Petrological studies of volcanic ash from Sakurajima volcano in 2013, Southern Kyushu, Japan

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Abstract. Many petrological studies of volcanic rocks have attempted to better predict future volcanic activity. In this study, we examined volcanic ash samples from Showa Crater in Sakurajima, Japan, which were erupted from January to October 2013. This study was used two types of juvenile material; black vesicular volcanic rock (BVVR) and black non-vesicular volcanic rock (BNVVR) to determine the variable of magmatic processes in the magma conduit during the 2013 eruption. We divided the duration into three periods such as January to April, April to July, and July to October based on the variable tendency of SiO2 contents and volume abundance of the interstitial glasses in BVVR and BNVVR. The estimated melt compositions demonstrate that the variability of SiO2 contents and volume abundance of microcrystal in the groundmass (BVVR and BNVVR) over time were caused by micro-crystallization processes. The estimated of water contents and vesicle volume shows the influence of degassing process in the rock forming. Also, the correlation of petrological features with the number of eruptions and eruptive volumes, exhibit the variable of magma supply into conduit in each period. Consequently, careful monitoring of the petrological features of erupted materials may provide useful constraints on future eruptive activity and thereby assist in the mitigation of volcanic hazards.

Keywords: Juvenile material; volcanic rock; interstitial glass; microcrystallization; conduit magma

1. Introduction
Petrological studies of volcanic ash have been extensively used to investigate recent volcanic eruptions and have been linked to geophysical observations of volcanoes. The volcanic glass and microlite compositions of juvenile material [1,2], crystal zoning [3], ash texture [4–6], and magmatic properties such as temperature, pressure, and volatile content [7] are all petrological monitoring tools. The integration of these studies with those involving timescales and geophysical observations is important for understanding magmatic processes.

Sakurajima is located in southern Kyushu, Japan, and is one of the most active volcanoes in the world. The types of eruption and nature of the crater of Sakurajima have changed through time. Previous studies have reported daily and inter-event variations in the eruptive mechanisms of small eruptions, including vulcanian, phreatic, and strombolian events, based on petrological studies of volcanic ash [2,4,6,8].
The objective of this study was to link petrological studies of volcanic ash and geophysical observations of the Sakurajima eruption in 2013, in order to reconstruct and understand the magma conduit system. This study presents compositional data for interstitial glass and microcrystal, calculations of groundmass melt compositions from 28 January to 29 October, 2013, and estimates temperature of magma, water content, and decompression- and magma ascent rates for each eruption. These data are used to develop a picture of cyclical variations of magma condition in a conduit, and to link with the number of eruptions and volume of erupted ejecta. Finally, these studies propose a simple model to explain the variable magmatic processes in the magma conduit of Sakurajima during the 2013 eruption.

2. Data and Methods

2.1. Data
The analyzed materials are all volcanic ash (Figure 1) from the Sakurajima eruption in 28 January – 29 October 2013. Seventeen samples representative of each month during the eruption were studied.

![Figure 1. Photomicrograph of volcanic ash of 28 January 2013 from Showa crater.](image)

2.2. Methods

2.2.1. Ash analysis
Volcanic ash samples from frequent Vulcanian explosions were periodically collected at distances between 2.8 and 10 km from the Showa crater (Figure 2). The volcanic ashes were sieved into different size fractions from 2.0 to 0.125 mm, and the 1.0–0.25 mm size fraction was used to clarify their components and to perform geochemical analysis. The grain components were examined using a stereoscopic microscope by counting at least 300 grains per sample. Several juvenile materials were handpicked, mounted in resin, polished, and carbon coated for scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS) analysis.

