUk, which corresponds to the Sakate tephra. This petrographic correlation remains controversial. For example, it can be complex to correlate and identify tephras around a source volcano, particularly in distal areas. Therefore, the relationship between the SUk and Sakate tephras remains ambiguous and requires more detailed investigation.

The differences in the minerals and volcanic glasses in the SUk and Sakate tephras are problematic. The SUk tephra has been regarded as a single tephra layer, which is termed the Sambe pumice fall deposit (Hattori et al., 1983) or Sambe–Ukinuno pumice fall (Hayashi and Miura, 1987). Fukuoka and Matsui (2002) divided the SUk tephra into three tephras based on geological surveys of outcrops near Sambe volcano: the Ukinuno pumice fall deposit (Uk-pfa; lowermost SUk), the Midorigaoka pyroclastic flow deposit (Md-fl), and the Ukinuno ash fall deposit (Uk-fa; uppermost SUk). In some outcrops near Sambe volcano, Uk-fa conformably overlies Md-fl (Fukuoka and Matsui, 2002). Fukuoka (2014) identified Md-fl directly overlying Uk-pfa at Loc. 23 and 24 of Fukuoka and Matsui (2002) (Figs. 2 and 3a).

The aforementioned tephra layers studied by Katoh et al. (2007) were correlated with the Sakate tephra (i.e., the upper unit of SUk, which can be considered to be Md-fl and/or Uk-fa). Albert et al. (2018, 2019) assumed that Md-fl was correlated with the Sakate tephra, but did not consider Uk-fa. Machida and Arai (2011) simply treated the Sakate tephra as a distal tephra correlated with SUk and not Md-fl. This is ambiguous because no previous study has identified an independent tephra layer that can be correlated with Uk-fa in distal areas, although Katoh et al. (2007) implied that the Sakate tephra may correlate to both Md-fl and Uk-fa. This requires further detailed investigation.

In addition, the distribution of the SUk and
Sakate tephras is complex. For example, no tephra that correlates with Uk-pfa has been identified in the Lake Suigetsu core. Moreover, the only tephra layers that have been correlated with the Sakate tephra are in a core from Lake Biwa (Fig. 1) (Yoshikawa et al., 1986; Yoshikawa and Inouchi, 1991; Takemura et al., 2010). These previous studies imply that the distribution of the Sakate tephra may be different from that of the Uk-pfa tephra. This possibility has not been examined in detail in previous studies.

There are also ambiguities regarding the chemical compositions of these tephras. Maruyama et al. (2020) showed that the elemental pattern of volcanic glass shards of the distal Sakate and proximal Md-fl tephra can be clearly distinguished from that of the proximal
Uk-pfa tephra.

At present, access to outcrops near Sambe volcano is becoming more difficult. The type locality of Md-fl (Loc. 2 in Fig. 2) was lost completely in the early 2000s because of a housing development. The relationship between the three Ukinuno and Sakate tephras needs to be established as soon as possible, before other proximal outcrops are lost.

In this study, we present refractive index values of volcanic glass shards and amphiboles in samples of Uk-pfa, Md-fl, and Uk-fa collected from around Sambe volcano, along with those of tephra samples obtained from distal areas, including Lake Suigetsu (Fig. 1; Nakagawa et al., 2012; Smith et al., 2013; Maruyama et al., 2019, 2020), Ikenohira Moor (Fig. 1; Takahara and Masuda, 2017), and Kakeya (Figs. 1 and 3b). In addition, we present a statistical comparison of the geochemical data for these volcanic glasses with the data of Maruyama et al. (2020), and show the distributions of the SUk tephras in and around the Chugoku and Kinki districts, based on previous studies.

II. Samples and analytical methods

1) Samples

The samples collected from the proximal and distal SUk tephras are listed in Table 1. The Uk-pfa-1 and Md-fl-1 samples correspond to the SUk and Sakate samples previously described by Maruyama et al. (2020). The Uk-pfa-1 sample was collected from the outcrop facing Lake Ukinunoike, Sambe-cho, Ohda City, Shimane Prefecture (Loc. 1 in Fig. 2), which corresponds to Loc. 19 and is the type locality of the Uk-pfa tephra (Fukuoka and Matsui, 2002). The Uk-pfa sample in this study corresponds to the upper Uk-pfa, and contains cummingtonite (~5% in pumice; Fukuoka and Matsui, 2002). The total thickness of Uk-pfa at Loc. 1 (Fig. 2) is ~4 m (Fukuoka and Matsui, 2002). A total of
six samples of Md-fl and Uk-fa were obtained from an outcrop in Midorigaoka, Shigaku, Sambe-cho, which is ~1.5 km ESE of Lake Ukinunoike (Loc. 2 in Fig. 2). The total thicknesses of Md-fl and Uk-fa at Loc. 2 (Fig. 2) are > 10 m and ~2 m, respectively (Fukuoka and Matsui, 2002).

The outcrop at Kakeya, Unnan City, Shimane Prefecture, is ~19.5 km ENE of Sambe volcano (Fig. 1). Two layers of SUk were found in the uppermost part of this outcrop (Fig. 3b; M. Watanabe, pers. comm.). In this outcrop, the upper grayish white layer was correlated with Md-fl and/or Uk-fa, and the lower yellow layer was correlated with Uk-pfa (Fig. 3b). The SUk-KKY-01 and -02 tephra samples were obtained from the lower Uk-pfa (~13 cm thick) and upper Md-fl/Uk-fa (~14 cm thick) layers, respectively.

The SUk-SG06 sample was obtained from the Lake Suigetsu drill core sample bored in 2006 (e.g., Smith et al., 2013). It corresponds to sample SG06-1965 described by Smith et al. (2013) and sample A-11-00 described by Maruyama et al. (2019, 2020). The thickness of the SUk-SG06 layer in the core sample is 0.7 cm (Smith et al., 2013).

