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PREFACE

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Special issue "Advancement of our knowledge on Aso volcano: current activity and background"

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Introduction

Aso volcano is one of the most active volcanoes in Japan located in the volcanic front on Kyushu-Ryuku Island arc. Central cones including the active Nakadake cone located inside the caldera which was formed by four pyroclastic flow eruptions. The Nakadake cone hosts a hot and acid crater lake and frequent phreatic-to-magmatic eruptions. From gigantic caldera-forming eruptions to fumarolic activities, Aso volcano provides us with a wide-range of research subjects which improve our understandings of the volcanic system.

The most recent magmatic eruptions at Aso volcano characterized by Strombolian explosions and continuous ash venting, began on 25 November 2014, after about 20 years of dormancy. In late 2015 and 2016, violent phreatic and phreatomagmatic explosions occurred repeatedly. This special issue focuses on scientific researches at Aso volcano completed before, during, and after the 2014–2016 eruptive activities. In total, 19 articles were published in the special issue; these are described accordingly with the investigating methods.

Geology, petrology, and material sciences

In the special issue, four articles are published on the geological, petrological, and mineralogical aspects of eruptions at Aso. A frontier letter by Miyabuchi and Hara (2019) presents the distribution, discharged mass, and components of tephra-fall deposits during the 2014–2015 eruption of the Nakadake first crater at Aso volcano. The tephra-fall deposits consisted of glass shards, crystal, and lithic grains. In the November 25–27, 2014 ash-fall deposits, lithic fragments, which are interpreted to be derived from lavas or pyroclasts of previous eruptions, were dominant (59–68%). Thereafter, the proportion of glass shards, which are probably juvenile materials of newly ascending magma, gradually increased with time, and the December 21–23, 2014 ash contained abundant glass grains (63%). The proportions of glass shards ranged from 29 to 50% until February 25, 2015. Subsequently, they decreased with time and reached 14% on March 17. Afterward, the proportions increased again prior to April 27 and ranged between 20 and 30% in May 2015. From November 25, 2014 to the end of January 2015, the cumulative erupted mass increased at a high discharge rate (2.2×10^4 tons/day). After February 2015, the cumulative erupted mass decreased to a low rate of 0.6×10^4 tons/day, although this rate rose slightly in March and late April 2015. The total erupted tephra mass was 2.1×10^6 tons (1.2×10^4 tons/day), which was less than the tephra deposits of previous activities that have occurred within the past few decades.

Namiki et al. (2018) conducted three series of measurements for high-porosity scoriae and ash ejected from the Nakadake crater during magmatic eruption in 2014–2015. From their results of measurements, Namiki et al. (2018) elucidated the eruptive conditions causing such ash emission and generation of scoriae and inferred the sequence of an eruption as follows. Cooling of the uppermost part of the high-porosity foam in the conduit causes fracturing of the magma foam, which creates the glassy brown ash to be ejected. Some part of the brown ash falls back onto the top of the high-temperature foam and is altered to black ash. The ash particles are initially mobile, and the ash layer has a large permeability. Ultimately,

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the bottom of the ash layer may undergo sintering and its permeability is reduced. The underlying foam layer is pressurized and ash eruption occurs. Once the debris layer at the top of the magma foam is removed, the underlying magma foam erupts as scoriae.

In Saito et al. (2018), petrological observations and chemical analyses on scoriae and related melt inclusions in mineral phases were used to investigate the magma ascent and eruption processes of the 1979, 1989, and 2014 eruptions of Nakadake crater, Aso volcano. The whole-rock analyses of the scoria produced by the November 26–27, 2014 eruption indicated that they are andesite in composition and identical to those of the 1979 and 1989 eruptions. Thermometry using the chemical composition of the groundmass and the rims of the phenocrysts indicated that the temperature of the 2014 magma was 1042–1092 °C. Melt inclusions in plagioclases, clinopyroxenes, and olivines in the 2014 scoria had an andesite composition similar to that of the groundmass. The volatile content of the melt inclusions was 0.6–0.8 wt% H_2O, 0.003–0.017 wt% CO_2, and 0.008–0.036 wt% S. The variation in CO_2 and S content of the melt inclusions was not correlated with the K_2O content, suggesting that the magma degassed as pressure decreased. Melt inclusions in plagioclases, clinopyroxenes, and olivines from the 1979 and 1989 scoria had similar major elements and volatile content to the 2014 eruption specimens. The similarity in chemical composition of both the whole-rock and melt inclusions among all samples suggests that the magmas of these eruptions were derived from the same magma chamber. The gas saturation pressure estimated from the H_2O and CO_2 contents of the 1979, 1989, and 2014 scoria ranged from 18 to 118 MPa, corresponding to depths of 1–4 km. Based on the bulk sulfur content of the magma and the SO_2 flux between January 2014 and December 2017, the amount of degassed magma over that period was estimated to be the equivalent of 1–3 km^3 of dense rock. The estimated volume was more than 600 times larger than that of eruptive products during the same period. This suggests degassing of magma in the chamber associated with magma convection within a conduit.