2.2.2. Scanning electron microscopy and energy dispersive spectrometry analysis
The petrography of the samples was examined by SEM using a JEOL JSM-6510LV scanning electron microscope at Ehime University, Japan. Quantitative crystal textural analysis was conducted on backscattered SEM images, with variable magnification depending on the microlite size and density. The groundmass microcrysts were outlined manually and crystal measurements were made using
imageJ (version 1.48) on at least 100 crystals in each sample. Mean crystal area, crystal volume fraction, and crystal dimensions (short and long axes) were measured with a crystal size distribution (CSD) software package. The crystal dimensions were calculated using a best-fit ellipsoidal method [9,10]. Microlite number density was calculated by dividing the number of whole crystals in the analyzed area by the area of the studied groundmass [7,9].

The major element compositions of the glasses and microcrystals were determined using a X-max 50 mm2 Oxford electron microprobe. The acceleration voltage and sample current were 15 kV and 0.8 nA, respectively. The glass compositions were normalized to 100% and calculated using the INCA quantitative analysis program. A range of glasses (K-glass, obsidian, and Na-glass) and silicate (enstatite, clinopyroxene, and K-feldspar) standards were used for calibration of the data.120º E

Figure 2. Sampling location map (solid rectangle)

3. Results

3.1. Volcanic ash component

Our previous studies have divided the volcanic ash into eight characteristic materials, which are black vesicular volcanic rock (BVVR), black non-vesicular volcanic rock (BNVR), light brown volcanic rock (LBVR), white vesicular volcanic rock (WVVR), silicified rock (SR), oxidized rock (OR), altered volcanic rock (AVR), and isolated phenocrysts (IP) [11,12]. The BVVR, BNVR, LBVR, WVVR, and IP are juvenile materials, and the SR, OR, and AVR are additional materials [11,12]. The juvenile material is component without a secondary process such as a hydrothermal or weathering process [11]. In this study, only BVVR and BNVR were analyzed, given that both of these components are the same color and the dominant components (59.5%–96% BNVR and 4%–40.5% BVVR; Figure 3).

The BVVR has an angular shape and is vesicular with an intersertal texture (Figure 4). The modal mineralogy of the groundmass comprises plagioclase (11.4%–38.3%), pyroxene (1.78%–15.8%), Fe–Ti oxides (0%–2.37%), and interstitial glass (56.5%–79.9%). The modal abundance of vesicles is 1.78%–15.8%. Microlites in this material are nominally acicular in shape (short/long axis ratio of 0.30), and the average microlite number density is 38,773 mm–2.

The BNVR material, contains plagioclase and pyroxene phenocrysts that are angular in shape, and has an intersertal texture. The groundmass components are interstitial glass (47.7%–63.9%) and microcrysts of plagioclase (22.6%–43.2%), pyroxene (5.34%–18.3%), and Fe–Ti oxides (0.13%–4.69%) (Figure 4). The microlites are nominally acicular in shape (short/long axis ratio of 0.26) and
the average microlite number density is 41,654 mm$^2$. The result of each grain per eruption could be seen in Appendix 1.

![Graph showing the volume abundance of black vesicular volcanic rock (light gray) and black non-vesicular volcanic rock (dark gray).](image1)

**Figure 3.** The volume abundance of black vesicular volcanic rock (light gray) and black non-vesicular volcanic rock (dark gray).

![Backscattered electrons images of groundmass of BVVR (a) and BNVVR (b).](image2)

**Figure 4.** Backscattered electrons images of groundmass of BVVR (a) and BNVVR (b) (ig: interstitial glass, pl: plagioclase, cpx: clinopyroxene, opx: orthopyroxene, opq: opaque mineral, and ves: vesicular).

The volume abundance of interstitial glass of BVVR and BNVVR, and vesicular of BVVR demonstrates the variable tendency over time and could be divided into three periods in 2013 as such January – April, April to July, and July to October (Figure 5). The volume abundance of interstitial glass of BVVR is more glass than BNVVR. The variable tendencies of volume abundance of interstitial glass of BVVR and BNVVR, and vesicular of BVVR vesicles are enrich in Period 1 and 2. Then, Period 3 has different tendency with depleted of interstitial glass and vesicles.