The SUk-IKH-01 and -02 samples were obtained from Ikenohira Moor (~630 m above sea level; ~6,000 m$^2$) on a hillside of Mt. Kuroso, Mie Prefecture (Fig. 1). Takahara and Masuda (2017) identified the SUk tephra layer in a sediment core that was 800 cm long. The SUk layer was found at a depth of 702–709 cm. This SUk layer is divided into lower SUk-IKH-01 (~4.5 cm thick) and upper SUk-IKH-02 (3 cm

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Table 1 Summary of modal grain compositions in the Ukinuno tephra samples.

| Tephra sample | Sample ID | Modal grain composition (%) | Remark |
|---------------|-----------|-----------------------------|--------|
| Proximal tephra (Loc. 1 and 2 in Fig. 2) |          |                             |        |
| Uk-fa-5       | 96040701-6 (Loc. 2) | 7.5 53.0 22.5 17.0 tr | Uppermost sample from Loc. 2 |
| Uk-fa-4       | 96040701-5 (Loc. 2) | 8.5 55.0 16.0 20.5 tr | (Md-fl-1 and five Uk-fa samples obtained from Loc. 2 are arranged in descending order in this table.) |
| Uk-fa-3       | 96040701-4 (Loc. 2) | 13.5 55.0 15.5 16.0 tr |        |
| Uk-fa-2       | 96040701-3 (Loc. 2) | 18.0 46.0 17.5 18.5 0.0 |        |
| Uk-fa-1       | 96040701-2 (Loc. 2) | 22.0 44.0 14.0 20.0 0.0 |        |
| Md-fl-1       | 96040701-1 (Loc. 2) | 12.0 53.0 20.5 14.5 0.0 | Lowermost sample from Loc. 2 |
| Uk-pfa-1      | 96040601 (Loc. 1)  | 51.5 33.5 15.0 0.0 0.0 | Upper Uk-pfa (Fukuoka and Matsui, 2002) |

Distal tephra (Kakeya outcrop) |          |                             |        |
| SUk-KKY-02    | 10032703 Kakeya-1 | 17.0 41.5 10.0 31.5 0.0 | Upper layer |
| SUk-KKY-01    | 10032703 Kakeya-2 | 11.5 59.0 26.5 3.0 0.0 | Lower layer |

Distal tephra (Suigetsu 2006 drill core) |          |                             |        |
| SUk-SG06      | A-11-00     | 34.0 46.0 9.0 11.0 0.0      | A-11-00 of Maruyama et al. (2019, 2020) |

Distal tephra (Ikenohira Moor sediment) |          |                             |        |
| SUk-IKH-02    | IKH2010 lot13 8-11 cm | 38.0 36.0 16.5 9.5 0.0 | Upper layer |
| SUk-IKH-01    | IKH2010 lot13 11-15.5 cm | 25.5 37.0 30.5 7.0 0.0 | Lower layer |

Notes: Two hundred grains were analyzed for the analyses of the grain composition of each tephra sample. Heavy minerals are minerals with relative densities greater than ~2.85, which is approximately equivalent to that of bromoform (CHBr$_3$) used as a heavy liquid. The heavy minerals in tephra samples are shown in Table 2. Light minerals, whose relative densities are lower than ~2.85, are mostly quartz and feldspar-group minerals. The petrographic properties of the SUk-SG06 (A-11-00) summarized in Tables 1–3 were previously presented by Maruyama et al. (2019). Gl = glass; Lm = light minerals; Hm = heavy minerals; Rf = rock fragments. tr = trace.
thick) layers (H. Takahara, pers. comm.).

2) Analytical methods

The refractive index values of amphiboles and volcanic glass shards from the tephra samples were determined using a refractive index measurement system (RIMS; Kyoto Fission-Track; Danhara et al., 1992). The mineralogies of the tephra samples were also determined.

Fifty-eight major and trace elements in volcanic glass shards from the Uk-pfa-1, Md-fl-1, and SUk-SG06 samples were analyzed with a Thermo Fisher Scientific iCAP Qc quadrupole ICP–MS instrument coupled to a Cyber Laser IFRIT femtosecond laser ablation system at the University of Tokyo, Tokyo, Japan. Details of the analytical conditions and data processing are described by Maruyama et al. (2016, 2017, 2020).

The Tukey–Kramer pairwise multiple comparison test (Kramer, 1956; Hayter, 1984) was used to make statistical comparisons of the elemental data for the Uk-pfa-1, Md-fl-1, and SUk-SG06 samples. The major element data for the three tephra samples examined in this study have unimodal normal distributions, which are necessary for applying the Tukey–Kramer test (e.g., Lowe, 2011; Ikuta et al., 2016; Maruyama et al., 2017). The Tukey–Kramer analysis was performed using the R software package (R Core Team, 2019). P values of < 0.05 were considered to be statistically significant.

III. Results

1) Petrographic properties

1-1) Proximal tephra samples

The mineralogies of the Uk-pfa, Md-fl, and Uk-fa proximal tephra samples are listed in Tables 1 and 2. The refractive index values of the volcanic glass shards and greenish amphiboles are summarized in Table 3, and histograms of the refractive index values are shown in Fig. 4.