Ishibashi et al. (2018) investigated chemical compositions of amphibole phenocrysts in pyroclasts collected from the initial and largest pyroclastic unit(4I-1) of the Aso-4 caldera-forming eruption occurred at ~90 ka to clarify their crystallization conditions and pre-eruptive magmatic processes. The results suggest the following: (1) most of the amphibole phenocrysts coexisted with silicate melt with 66–72 wt% SiO_2 and temperatures of 910–950 °C, whereas some amphiboles crystallized from more mafic and higher-T melt; (2) the amphibole phenocrysts are in thermal and chemical disequilibrium with the host 4I-1 melt, indicating that they were incorporated into the melt immediately prior to eruption; and (3) amphibole phenocrysts crystallized at a depth of ~13.9±3.5 km, which coincides with the depth of the present low-velocity zone beneath the volcano, implying that the depth of the post-caldera magma plumbing system is strongly influenced by a relic collapsed magma reservoir related to the most recent caldera-forming eruption.

Geophysical research

There are seven articles in the special issue on geophysical studies. In Kanda et al. (2019), AMT data acquired between 2004 and 2005 were reanalyzed using a recently developed 3-D inversion code incorporating detailed topography into the model in order to estimate the detailed shallow resistivity structure of Aso volcano. A highly conductive zone is observed beneath the active crater down to a depth of approximately 300 m. Based on the recent findings regarding the shallow hydrothermal system of the volcano such as Ichimura et al. (2018), this conductive zone could be interpreted as formed by highly conductive acidic fluids filling a fractured region. This view modifies the past interpretation made based on the 2-D models and promotes understanding of fluid behavior beneath the active crater. And this 3-D model was used as an initial model in Minami et al. (2018).

Huang et al. (2018) derived crustal Vs structures beneath Aso caldera using analyses of ambient seismic noise signals. Daily CCFs of seismic station pairs were calculated and then CCFs were stacked monthly, to obtain Rayleigh wave phase velocity dispersion curves. And 1–5-s phase velocity maps were constructed with 0.05° grid spacing. The post-caldera central cones are characterized by high velocities from the surface to a depth of 1 km. In the center of the post-caldera central cones, low velocities prevail at the surface and extend to major anomalies at depths of 1–2.5 km. These low-velocity anomalies can be assumed to be shallow hydrothermal reservoirs that might be related to surface geothermal activity. The low velocities identified at depths of 5–6 km beneath the post-caldera central cones might indicate the top of magma chambers. The low-velocity belts situated at 2.5–5 km depths are likely pathways for the transfer of hydrothermal fluids, volcanic gases, or melting magma to the surface.

Ichimura et al. (2018) estimated the source locations of continuous tremors at Aso volcano over a 2-month period preceding ash–gas emissions in January 2014. During the period from December 2013 to January 2014, a significant variation in the amplitude of continuous seismic tremors corresponding to surficial volcanic activity was observed around the Nakadake crater. The tremor source locations were estimated by a three-dimensional grid search using the tremor amplitude ratio of 5–10 Hz band-pass filtered waveforms. The estimated source locations were distributed in a roughly cylindrical region (100–150 m in diameter) ranging from the ground surface to a depth of 400 m just beneath the crater. Migration of the estimated source location was also identified and was associated with changes in volcanic activity.

Minami et al. (2018) reported results of ACTIVE during the previous magmatic eruption period of Aso volcano (November 2014 to May 2015). 3-D inversion using a finite-element method of the ACTIVE data sets from August 2014 and August 2015 succeeded in revealing temporal variations in the resistivity structure between the period before and that after the magmatic eruptions as follows: a noticeable decrease in resistivity at an elevation of ~ 1050 m on the western side of the crater, and an increase in resistivity at elevations of 750 to 850 m, not only below the crater bottom but also extending outside of the crater. The increase in resistivity can be ascribed to a decrease in the amount of conductive groundwater in the upper part of an aquifer located below the elevation of 800 m, while the decrease in resistivity implies that enhanced fluid temperature and pressure changed the subsurface hydrothermal system and formed a temporal fluid reservoir at the shallow level during the magmatic eruption period.