3.2. Geochemical features

The interstitial glass compositions of the BVVR and BNVVR components differ markedly. The SiO$_2$ contents of interstitial glass in the BVVR are more mafic than in the BNVVR. The SiO$_2$ contents of both of them show variable tendency over the time. Further, the border between the tendency is consistent with the volume abundance of interstitial glass and vesicles in the groundmass and comprise
into three periods in 2013 (Figure 6a). In the first period (January–April 2013), the BNVVR has SiO$_2$ contents of 71.1 to 76.8 wt.%, which are generally higher than the BVVR (68.3–72.1 wt.%) and tend to decrease with time. In the second period (April–July 2013) the BNVVR has SiO$_2$ contents of 69.5 to 78.1 wt.%, which are generally higher than the BVVR (67.6–74.7 wt.%) and tend to decrease with time. In the third period (July–October 2013) the BNVVR has SiO$_2$ contents of 69.6 to 76.6 wt.%, which are generally higher than the BVVR (68.5–73.8 wt.%) and increase with time.

![Figure 5](image)

**Figure 5.** The modal abundance of (a) interstitial glass and (b) vesicles (vol.%).

![Figure 6](image)

**Figure 6.** (a) SiO$_2$ content of interstitial glass and (b) An content of plagioclase (mol.%) of BVVR and BNVVR.
The pyroxene microcrystals can be classified into orthopyroxene (enstatite) and clinopyroxene (pigeonite and augite). The Mg\# values (100 × Mg/(Mg + Fe + Mn)) of the analyzed pyroxene microcrystals in the BVVR and BNVVR are relatively similar in all three periods (Appendix 2). No systematic chemical zoning was observed in the microcrystal cores. However, the microcrystal rims mostly have higher Mg contents than the cores (i.e., the light color in the BSE image in Figure 4). The pyroxene Mg\# values of the BVVR are higher than those of the BNVVR in all three periods, but do not change significantly over time. In the first, second, and third periods, pyroxene Mg\# values for BVVR and BNVVR are 40.0–62.3 and 37.1–60.7, 44.0–60.3, and 37.1–47.3, and 39.2–64.3 and 37.1–62.3, respectively.

Plagioclase microcrystal from the two types of juvenile material exhibit similar range of An (100 × Ca/(Ca + Na + K)) contents (Figure 5) with a few additional high An content in several eruption. In the first, second, and third periods, the plagioclase An contents for BVVR and BNVVR are 0.40–0.57 and 0.38–0.85, 0.41–0.84 and 0.44–0.85, and 0.38–0.81 and 0.42–0.84, respectively.

4. Discussion

Mass-balance calculations using microcrystal phases and interstitial glass compositions were used to estimate the melt composition of each rock type. The groundmass compositions for each rock fragment were assumed to be the final melt composition (new melt), and the composition of the microcrystal phases was assumed to have been removed from the original melt composition [11,12]. Point and/or area counting analysis using the ImageJ 1.48 software package was employed to calculate the total volume of microcrystals. The modal compositions (volumes) of microcrystal and interstitial glass were converted into a weight fraction basis using assumed densities for the minerals and interstitial glass. The densities of the minerals used in these calculations were as follows: bytownite = 2.58 g/cm³; labradorite = 2.84 g/cm³; anorthite = 3.11 g/cm³; enstatite = 3.2 g/cm³; pigeonite = 3.38 g/cm³; augite = 3.51 g/cm³; ilmenite = 4.75 g/cm³; and interstitial glass = 2.35 g/cm³ [2,11–13].

The SiO₂ contents of the estimated melt compositions are relatively similar for each eruption (Figure 7). The range in SiO₂ contents between BVVR and BNVVR in each eruption is 2–3 wt.%, and the range of SiO₂ in all periods is 60.5–65.6 wt.%. From these results, we suggest that the magma was the same in the three periods and that the differences between the BVVR and BNVVR resulted from micro-crystallization processes in the groundmass.