The shapes of the volcanic glass shards in
these tephra samples were classified into the pumiceous and irregularly shaped types defined by Yoshikawa (1976). The volcanic glass shards are almost completely hydrated. The volcanic glass shards comprise > 50% of the Uk-pfa-1 samples, and 8–22% of the Md-fl and five Uk-fa samples (Table 1). The mineralogies of the Uk-pfa, Md-fl, and Uk-fa samples are similar (Tables 1 and 2). The Md-fl and Uk-fa samples contain small amounts of brownish amphibole, in addition to greenish amphibole. Cummingtonite is also present in these samples (Table 2). The Uk-pfa-1 sample also contains cummingtonite (3.0%; Table 2). The Uk-pfa-1 sample contains almost no biotite, whereas the heavy mineral fractions of the Md-fl-1 and Uk-fa samples contain 2.5–19.0% biotite (Table 2). The Uk-pfa, Md-fl, and Uk-fa samples contain almost no pyroxene. Plagioclase is the dominant felsic mineral in these tephra samples. Md-fl and Uk-fa contain small amounts of quartz. The Uk-fa-1 and -2 samples also contain a small amount of K-feldspar, and b-quartz was found in sample Uk-fa-2. The Md-fl and Uk-fa samples contain glassy or rock fragments (15–21%; Table 1). The Uk-pfa-1 sample contains no rock fragments (Table 1).

The refractive index values of the volcanic glass shards in the Uk-fa-1 sample are 1.503–1.506 (Table 3). The refractive index values of the volcanic glass shards in the Md-fl and Uk-fa samples obtained in this study are 1.498–1.500 (1.499) and 1.497–1.501 (1.499), respectively (Table 3). The mode values for the Md-fl-1 and Uk-fa samples are both 1.499 (Table 3). The range of refractive index values of amphibole in the proximal samples is 1.670–1.680 (Table 3).

1-2) Distal tephra samples
The mineralogies of the SUk-KKY-01 and -02, SUk-SG06, and SUk-IKH-01 and -02 distal tephra samples are summarized in Tables 1

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Table 3 Summary of refractive index values of greenish amphibole and volcanic glass shards in the Ukinuno tephra samples.

| Tephra sample | Refractive index of volcanic glass (n<sub>g</sub>) | Glass shape<sup>b</sup> | Refractive index of greenish amphibole (n<sub>a</sub>) |
|---------------|-----------------------------------------------|----------------------|---------------------------------|
|               | N<sup>a</sup> | Range        | Mode       | Mean | N<sup>a</sup> | Range        | Mode       | Mean |
| Proximal tephra (Loc. 1 and 2 of Fig. 2) | | | | | | | | |
| Uk-fa-5       | 30       | 1.4964–1.5007  | 1.499     | 1.4987 | irr > pm | (not analyzed) |
| Uk-fa-4       | 30       | 1.4977–1.5002  | 1.499     | 1.4990 | pm, irr  | (not analyzed) |
| Uk-fa-3       | 30       | 1.4975–1.5008  | 1.499     | 1.4990 | pm > irr | 30 | 1.670–1.680 | 1.674, 1.675 | 1.675 |
| Uk-fa-2       | 30       | 1.4980–1.5002  | 1.499     | 1.4991 | pm > irr | (not analyzed) |
| Uk-fa-1       | 30       | 1.4975–1.4999  | 1.499     | 1.4988 | pm > irr | 30 | 1.671–1.679 | 1.675 | 1.675 |
| Md-fl-1       | 30       | 1.4982–1.5001  | 1.499     | 1.4991 | pm > irr | 30 | 1.671–1.678 | 1.673–1.674 | 1.674 |
| Uk-pfa-1      | 30       | 1.5033–1.5046  | 1.504     | 1.5041 | pm     | 30 | 1.672–1.678 | 1.676 | 1.675 |
| Distal tephra (Kakeya outcrop) | | | | | | | | |
| SUk-KKY-02    | 60       | 1.4972–1.5005  | 1.499     | 1.4986 | pm, irr | 60 | 1.667–1.689 | 1.675 | 1.677 |
| SUk-KKY-01    | 61       | 1.4985–1.5049  | 1.504     | 1.5036 | pm     | 60 | 1.670–1.686 | 1.673 | 1.674 |
| Distal tephra (Suigetsu 2006 drill core) | | | | | | | | |
| SUk-SG06      | 61       | 1.4974–1.5012  | 1.499     | 1.4990 | pm, irr | 50 | 1.671–1.679 | 1.675 | 1.675 |
| Distal tephra (Ikenohira Moor sediment) | | | | | | | | |
| SUk-IKH-02    | 50       | 1.4995–1.5057  | 1.501     | 1.5014 | pm     | (not analyzed) |
| SUk-IKH-01    | 50       | 1.4997–1.5095  | 1.505     | 1.5038 | pm     | (not analyzed) |

<sup>a</sup> Number of measurements.
<sup>b</sup> Classification of the shape of volcanic glass shards is based on Yoshikawa (1976): pm = pumice type, and irr = irregularly shaped type.
and 2. The refractive index values of the volcanic glass shards and greenish amphiboles are listed in Table 3 and shown in Fig. 5. The petrographic properties of the SUk-SG06 (A-11-00) sample were previously presented by Maruyama et al. (2019).

The volcanic glass shards in sample SUk-KKY-01 from the lower Uk-pfa layer are mainly of the pumiceous type, whereas those in sample SUk-KKY-02 obtained from the Md-fl/Uk-fa layer are pumiceous or irregularly shaped. Sample SUk-SG06 contains pumiceous and irregularly shaped glass shards. The pumiceous type is dominant in samples SUk-IKH-01 and -02 (Table 3). These samples contain cummingtonite and biotite, but no pyroxene (Table 2). Plagioclase and quartz are present in these tephra samples. The rock fragments are glassy. Samples SUk-KKY-01 and -02 contain no apatite (Table 2).