Tsunematsu et al. (2019) conducted a video camera observation of the Strombolian eruptions at Aso volcano in 2015 and analyzed the video images to investigate the gas flow effect on the particle transport of large pyroclasts (> 10 cm). Using the obtained trajectory data, the features of Strombolian activity such as ejection velocity, explosion energy, and particle release depth were investigated. The gas flow velocities were estimated by comparing the simulated and observed trajectories. The range of the ejection velocity of the observed eruptions was 5.1–35.5 m/s, while the gas flow velocity, which is larger than the ejection velocity, reached a maximum of 90 m/s, with mean values of 25–52 m/s for each bursting event. The particle release depth, where pyroclasts start to move separately from the chunk of magmatic fragments, was estimated to be 11–13 m using linear extrapolation of the trajectories. Although these parabolic trajectories provide us with an illusion of particles unaffected by the gas flow, the parameter values show that the particles are transported by the gas flow, which is possibly released from inside the conduit.

Ishii et al. (2019) analyzed characteristic VLP signals, eruption earthquake signals, and infrasound signals accompanying Strombolian explosion events at Aso volcano in late April 2015. The explosion depth and ascent velocity of a gas phase in the conduit were estimated using the differences in the seismo-acoustic signal arrival times. The obtained depth was < 400 m and the ascent velocity of the gas phase was estimated to be 1–160 m/s. This velocity is too fast to assume the migration of a gas slug through the conduit. The ascent velocity of a slug from theoretical and experimental approaches cannot exceed 7.5 m/s under the conditions present at Aso volcano. To explain the estimated values, they proposed a revised model describing the migration of the gas phase via a more complicated mechanism, such as annular flow.

Yokoo et al. (2019) provides detailed descriptions of monochromatic infrasound waves observed at Aso volcano. Throughout the entire eruption period in 2014–2015, when both ash venting and Strombolian explosions occurred, monochromatic infrasound waves were observed nearly every day. The source location of the signals was highly stable at the active vent. Although the peak frequency of the signals (0.4–0.7 Hz) changed over time, the frequency exhibited no reasonable correlation with the eruption style. Based on finite-difference time-domain modeling using 3-D topographic data of the crater during the eruption (March 2015), the propagation of infrasound waves from the conduit was calculated assuming that the shape of the conduit was a simple pipe. The peak frequency of the observed waveforms was well reproduced by the calculation, while the length of the pipe markedly defined the peak frequency. By replicating the observed waveform, the gas exhalation with a gas velocity of 18 m/s occurred at 120 m of depth in the conduit.

Geochemical research

Three articles on geochemical research were published in this special issue. A frontier letter by Shinohara et al. (2018a), reports chemical compositions of the salt fallouts observed during the intensive gas emission and ash eruption stages of the Nakadake crater of the Aso volcano. Spherical hollow salt shells were observed on several occasions during and shortly after the weak ash eruptions. Most of the salt fallouts have composition similar to those of the dried crater lake water samples and are quite different from those of the ash leachates. The hollow structure of the shells suggests that they were formed by the heating of hydrothermal solution droplets suspended by a mixed stream of gas and ash in the plume. The salt shells indicate a close distribution of the hydrothermal system surrounding the erupting vent, even during the continuous magmatic eruption stage.

Morita et al. (2019) conducted continuous monitoring of soil CO_2 flux in the flank of Nakadake cone, Aso volcano, from January 2016 to November 2017. After applying a multivariate linear regression analysis, the obtained time series of soil CO_2 flux presented some anomalous peaks in both the active and calm periods. Careful comparison of the anomalous peaks with the environmental parameters revealed that most of the anomalous peaks were likely due to an increase in wind speed and/or a decrease in barometric pressure. However, the anomaly after the 8 October 2016 eruption could not completely be explained by the variations in the environmental parameters and coincided with increases in seismic amplitude and plume SO_2 flux. This anomaly was possibly attributed to an increase in magmatic CO_2 flux. These findings emphasized the importance of careful statistical treatment of the soil CO_2 flux data by excluding the influences of the environmental parameters at each measurement site.

Shinohara et al. (2018b) reported gas composition measurement obtained by means of multi-GAS, which was collecting data during the 2014–2015 eruptive phase, as well as the quiet period preceded the above events. Volcanic gas composition during the eruptive period is characterized by rapid and large variation. In particular, the CO_2/SO_2 and SO_2/H_2S varied in the rages of 1–8 and 3–300 during the ash eruption with intermittent Strombolian activity. The variation shows a well-constrained correlation between two end-member compositions: one is $CO_2/SO_2=8$ and $SO_2/H_2S=3$ and the other is $CO_2/SO_2=1.5$ and $SO_2/H_2S=300$. The large variation and the negative correlation in compositions are attributed to a marked difference in the degassing pressure with reaches two orders of magnitude, such as 20 and 0.2 MPa; the gases with the large CO_2/SO_2 and the small SO_2/H_2S are related to high-pressure conditions. The rapid and large compositional variation suggests frequent ascent of bubbles formed at various depth during the eruption. The maximum CO_2/SO_2 decreased with the intensity of the eruption suggesting a decline of the bubbles derived from a large depth. With time, H_2O/SO_2 increases from 30 to >60, suggesting an increase in a hydrothermal contribution at lower depth.