![Figure 7. The result of estimation of melt composition (a) and water content (wt.%) (b).](image_url)
Magmatic temperatures and approximate water contents were estimated from the experimentally calibrated plagioclase–melt geothermometer and hygrometer of [14]. In these calculations, several hypothetically value was determined, like the initial water content was 2.6 wt.% [15] and An content was used the majority An content as the equilibrium with the melt.

Based on these results, the different magma conditions for each period are shown. Periods one and two have relatively similar conditions. Period one is characterized by: (1) generally decreasing SiO$_2$ contents of interstitial glass in the BVVR; (2) melt SiO$_2$ contents for the BVVR and BNVVR of 62.9–64.8 and 61.0–65.4 wt.%, respectively, with SiO$_2$ contents increasing with time; (3) plagioclase temperatures of 1061–1118°C, and (4) generally decreasing water contents (1.75–6.12 wt.%). Period two is characterized by: (1) generally decreasing SiO$_2$ contents of interstitial glass in the BVVR; (2) melt SiO$_2$ contents for the BVVR and BNVVR of 62.0–65.7 and 60.8–63.5 wt.%, respectively, with melt SiO$_2$ contents in both rock types increasing over time; (3) plagioclase temperatures of 1086–1131°C; and (4) increasing water contents (1.75–5.51 wt.%). Period three is different to the other periods and shows: (1) generally increasing SiO$_2$ contents of interstitial glass in the BVVR and BNVVR; (2) melt SiO$_2$ contents for BVVR and BNVVR of 61.2–66.1 and 60.6–64.3 wt.%, respectively, with SiO$_2$ contents increasing with time; (3) plagioclase temperatures of 1050–1147°C, and (4) decreasing water contents (0.06–6.60 wt.%).

The estimates of melt temperatures and water contents in periods 1 and 2 are similar, but are different for period 3. This suggests that the change from period 2 to 3 was influenced by water enrichment. The enrichment in water and change in vesicle volume show that each period had different degassing processes, particularly during the change from period 2 to 3.

Therefore, we consider that the variations between BVVR and BNVVR over time are due to microcrystallization processes in the groundmass, and the geochemical variations in the interstitial glass were caused by different degassing processes. This inference is consistent with a previous study [12] that showed that the different types of juvenile material likely resulted from cooling- and decompression-induced crystallization in the conduit.

**Figure 8.** The result of estimation of decompression rate (kPa/s) and magma ascent (m/s).
We have also calculated the decompression and magma ascent rates required to explain the decompression processes that induced the variations in rock and geochemical features during the 2013 eruption. These calculations used the water exsolution rate meter model of [16], and used the anorthite content of the plagioclase microcrystal as an indicator of the water content at the nucleation. The results show that the decompression and magma ascent rate varied during each period (Figure 8). The decompression rate continuously changed over the time. In period 1, the decompression tended to decrease, whereas in period 2 it increased. The increase in the decompression rate was related to water enrichment, which decreased again in period 3. The magma ascent rates in periods 1 and 2 are similar, but differ in period 3. Period 3 was characterized by a slower magma ascent rate compared with the other periods, and it resulted in the SiO$_2$ content of interstitial glass changing differently (i.e., increasing) compared with the other periods (i.e., decreasing).

We then compared our petrological results with the eruption number and volume (Figure 9). The comparative data were obtained from the Kagoshima Meteorological Agency [17]. The total number of eruptions and volume of erupted material correlate with the three periods defined from the SiO$_2$ contents of interstitial glass. The timing of the boundaries between the three periods coincide with changes in the total number of eruptions and volume of erupted material.

In periods 1 and 2, when the SiO$_2$ contents decreased with time, the total number of eruptions and volume of erupted material have a normal distribution with a different total number of eruptions and eruptive volumes. Period 1 appears to have had a larger eruptive volume and was more active than period 2. Period 3 had a greater number of eruptions and a larger eruptive volume than the previous period (Figure 9). This indicates that the number of eruptions and eruptive volume were related to the total volume of magma supply in the conduit.