The refractive index values of the volcanic glass shards in sample SUk-KKY-01 vary from 1.499 to 1.505 (Table 3). The refractive index values in samples SUk-KKY-02 and SUk-SG06

Fig. 4 Histograms of the refractive index values of the volcanic glass shards and greenish amphibole in Uk-pfa-1, Md-fl-1, and five Uk-fa proximal tephra samples.
are 1.497–1.501 (Table 3). The mode values for sample SUk-KKY-02 and SUk-SG06 are both 1.499 (Table 3). The refractive index values of the volcanic glass shards in samples SUk-IKH-01 and -02 are more variable (Fig. 5) than those of the proximal samples (Fig. 4). The refractive index values of sample SUk-IKH-01 exhibit two peaks (1.503 and 1.505; Fig. 5). The mode value of the overlying sample SUk-IKH-02 (1.501; Table 3) is higher than those of the proximal Md-fl and Uk-fa samples and distal SUk-SG06 sample (1.499; Table 3). The refractive index values of amphibole in the SUk-KKY and SUk-SG06 samples are 1.667–1.689 (Table 3).

2) Glass shard chemistry
The chemical data for the Uk-pfa-1, Md-fl-1, and SUk-SG06 samples were presented by Maruyama et al. (2020). The mean major and trace element abundances of the volcanic glass shards are summarized in Appendix 1, and Harker diagrams are shown in Fig. 6. The elemental patterns of the volcanic glass shards are shown in Fig. 7, along with the results of the Tukey–Kramer test. The elemental patterns are shown relative to crustal abundances in Fig. 7. The crustal abundances proposed by McLennan (2001) were used except for phosphorus. That of P was calculated from the P₂O₅ value estimated by Rudnick and Fountain (1995), because McLennan (2001) did not propose the P composition of the bulk crust.

IV. Discussion

1) Petrographic properties
The refractive index values of the volcanic glass shards in the Uk-pfa-1 sample (Table 3) are consistent with those of the U₂ sample.
The refractive index values of the Md-fl-1 and Uk-fa samples obtained in this study (Table 3) are also consistent with those of the Sakate tephra samples found in an outcrop at Sakate (Fig. 1; Yoshikawa et al., 1986) and from the core in Lake Biwa (Fig. 1; Yoshikawa and Inouchi, 1991) (1.498–1.503). The distribution of refractive index values for the volcanic glass shards in the Uk-pfa-1 sample differs from those of the Md-fl and Uk-fa samples (Fig. 4).

The refractive index values of the volcanic glass shards in sample SUk-KKY-01 (Fig. 5) are similar to those of sample Uk-pfa-1. Samples SUk-KKY-02 and SUk-SG06 (Fig. 5) have similar refractive index values to those of the Md-fl-1 and five Uk-fa samples (Fig. 4). The distributions of the refractive index values of the volcanic glass shards of SUk-IKH-01 and -02 appear to be shifted toward 0.001–0.002.

Fig. 6  Harker diagrams for the volcanic glass shards in the Uk-pfa-1, Md-fl-1, and SUk-SG06 tephra samples. The chemical data for the Uk-pfa, Md-fl-1, and SUk-SG06 samples were presented by Maruyama et al. (2020).
higher values than those for the proximal samples (Fig. 4) and the other distal samples (Fig. 5). However, the refractive index ranges of these samples overlap each other, and the mode values of the SUk-IKH samples are close to refractive index ranges for the other distal/proximal samples (Table 3). The bimodal histogram for sample SUk-IKH-01 suggests that the volcanic glass shards in SUk-IKH-01 originated from both Md-fl/Uk-fa and Uk-pfa (Fig. 5). Moreover, the proportion of Md-fl/Uk-fa is higher in sample SUk-IKH-02 than in SUk-IKH-01. The presence of brownish amphibole, cummingtonite, and biotite in Md-fl and Uk-fa, andapatite in Uk-pfa, is consistent with samples SUk-IKH-01 and -02 being mixtures of Uk-pfa and Md-fl/Uk-fa (Table 2).

However, the distributions of the refractive index values of greenish amphiboles are very similar in both the proximal and distal samples (Figs. 4 and 5). The refractive index values of amphibole in the SUk-KKY samples are more variable (1.667–1.689 for SUk-KKY-02; Fig. 5). However, the mode values are 1.670–1.680, similar to the range for amphibole in the proximal samples (Fig. 4).

The petrographic properties of the Uk-fa samples are generally similar to those of the proximal and distal Md-fl samples (Tables 1–3). The petrographic properties of the distal samples suggest that the SUk-KKY-01 sample can be correlated with Uk-pfa, and that samples SUk-KKY-02 and SUk-SG06 can be correlated with Md-fl/Uk-fa.

The glass shard and biotite contents continuously decrease up-section (i.e., from Md-fl-1 to Uk-fa-5), and the presence of cummingtonite is characteristic of the Md-fl and Uk-fa tephras (Table 2). Therefore, the Uk-fa and Md-fl tephras defined by Fukuoka and Matsui (2002) can be treated as a single tephra from a petrographic perspective. As such, it is not surprising that the Uk-fa tephra has not been independently identified in previous studies.

The refractive index values of the volcanic glass shards in the Uk-pfa and Md-fl/Uk-fa
Tephra samples are distinguishable in both proximal and distal areas. However, the very similar amphibole refractive index values and petrographic properties suggest these tephras were deposited in a related eruptive sequence.

2) Glass shard chemistry

2-1) Major elements

The refractive index values of volcanic glass shards depend mainly on major element compositions and, in particular, SiO$_2$ contents. The refractive index correlates negatively with the SiO$_2$ content, and an increase in some other elements can also decrease the refractive index (Danbara, 1991; Nagahashi et al., 2004). However, in contrast to the changes in SiO$_2$ contents from Uk-pfa-1 (74–82 wt.%) to following Md-fl-1 (73–80 wt.%) and SUk-SG06 (73–77 wt.%) (Fig. 6), the refractive index values of the volcanic glass shards in the Md-fl sample are obviously lower than those of Uk-pfa-1 (Table 3; Fig. 4).

