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Magma Migration and Eruptions in a Volcanic Group: Case Studies for the 2017-2018 Activity of the Kirishima Volcano Group and Other Global Examples

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Prof. Masahito Nosé
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eic-2025@earth-planets-space.org

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PREFACE

Open Access

Special issue "magma migration and eruptions in a volcanic group: case studies for the 2017–2018 activity of the Kirishima Volcano Group and other global examples"

Takayuki Kaneko[1*], Mie Ichihara[1], Kostas I. Konstantinou[2], Antonio Costa[3], Yasuo Miyabuchi[4] and Koki Aizawa[5]

Graphical Abstract

*Correspondence:
Takayuki Kaneko
kaneko@eri.u-tokyo.ac.jp
[1] The University of Tokyo, Tokyo, