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Constituent Mineral and Water-Soluble Components of Volcanic Ash from the 2018 Eruption of Mt. Motoshirane of Kusatsu-Shirane Volcano, Japan

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Constituent minerals and water-soluble components of the volcanic ash discharged from the eruption of Mt. Motoshirane on January 23, 2018, were analyzed to investigate the source environment of this eruption. The ash sample included quartz, plagioclase, cristobalite, pyrite, alunite, kaolinite, and pyrophyllite; its mineral assemblage suggests that a high-temperature acid alteration zone had been formed in the volcanic edifice of Mt. Motoshirane. The presence of pyrophyllite in the ash sample indicates that the explosion of this eruption took place at a depth reaching the basement rocks of Mt. Motoshirane. Further, the adhesion amount of water-soluble components detected from the ash sample is smaller than that in the ashes from the 1982 eruption of Mt. Shirane, indicating that the ash discharge of the 2018 eruption of Mt. Motoshirane took place in a condition in which the degree of involvement of the liquid phase was relatively small.

Keywords: Mt. Motoshirane, phreatic eruption, volcanic ash, hydrothermal mineral, water-soluble component

1. Introduction

One died and eleven were injured in the phreatic eruption on January 23, 2018, at Mt. Motoshirane (altitude: 2,171 m), which is one of the peaks of the Kusatsu-Shirane volcano (collective name for Mt. Shirane, Mt. Ainomine, and Mt. Motoshirane, counting from the north; **Fig. 1**). To understand the mechanism of a phreatic eruption, clarification on the structure of the hydrothermal system where phreatic eruptions occur is needed. An effective means of achieving this clarification is a geochemical analysis of the material samples such as volcanic gas, thermal water, or volcanic ash [3–5].

Also beneath Mt. Motoshirane, the presence of a hydrothermal system has been pointed out [6]. However, there is only a weak seeping of low-temperature volcanic gases (mostly ambient temperature and rich in CO_2 and H_2S excluding the atmospheric components) at a part of the edifice of Mt. Motoshirane, but there is no discharge of high-temperature volcanic gases or thermal waters. Therefore, very few studies on the hydrothermal system beneath Mt. Motoshirane based on material samples have been conducted [7]. Also, in the 2018 eruption, volcanic gas from the craters was not sampled because the gas discharge ceased while we were unable to approach the craters.

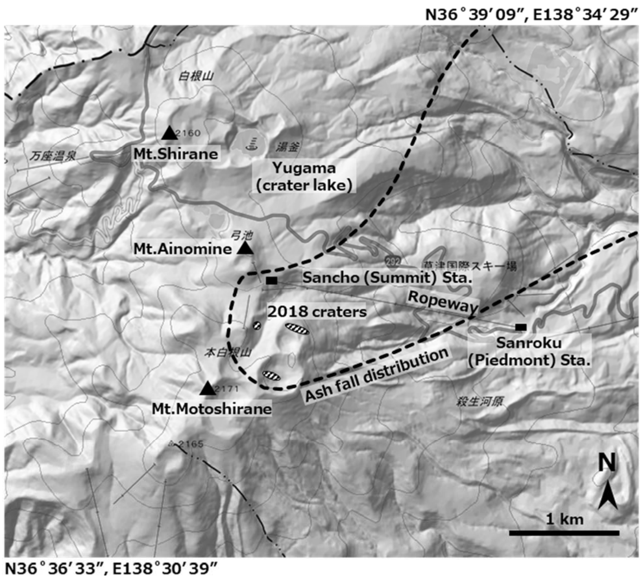

Fig. 1. Index map of Mt. Motoshirane of Kusatsu-Shirane volcano. Ash sample was collected from the windshield of the ropeway gondola at Sanroku (Piedmont) station. Base map was created by overlaying the standard map and shaded relief map of the Geographical Survey Institute of Japan [1]. Ash fall distribution was simplified from the Joint Research Team for ash fall in Kusatsu-Shirane 2018 eruption [2].