In generally, we propose a model that explains the magma conditions in the conduit during 2013 (Figure 10). Three periods can be identified from both petrological studies and volcanic activity. In periods 1 and 2, SiO$_2$ contents decreased over time, reflecting microcrystal crystallization in the magma conduit. The difference between periods 1 and 2 is related to the total volume of magma supply, with this being greater in period 1 than period 2. Period 3 involved water enrichment and an enhanced magma supply. The water enrichment and increased vesicle volume were related to
degassing processes. The water enrichment towards the end of period 2 resulted in an increase in the number of eruptions and eruptive volume of period 3 compared with periods 1 and 2.

![Figure 10. The model of magma conditions in the conduit during 2013.](image)

5. Conclusions
This study has shown led to the following findings. (1) The SiO$_2$ contents of interstitial glass of the BVVR and BNVVR varied in three periods between January and October 2013; i.e., period 1 from January to April, period 2 from April to July, and period 3 from July to October. (2) The estimated melt compositions demonstrate that the variations of petrological feature in the volcanic rocks (BVVR and BNVVR) over time were caused by micro-crystallization processes in the groundmass. (3) The magmatic temperatures, water contents show different trends in each period. In particular, from period 2 to 3 the water content and vesicle volume increased. It is suggested that this reflects different degassing processes in each period. (4) The decompression and magma ascent rates influenced the rock-forming processes in the magma conduit; depleted of decompression and magma ascent rate will result in the enrichment of SiO$_2$ content of interstitial glass (i.e period 3). (5) Petrological features correlate with the number of eruptions and eruptive volumes, show the magma supply into conduit in each period is variable; period 1 and 3 are large, but period 2 is small magma supply. As such, it is apparent that careful monitoring of the petrological features of erupted materials can provide useful information for assessing future eruptive activity and can thereby be used to mitigate volcanic hazards.
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## Appendix