TiO$_2$, Al$_2$O$_3$, FeO, MgO, and CaO contents tend to decrease with increasing SiO$_2$, and the decrease in these components lowers the refractive index (Danbara, 1991; Nagahashi et al., 2004). Changing FeO contents could have produced the variable refractive index values of the volcanic glasses during the eruption of Uk-pfa and Md-fl/Uk-fa (Fig. 6). The FeO contents of the Uk-pfa-1 sample are 0.9–1.5 wt.%, whereas those of the Md-fl samples are 0.3–0.8 wt.%, except for one analysis of Md-fl-1 (~1.0 wt.%; Fig. 6). The decreasing FeO content will lower the refractive index (Danbara, 1991; Nagahashi et al., 2004), and the distributions of FeO contents in Fig. 6 are consistent with those of the refractive index values in Fig. 4. FeO contents in the magma may have been lowered by crystallization of Fe-bearing minerals just prior to the eruption Md-fl/Uk-fa. The TiO$_2$ contents of these tephra samples are similar (Appendix 1; Fig. 6) and, therefore, an Fe oxide mineral such as magnetite (Fe$^{2+}$Fe$^{3+}$O$_4$) may have crystallized rather than titanomagnetite (Fe$^{2+}$[Fe$^{3+}$, Ti]$_2$O$_4$). The Uk-pfa-1 sample contains almost no biotite, whereas the proximal and distal Md-fl samples contain biotite (15–18% of the heavy minerals; Table 1). There is also the possibility that FeO was partly removed by biotite crystallization. However, MgO contents of the proximal and distal Md-fl samples (0.1–0.4 wt.%) are almost the same as those of Uk-pfa-1 (~0.1 wt.%), although Uk-pfa tends to have slightly higher MgO contents (Fig. 6). As such, it is more reasonable that Fe-bearing oxides crystallized in the magma just before the eruption of Md-fl. However, the amounts of opaque minerals in the analyzed tephra samples are similar (Table 2). Therefore, other processes such as magma mixing/transfer should be also considered.

2-2) Major and trace element patterns

The elemental pattern of Uk-pfa is generally similar to those of the proximal and distal Md-fl samples (Fig. 7). However, differences are evident for some of the light rare earth elements (REE) and major elements (e.g., Mg and Fe). The Tukey–Kramer test shows that ~55% of the 58 elements show no significant differences between the Uk-pfa and proximal–distal Md-fl samples (Fig. 7). There are significant differences in the major element concentrations (apart from Ca and Mn), light REE, and some trace elements (e.g., Co, Rb, Nb, Sn, Ta, W, Th, and U) (Fig. 7).

The Tukey–Kramer test indicates that the distal SUk-SG06 sample can be reasonably correlated with the proximal Md-fl-1 sample (~78% of elements; Fig. 7), considering that >70% of the elements show no significant difference to the Shishimuta–Pink volcanic glass samples from various parts of Japan (Maruyama et al., 2017).

The decrease in FeO contents of the Md-fl volcanic glasses (Fig. 6) is inconsistent with the eruption of rhyolitic and then more mafic melts. Given the differences in the elemental patterns (Fig. 7) and mineralogies (Tables 1 and 2) of the Uk-pfa and Md-fl tephra samples, the chemical composition of Md-fl may have been slightly modified by fractional crystallization (e.g., of Fe-bearing minerals) or inputs of other magma(s). Asano et al. (2018) suggested that four types of magma have produced the
four lava domes of Sambe volcano, involving anatexis of basaltic lower crust at different degrees of partial melting. Moreover, the trace element patterns of volcanic glass shards from Sambe volcano may have changed between the older and younger tephras (e.g., Maruyama et al., 2016, 2020; Albert et al., 2018, 2019; Fig. 7). These previous studies indicate more than one magma source and/or reservoir beneath Sambe volcano. In either case, the chemical composition of the melt (i.e., the source of the volcanic glasses) has changed during the eruptive sequence of SUk.

3) Presumed distribution of the Ukinuno tephras

The petrographic properties of the Uk-fa tephra samples strongly suggest that the Md-fl and overlying Uk-fa tephras can be regarded as a single tephra. Hereafter, the Uk-pfa (normally regarded as the SUk) and Md-fl/Uk-fa (i.e., distal Sakate) tephras are tentatively redefined as the SUk-L and -U tephras, respectively.

Katoh et al. (2007) suggested that the upper fall unit of the SUk tephra (i.e., Sakate = SUk-U) was more widely, but thinly, distributed over the central and northern parts of the Kinki district, whereas the lower fall unit (i.e., SUk-L) was thicker in the Chugoku district and southwestern Kinki district. Considering that SUk-L and -U are fall deposits of pumice and pyroclastic flow/ash, respectively, the range and distribution of these tephras are likely to be different.

Figure 8 shows the locations where the SUk tephra layers have been found, and the presumed distributions of SUk-L and -U. Most of the distal tephras correlated with the SUk tephra in previous studies correspond to the Sakate tephra (i.e., SUk-U) or a mix of SUk-L and -U. The distribution of SUk-U is generally similar to that of SUk shown by Machida and Arai (2011). The studied tephras have been
correlated according to their petrographic properties, mineralogies, glass shard shapes, and refractive index values of glass shards and amphiboles. Major element data for the glass shards have also been used in these correlations (Nakamura et al., 2011).