On the other hand, in the 2018 eruption of Mt. Motoshirane, some of the volcanic ash deposited on the ceiling and adhered to a windshield of a ropeway gondola that operated in an ash fall area (**Fig. 1**). The gondola was stored at the Sanroku (Piedmont) station of the

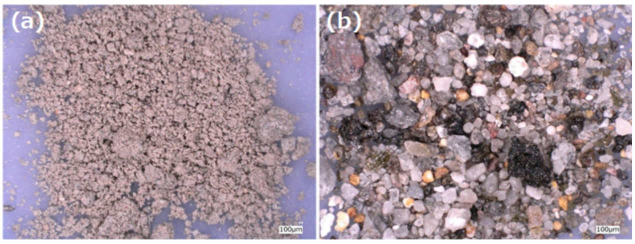

Fig. 2. Digital microscope images (Keyence, VHX-6000) of ash sample of the 2018 eruption of Mt. Motoshirane of Kusatu-Shirane volcano. (a) Unwashed. (b) After ultrasonic washing in pure water and decantation.

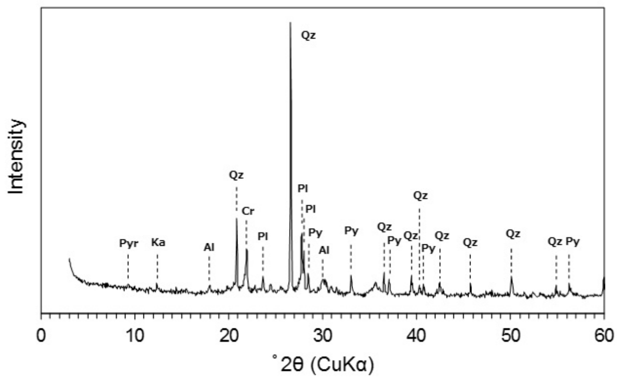

Fig. 3. XRD patterns of crushed bulk ash sample of the 2018 eruption of Mt. Motoshirane of Kusatsu-Shirane volcano. Pyr, Pyrophyllite; Ka, Kaolinite; Al, Alunite; Qz, Quartz; Cr, Cristobalite; Pl, Plagioclase; Py, Pyrite.

ropeway just after the eruption; therefore, the volcanic ash could be collected from it. The volcanic ash discharged by a phreatic eruption generally includes non-magmatic materials that are derived from the volcanic edifice and their basement rocks, and their mineral assemblage has great importance in investigating the hydrothermal conditions, such as the alteration temperature and acidity, at the source of the eruption [5, 8]. In addition, water-soluble components, which are derived from volcanic gas and thermal water, adhering to the surface of the ash particles can be used to estimate the chemical composition and degree of involvement of liquid phase of the volcanic fluid involved in the eruption [5, 9]. In this study, constituent minerals and water-soluble components of the volcanic ash discharged by the 2018 eruption of Mt. Motoshirane were analyzed, and the source environment of the eruption is also discussed.

2. Sample and Analysis

Volcanic ash, adhered and frozen on the windshield of a gondola (sixteenth vehicle), was collected at the Sanroku (Piedmont) station of the Shirane volcano ropeway on January 24, 2018, a day after the eruption (**Fig. 1**). Untreated volcanic ash was covered by fine particles and exhibited a gray color (**Fig. 2(a)**). In the washed ash sample, predominant whitish particles, altered rock fragments, and fine pyrite particles could be recognized (**Fig. 2(b)**).

The constituent minerals of the ash sample were analyzed using the X-ray powder diffraction (XRD) technique (Bruker, D8 Advance; operated in the 2θ range of 3–60° at an increment of 0.05° using CuKα radiation at 40 kV and 40 mA) after grinding the bulk ash samples with an agate mortar.

Water-soluble components were determined through analysis of the waterextracted leachate. For the preparation of the ash leachate, approx. 0.5 g of an air-dried ash sample was correctly weighted and mixed with 10 mL of pure water and warmed in an ultrasonic bath at 50°C for 15 min. The suspended solution was then filtered through a 0.45 μm membrane filter. Thereafter, the concentrations of Cl^- and $SO_4{}^{2-}$ ions in the ash leachate were analyzed using ion chromatography (Thermo, Integrion) and expressed as mg per kg of dried ash (mg/kg).