Remote sensing

Four articles in the special issue are based on remote-sensing analysis. Cigolini et al. (2018) analyzed the thermal signature of Nakadake crater of Aso volcano during unrest episodes by combining the MODIS-MIROVA data set (2000–2017) with high-resolution images (LANDSAT 8 OLI and Sentinel 2) together with ground-based thermal observations (2013–2017). During fumarolic activity, VRP detected by both of the satellite and ground observation was below 0.5 MW and reached 2–2.8 MW with increasing activity. Prior, during, and after the major Strombolian explosions, satellite VRP data are above 10 MW, reaching peak values of 15.6 MW. After the volcano re-entered the phreatic phase, satellite data processed by MIROVA exhibit very few thermal alerts, whereas ground-based measurements initially were fluctuating around 1 MW. They provided VRP threshold values that define the transition from high fumarole activity, through phreatic–phreatomagmatic activity, to a Strombolian phase at active Nakadake crater.

Morita (2019), using land observation data of the plume height and satellite observation data of SO_2 mass, reports on the degassing activity before the 8 October 2016 phreatomagmatic eruption of Aso volcano. In this study, the temporal variations of the plume height, the SO_2 mass, and ground-based SO_2 flux during 6 months before the eruption were investigated. The results show that the maxima and the increasing trends in the above parameters, respectively, occurred about 2 months and 6 days before the eruption. This result indicates that the degassing system had been stable during 6 months before the eruption and that the accumulation of volcanic gas in the conduit, since August might trigger the phreatomagmatic eruption. It was shown that these techniques can be effective to monitor the degassing activity of the volcanoes.

Ishii et al. (2018) used the Ash RGB images from Himawari-8 to detect and track SO_2 cloud from a phreatomagmatic eruption of Aso volcano on October 8, 2016. The Ash RGB is a composite image of three observation bands of Himawari-8 (RED: brightness temperature difference between 12.4 and 10.4 μm, GREEN: brightness temperature difference between 10.4 and 8.6 μm, and BLUE: 10.4 μm), and can discriminate SO_2 clouds and volcanic ash clouds from meteorological clouds. They could estimate the height of the SO_2 cloud by comparing the Ash RGB images and simulations of the JMA Global Atmospheric Transport Model: the estimated height of the SO_2 cloud was 7–13 or 7–14 km. Using the cloud height and eruption duration, the total mass of volcanic ash from the eruption was estimated to be $6.1–11.8 \times 10^8$ kg, which is consistent with $6.0–6.5 \times 10^8$ kg obtained from field observations.

Weather radars of JMA also captured the volcanic ash cloud from the explosive eruption of Aso on October 8, 2016 (JST). Sato et al. (2018) used five radars' data and found that the ash cloud travel more than 200 km away from the crater. The eruption altitude was estimated to be 12,000 m ASL $\pm$ 687 m (1σ). Using this result and the duration of the earthquake (160–220 s) due to the eruption, the total mass of the ejecta was estimated to be $3.2–7.5 \times 10^8$ kg, which is consistent with the value of the field survey.

Modeling

Data assimilation methods were applied to estimate the mass of eruption plume column. Ishii (2018) developed a data assimilation system based on the 4D-Var for estimating the mass of eruptive columns as a function of altitude and ash particle size and applied this method to analyze the October 8, 2016 eruption of Aso volcano. Using both field observation on ash fall and meteorological radar observations for the data assimilation system, emission mass from the eruption plume column (as a function of altitude and particle size) was estimated and subsequent modeling was consistent with observations. The total mass of eruptive column was estimated to be 1.32×10^8 kg.

Abbreviations
4D-var: four-dimensional variational method; ACTIVE: a controlled-source electromagnetic volcano monitoring experiment; AMT: audio-frequency magnetotelluric; CCFs: cross-correlation functions; JMA: Japan Meteorological Agency; JST: Japan standard time (UTC + 9); VLP: very long period; VRP: volcanic radiative power.

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Authors' contributions
TO drafted the manuscript. AK, YM, JF, CC and VA improved the manuscript. All authors read and approved the final manuscript.

Competing interests
The author declares that they have no competing interests.

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