The Kakeya outcrop (Loc. 1 in Fig. 8) is located within the distribution of SUk-L and -U. Nomura and Tanaka (1987) reported that the refractive index values of volcanic glasses in the upper part of the U2 tephra (Matsui and Inoue, 1971) obtained from an outcrop at Misaka, Saijo, Shobara City, Hiroshima Prefecture (Loc. 2 in Fig. 8), were 1.498–1.503. This range suggests that the obtained tephra sample was a mixture of SUk-L and -U. Nomura (1991) reported that the lower part of the U2 tephra obtained from near Mt. Neko, Hiroshima Prefecture (Loc. 3 in Fig. 8), has refractive index values of 1.503–1.507. This range corresponds to that of SUk-L.

Nomura et al. (1995) found some tephra layers in cores from Hosoike Moor (Loc. 4 in Fig. 8), which is almost at the boundary of the distribution of SUk-L and in the central part of that of SUk-U (Fig. 8). Nomura et al. (1995) identified a tephra layer (Hs-3) with volcanic glass shards that have refractive index values of 1.498–1.506. The Hs-3 layer was correlated with SUk-L, based on petrographic properties, including the mineralogy and refractive index of amphibole (Nomura et al., 1995). The range of refractive index values of these volcanic glasses overlaps those of SUk-L and -U.

Nakamura et al. (2011) proposed that volcanic glass shards and glasses enclosed by greenish amphibole (i.e., glass inclusions) in a tephra sample from an outcrop near Kannabe volcano (Loc. 5 in Fig. 8) could be correlated with SUk-U. Moreover, Nakamura et al. (2011) suggested that SUk-U volcanic glass shards could be identified in a core in Ookute Basin, Gifu Prefecture (Loc. 21 in Fig. 8), although no visible tephra layer was present in the core. At present, this may be the most distal discovery of SUk-U on land.

In addition to Hosoike Moor (Nomura et al., 1995; Loc. 4 in Fig. 8), Ohnuma Moor (Katoh et al., 2007; Loc. 6 in Fig. 8), and Ikenohira Moor (Takahara and Masuda, 2017; this study; Loc. 20 in Fig. 8), Takahara et al. (1999) found a tephra layer (1 cm thick) that was correlated with SUk-U in a core from Oofuke Moor (Loc. 7 in Fig. 8). Hosoike, Ohnuma, and Oofuke moors are in the region in which SUk-U was deposited, whereas Ikenohira Moor is within the region in which both SUk-L and -U were deposited (Loc. 20 in Fig. 8).

Nishiyama et al. (2012) identified the SUk tephra in six cores from Tokushima Plain, Tokushima Prefecture, Shikoku (Loc. 8 in Fig. 8). Nishiyama et al. (2012) did not describe the petrographic properties of the identified tephra layers. However, this location on the Tokushima Plain may be close to the southern limit of the distribution of the SUk-L pumice fall deposit, considering the presence of the SUk tephra in the Kumano Trough (JAMSTEC, 2012; Loc. 23 in Fig. 8).

Katoh et al. (1996) suggested that the tephra layer in Kobe City (Loc. 9 in Fig. 8) could be correlated with the Ukinuno pyroclastic flow deposit (U1 pfl) defined by Matsui and Inoue (1971). U1 pfl corresponds to the Oda pyroclastic flow deposit (Od-fl) defined by Fukuoka and Matsui (2002). SUk-L directly overlies Od-fl at Loc. 1 in Fig. 2. Katoh et al. (1996) obtained samples of Od-fl and SUk-L from Loc. 1 for correlation with the Kobe sample. The refractive index values of the volcanic glass and amphibole in the Kobe sample are 1.500–1.506 and 1.671–1.677, respectively, and the Kobe sample contains 6% cummingtonite (Katoh et al., 1996). Refractive index values of volcanic glass and amphibole in Od-fl are 1.501–1.505 and 1.671–1.680, respectively, and it contains a small amount (< 2%) of cummingtonite (Katoh et al., 1996). However, the refractive index values of the volcanic glass and amphibole in the Kobe sample are similar to those of SUk-L and -U obtained in this study (Table 3; Figs. 4 and 5). The mineralogy of the Kobe sample, which contains small amounts of brownish amphibole, apatite, and cummingtonite, also
suggests that this sample may be the SUk tephra (i.e., a mix of SUk-L and -U). Katoh et al. (1996) compared the petrographic properties of the Kobe sample with those of SUk-L, but did not compare it with SUk-U. Katoh et al. (1996) suggested that the Kobe sample may have been a co-ignimbrite ash of Od-fl. The presence of such an ash fall deposit has yet to be documented, although the maximum thickness of Od-fl is ~1.5 km SW of Lake Ukinuno (Loc. 26 in Fig. 2; Fukuoka and Matsui, 2002). It appears more reasonable that the Kobe sample is SUk-L and -U. The fact that Kobe City is within the distribution zone of both SUk-L and -U (Fig. 8) also supports this hypothesis.

Cores from Lake Biwa contain tephra layers correlated with the Sakate tephra (i.e., SUk-U of this study) (Yoshikawa et al., 1986; Yoshikawa and Inouchi, 1991; Takemura et al., 2010; Loc. 11–14 in Fig. 8). SUk-L has not been found in cores from Lake Biwa. Togo et al. (1997) also only identified the Sakate tephra (i.e., SUk-U) in a trench excavated in the Oomiyagawa alluvial fan on the southwestern lakeshore of Lake Biwa (Loc. 15 in Fig. 8). In the Lake Suigetsu core (Loc. 10 in Fig. 8), only SUk-U has been identified as a visible tephra layer (e.g., Takemura et al., 1994). Ooi et al. (2004) found the SUk-U tephra layer in cores from the Naka-ikemi waste-filled valley, ~21 km ENE of Lake Suigetsu (Loc. 19 in Fig. 8).