3. Results and Discussion

3.1. Constituent Minerals

Based on the result of the XRD analysis (**Fig. 3**), the main constituent mineral of the volcanic ash was found to be quartz, in addition to plagioclase, cristobalite, and pyrite. Further, small amounts of alunite, kaolinite, and pyrophyllite were also detected. Among them, alunite, kaolinite, and pyrophyllite are stable under acidic condition [10]. It is known that alunite and kaolinite can be stable even at a low temperature of 100°C or lower; on the other hand, pyrophyllite is stable at higher temperatures [10] (under experimental condition, pyrophyllite is generated from kaolinite at approx. 200°C or more [11]). That is, the mineral assemblage of the volcanic ash shows that the high-temperature acid alteration zone had been formed in the volcanic edifice of Mt. Motoshirane. Around the Kusatsu-Shirane volcano, pyrophyllite exists only in the hydrothermal alteration zone formed in the basement rocks (Neogene) of this volcano [12]. In other words, the presence of pyrophyllite in the volcanic ash shows that the source depth of this eruption had reached the basement rocks of Mt. Motoshirane. On another note, the upper limit of the basement rocks around Mt. Motoshirane is at an altitude of about 2,000 m [13]; thus, the cutoff depth of the eruption is assumed to be lower than this elevation.

3.2. Water-Soluble Components

The water-soluble Cl^- and $SO_4{}^{2-}$ detected from the ash leachate of the 2018 eruption of Mt. Motoshirane were 2,640 mg/kg and 2,530 mg/kg, respectively, and its $Cl^-/SO_4{}^{2-}$ molar ratio was 2.8 (**Table 1**). This $Cl^-/SO_4{}^{2-}$ molar ratio of 2.8 is relatively large as com-

Table 1. Water-soluble components of the ash sample of the 2018 eruption of Mt. Motoshirane and the 1982 eruption of Mt. Shirane of the Kusatu-Shirane volcano.

Eruptions	Water-soluble components		
	Cl^- [mg/kg]	SO_4^{2-} [mg/kg]	Cl^-/SO_4^{2-} molar ratio
Mt. Motoshirane* (January 23, 2018)	2,640	2,530	2.80
Mt. Shirane** (October 26 and December 29, 1982)	276–13,300	12,090–20,080	0.04–2.98

*This study. **Hirabayashi [14].

pared with the ashes discharged from the past eruptions of the Kusatsu-Shirane volcano (Cl^-/SO_4^{2-} molar ratio of the ashes discharged by the 1982 eruption of Mt. Shirane were between 0.04 to 2.98 [14], **Table 1**). Regarding Mt. Shirane, the Cl^-/SO_4^{2-} molar ratio of the water-soluble components adhering to the volcanic ash was higher when the scale of eruption was larger, and the temperature of the volcanic gas involved in the eruption was higher [14]. Although we need to consider whether such characteristics can be applied to the volcanic ash of Mt. Motoshirane, it is important to clarify the factors responsible for such a high Cl^-/SO_4^{2-} molar ratio for understanding the mechanism of this eruption.

Adhesion amount of the water-soluble components of the volcanic ash from the 2018 eruption of Mt. Motoshirane was smaller than that of ashes from the 1982 eruption of Mt. Shirane (**Table 1**). In general, volcanic ash discharged by phreatic eruptions is characterized by a large adhesion amount, and one reason for this is adhesion of the liquid thermal water, which has high concentrations of soluble components [5]; that is, the small adhesion amount of water-soluble components in the volcanic ash from the 2018 eruption of Mt. Motoshirane suggests that the ash discharge during this eruption took place in a relatively dry condition dominated by the gas phase rather than liquid phase-rich conditions such as those associate with thermal water discharge. This implication is consistent with the implications based on the geophysical observations that the volume change beneath Mt. Motoshirane associated with the eruption on January 23, 2018, was mainly caused by the gas phase [15].

4. Concluding Remarks

In this study, constituent minerals and water-soluble components of the volcanic ash from the 2018 eruption of Mt. Motoshirane were analyzed, and the source environment of this eruption was discussed. The following conclusions can be drawn from this study:

(1) A high-temperature acid alteration zone (approx. 200°C or more) had been formed beneath Mt. Motoshirane.

(2) The source of the explosion of the 2018 eruption of Mt. Motoshirane reached the basement rocks of this volcano.

(3) The ash discharge during the 2018 eruption of Mt. Motoshirane took place in a relatively gas phase-rich condition, as compared with the 1982 eruption of Mt. Shirane.

There are still many obscure points in the mechanism of the 2018 eruption of Mt. Motoshirane. For further understanding, it is important to understand the underground structure, such as the zonal structure of the hydrothermal alteration zone, as well as to clarify the reservoir and the chemical property of hydrothermal fluid, which is a driving source of the eruption.

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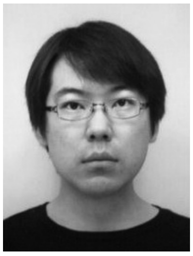

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