### Appendix 1. Modal composition of BVVR and BNVVR

| No | Time (day) | Date        | Type rock | SiO$_2$ content of interstitial glass (wt.%) | Plagioclase | Pyroxene | Fe-Ti mineral | Interstitial glass | Vesicular/bubble |
|----|------------|-------------|-----------|---------------------------------------------|-------------|----------|---------------|-------------------|-----------------|
| 1  | 28         | 28-Jan-2013 | BVVR      | 71.7                                        | 23.7        | 13.7     | 1.22          | 61.4              | 1.52            |
| 2  | 43         | 12-Feb-2013 | BVVR      | 70.3                                        | 35.1        | 7.47     | 0.97          | 56.5              | 8.28            |
| 3  | 55         | 24-Feb-2013 | BVVR      | 70.4                                        | 38.3        | 3.30     | 0.12          | 58.2              | 0.07            |
| 4  | 61         | 2-Mar-2013  | BVVR      | 69.8                                        | 27.1        | 6.03     | 1.16          | 65.8              | 3.87            |
| 5  | 78         | 19-Mar-2013 | BVVR      | 70.5                                        | 19.2        | 7.57     | 0.92          | 72.3              | 10.7            |
| 6  | 121        | 01-May-2013 | BVVR      | 74.0                                        | 24.3        | 8.62     | 0.81          | 66.2              | 3.54            |
| 7  | 125        | 05-May-2013 | BVVR      | 70.5                                        | 32.0        | 9.26     | 0.60          | 58.2              | 0.44            |
| 8  | 140        | 20-May-2013 | BVVR      | 70.9                                        | 32.7        | 5.61     | 1.00          | 60.6              | 1.61            |
| 9  | 164        | 13-Jun-2013 | BVVR      | 69.7                                        | 34.7        | 1.78     | 0.16          | 63.4              | 21.8            |
| 10 | 200        | 19-Jul-2013 | BVVR      | 68.2                                        | 22.9        | 4.50     | 0.04          | 72.6              | 0.01            |
| 11 | 205        | 24-Jul-2013 | BVVR      | 69.2                                        | 28.9        | 2.55     | 0.00          | 68.5              | 19.9            |
| 12 | 233        | 21-Aug-2013 | BVVR      | 68.8                                        | 34.1        | 7.54     | 0.16          | 58.2              | 24.8            |
| 13 | 248        | 04-Sep-2013 | BVVR      | 69.9                                        | 14.4        | 7.92     | 0.02          | 77.7              | 11.4            |
| 14 | 268        | 25-Sep-2013 | BVVR      | 69.3                                        | 11.4        | 15.8    | 0.34          | 72.4              | 44.4            |
| 15 | 274        | 01-Oct-2013 | BVVR      | 70.1                                        | 22.2        | 4.87     | 1.10          | 71.9              | 0.01            |
| 16 | 288        | 15-Oct-2013 | BVVR      | 73.5                                        | 26.2        | 7.55     | 2.37          | 63.9              | 9.83            |
| 17 | 302        | 29-Oct-2013 | BVVR      | 70.8                                        | 15.2        | 3.65     | 1.24          | 79.9              | 11.5            |
| 18 | 28         | 28-Jan-2013 | BNVVR     | 74.17                                       | 33.4        | 6.30     | 1.79          | 58.6              | 0              |
| 19 | 43         | 12-Feb-2013 | BNVVR     | 71.28                                       | 22.6        | 18.3     | 1.80          | 57.3              | 0              |
| 20 | 55         | 24-Feb-2013 | BNVVR     | 76.27                                       | 29.6        | 10.6     | 1.09          | 58.6              | 0              |
| 21 | 61         | 2-Mar-2013  | BNVVR     | 74.23                                       | 24.5        | 10.1     | 1.54          | 63.9              | 0              |
| 22 | 78         | 19-Mar-2013 | BNVVR     | 73.55                                       | 23.6        | 14.1     | 1.86          | 60.4              | 0              |
| 23 | 121        | 01-May-2013 | BNVVR     | 77.59                                       | 33.1        | 10.2     | 2.07          | 54.6              | 0              |
| 24 | 125        | 05-May-2013 | BNVVR     | 72.82                                       | 36.4        | 6.55     | 1.05          | 56.0              | 0              |
| 25 | 140        | 20-May-2013 | BNVVR     | 73.16                                       | 39.1        | 6.61     | 3.77          | 50.5              | 0              |
| 26 | 164        | 13-Jun-2013 | BNVVR     | 71.47                                       | 32.6        | 9.26     | 0.13          | 58.0              | 0              |
| 27 | 200        | 19-Jul-2013 | BNVVR     | 70.14                                       | 24.1        | 12.8     | 0.47          | 62.7              | 0              |
| 28 | 205        | 24-Jul-2013 | BNVVR     | 70.78                                       | 32.6        | 5.54     | 0.81          | 61.1              | 0              |
| 29 | 233        | 21-Aug-2013 | BNVVR     | 69.76                                       | 43.2        | 7.40     | 1.62          | 47.7              | 0              |
| 30 | 248        | 04-Sep-2013 | BNVVR     | 72.76                                       | 28.2        | 9.46     | 0.89          | 61.5              | 0              |
| 31 | 268        | 25-Sep-2013 | BNVVR     | 73.00                                       | 31.0        | 14.1     | 0.78          | 54.2              | 0              |
| 32 | 274        | 01-Oct-2013 | BNVVR     | 74.95                                       | 35.7        | 5.34     | 2.56          | 56.4              | 0              |
| 33 | 288        | 15-Oct-2013 | BNVVR     | 76.23                                       | 29.1        | 5.47     | 4.69          | 60.8              | 0              |
| 34 | 302        | 29-Oct-2013 | BNVVR     | 75.27                                       | 27.0        | 7.77     | 3.88          | 61.4              | 0              |
Appendix 2. The Mg# value (mol.%) of microcrystal of pyroxene