Yoshikawa et al. (1986) first defined the Sakate tephra in an outcrop in the Nara Basin (Loc. 17 in Fig. 8). Azuma et al. (1983) and Yoshikawa et al. (1986) divided the Sakate tephra found in this outcrop into three sub-layers (3, 3, and 6 cm thick, from base to top). The sampling location of Yoshikawa et al. (1986) is within the zone in which both SUk-L and -U are found (Fig. 8). Considering this, the middle and/or uppermost sub-layers may correspond to SUk-U, and the lowermost layer may correspond to SUk-L. It is unknown as to which sub-layer Azuma et al. (1983) and Yoshikawa et al. (1986) examined and correlated. However, the tephra sample may have been obtained from the uppermost sub-layer, because Yoshikawa et al. (1986) reported that the grain size was apparently coarser than those of the other two sub-layers. If they obtained the sample from the lowermost sub-layer, they may have correlated it with SUk-L. Ooi (1992) also obtained tephra samples from the same sampling location (Loc. 18 in Fig. 8), and identified the SUk-U tephra layer.

Yoshikawa et al. (1986) also correlated tephra layer O10M from Fukono, Daito City, Osaka Prefecture (Loc. 16 in Fig. 8), with SUk-U (i.e., Sakate). The sampling location in Fukono is within the distribution of the SUk-L pumice fall (Fig. 8), and the distribution of the refractive index value of the volcanic glass shards (1.499–1.504; Yoshikawa et al., 1986) overlaps that of SUk-U. However, as for the Sakate tephra, Yoshikawa et al. (1986) only identified SUk-U at the Fukono site.

Ikehara et al. (2011) identified the SUk tephra in four piston cores from the Enshu Trough off the Tokai area (Loc. 22 in Fig. 8). The pumiceous volcanic glass shards in the tephra layers correlated with the SUk have refractive index values that overlap those of SUk-L and -U (1.499–1.508; Ikehara et al., 2011). Therefore, the identified SUk tephra layers (1.0–8.5 cm thick) are mixtures of SUk-L and -U. Tephra layers that could be correlated with SUk-L were found in cores from the Kumano Trough subduction zone (K. Ikehara, pers. comm.) during the KR09-15 cruise in 2009 (Loc. 23 in Fig. 8; JAMSTEC, 2012), although these results are unpublished.

The distributions of SUk-L and -U from Sambe volcano inferred in previous studies and the present study (Fig. 8) are consistent with the findings of Katoh et al. (2007). However, there is still a possibility that the SUk samples obtained from Locs. 8 and 23 may have been mixtures of SUk-L and -U or two distinct layers of them. Therefore, the southern limit of the distribution of SUk-U should be presumed to be the same as that of SUk-L for the present (Fig. 8). The fact that the SUk tephra is a mixture of SUk-L and -U is consistent with the hypothesis
that SUk-U was erupted just after SUk-L in an eruption sequence from Sambe volcano.

Figure 9 shows the distributions of the refractive index values of the volcanic glass shards in the SUk samples described in the above-mentioned previous studies and this study. The uppermost values for some samples are obviously higher than the mode of the proximal SUk-L samples (1.503–1.505; Fig. 4). As shown in Fig. 5, the samples from Ikenohira Moor exhibit this tendency significantly (20 of Fig. 9; this study). The samples described in some previous studies also exhibit a similar tendency (3, 4, 9, and 22 in Fig. 9; Nomura, 1991; Nomura et al., 1995; Katoh et al., 1996, and Ikehara et al., 2011, respectively). The sampling points of them are within the zone in which both SUk-L and -U are found (Fig. 8). On the other hand, the refractive index values of the samples from the northern part of the zone in which only SUk-U is found (e.g., Lake Biwa) almost overlap the mode of the proximal SUk-U samples (1.498–1.501; Fig. 4), and higher refractive index values can be reasonably explained as incorporation of SUk-L glasses. The wider distribution for the samples from Fukono and Sakate (16 and 17 in Fig. 9, respectively; Yoshikawa et al., 1986) can be also explained as the same phenomenon. However, the distribution for the samples from Kobe City, Ikenohira Moor, and
Enshu Trough (9, 20, and 22 in Fig. 9, respectively), which may be the mixtures of SUk-L and -U, cannot be explained simply as incorporation of SUk-L glasses. In the refractive index distributions for these samples, both uppermost and lowermost values are shifted toward higher values (Fig. 9). More detailed studies about not only proximal SUk samples but also distal SUk-L samples are essential to trace this regional variation of the refractive index distributions of the volcanic glass shards.

4) Re-classification of the Sambe-Ukinuno tephras

The terms SUk-L and -U were informally used in this study to simplify the discussion, and need to be named formally. Machida and Arai (2011) proposed a naming system where the first part identifies the source volcano and the second part identifies the type locality of the tephra. According to this system, SUk-L may be renamed “Sambe-Ukinuno” as originally used for this tephra, because Loc. 1 in Fig. 2 can be regarded as the type locality of SUk-L.

In contrast, the renaming of SUk-U is more challenging. The use of “Sambe-Sakate” may be controversial, because it is not clear whether Sakate (Loc. 17 in Fig. 8) can be regarded as the type locality of SUk-U. Considering that the outcrop in Midorigaoka (Loc. 2 in Fig. 2) was the type locality of Md-fl, “Sambe-Midorigaoka” seems a more suitable name. However, this outcrop no longer exists.

The Kakeya outcrop (Loc. 1 in Fig. 8) is an alternative type locality for both SUk-L and -U. In this case, “Sambe-Kakeya (lower) and (upper)” are suitable as the names for SUk-L and -U, respectively. However, this outcrop is not widely known or described. This would be important because some other key Sambe tephras, such as the Sambe-Ikeda, -Unnan, and SK tephras (Fig. 7), have been found in this outcrop along with some well-known marker tephras (e.g., the Ata tephra) from the Kyushu calderas (Fig. 1) (M. Watanabe, pers. comm.). As such, “Sambe-Ukinuno (lower) and (upper)” are currently the best formal names for SUk-L and -U.

V. Conclusions

The petrographic properties of the SUk-L and -U tephras are summarized in Table 4, and their presumed distributions are shown in Fig. 8. The petrographic and chemical properties of the SUk-L and -U tephras provide important insights into the magmatic and eruptive activity of Sambe volcano. The petrographic and chemical differences between SUk-L and -U need to be carefully considered when identifying and correlating tephra samples. We propose that the terms SUk (lower) and SUk (upper) should be used instead of “SUk” (= SUk-L) and “Sakate” (= SUk-U), respectively.

The petrographic and chemical relationships between minerals and volcanic glasses in individual tephras need to be considered carefully to avoid misclassification of tephras. This can be achieved by utilizing both the petrographic properties and elemental data for volcanic glasses.

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Table 4 Summary of the petrographic properties of the SUk-L and -U tephras.

| Facies | Glass shape | Mineral composition | Refractive index* |
|--------|-------------|---------------------|------------------|
|        |             | Light mineral       | Heavy mineral     |
|        |             | Plg, Qtz            | GAmp, Bt, BAmp, Cum, Opq; (Zrn) |
| SUk-U  | afa         | pm, irr             | 1.496–1.501       |
|        |             |                     | 1.667–1.689       |
| SUk-L  | pfa         | pm                  | 1.503–1.510       |
|        |             | Plg                 | 1.670–1.686       |

Notes: afa: ash fall deposit; pfa: pumice fall deposit. Plg: plagioclase; Qtz: quartz. The other abbreviations are shown in the footnotes of Tables 1 and 2.

* Ranges of mode values are shown in parentheses.
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* Title etc. translated by S.M.
Appendix 1  Mean major and trace element abundances of volcanic glass shards from Uk-pfa-1, Md-fl-1, and SUk-06 tephra samples.

| Element | Uk-pfa-1 | Md-fl-1 | SUk-SG06 |
|---------|----------|---------|----------|
|         | (wt. %)  | (μg/g)  | (μg/g)   |
|         | mean 1σ  | mean 1σ | mean 1σ  |
| SiO₂    | 79.2     | 2.5     | 77.0     | 1.8     | 75.50 | 0.91 |
| TiO₂    | 0.133    | 0.053   | 0.093    | 0.032   | 0.093 | 0.039 |
| Al₂O₃   | 12.2     | 1.6     | 13.5     | 1.3     | 15.22 | 0.66 |
| FeO     | 1.07     | 0.23    | 0.53     | 0.15    | 0.593 | 0.072 |
| MnO     | 0.052    | 0.018   | 0.045    | 0.011   | 0.053 | 0.009 |
| MgO     | 0.33     | 0.17    | 0.213    | 0.082   | 0.184 | 0.021 |
| CaO     | 1.43     | 0.86    | 1.50     | 0.71    | 1.48  | 0.66 |
| Na₂O    | 3.09     | 0.72    | 3.90     | 0.67    | 3.76  | 0.31 |
| K₂O     | 2.35     | 0.66    | 3.05     | 0.50    | 2.94  | 0.25 |

* Number of analyses. Number of analyzed glass shards is shown in parentheses.
三瓶火山から噴出した浮布テフラと阪手テフラの関係の検討

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中国地方および近畿地方で見いだされている阪手テフラは、三瓶火山より噴出した三瓶浮布テフラ（SUk）に対比されている。SUkテフラは、三瓶山近傍の露頭観察により、下位から浮布降下軟石堆積物（Uk-pfa）、緑ヶ丘火砕流堆積物（Md-fl）、浮布降下火山灰堆積物（Uk-fa）に分けられている。これまでの研究では、阪手テフラはMd-flに対比されている。Md-fl（阪手）試料に含まれる風化石の屈折率は、Uk-pfa試料に含まれるものと似通っていた。それに対して、Md-fl（阪手）試料に含まれる火山ガラスの屈折率は、Uk-pfa試料に含まれるものより低かった。またUk-faの岩石学的特性から判断すると、Uk-faとMd-flは一つの同じテフラとみなすことが可能だった。Uk-pfaに含まれる火山ガラスのSiO₂濃度は、ガラス屈折率からの予測に反して、Md-flのものよりも高かった。しかしながら、Uk-pfaに含まれる火山ガラスのFeO濃度は、Md-flのものに比べて明らかに高かった。このことからガラス屈折率の差異は、SiO₂濃度ではなくFeO濃度の違

いによるものと推定された。火山ガラスに含まれる合計58元素の濃度パターンは、全体としてはMd-flとUk-pfaの間で非常に似通っているものの、軽希土類元素などの部分で明らかに区別が可能だった。こうした元素組成の違いは結晶分化の過程で起こったか、あるいは他のマグマ源からの混入による、マグマの化学組成の変化によるものと推定された。これまでの研究をみると、Md-fl/Uk-fa（阪手）テフラに対比されるテフラは、中国地方および近畿地方に広く分布していた。一方、Uk-pfaテフラに対比されるテフラは、近畿地方南部およびその近海、そして四国東端で見いだされていた。Uk-pfaとMd-fl/Uk-faは連続の噴火活動で噴出したものと考えられるが、テフラの分布域も明確に区別可能であることが判明した。本研究の結果から、Uk-pfaとMd-fl/Uk-faテフラはそれぞれ、SUk（lower）（下部）およびSUk（upper）（上部）テフラと、より単純なものに再定義可能である。

キーワード：三瓶浮布テフラ、阪手テフラ、火山ガラス、屈折率、化学組成、テフラ降下域

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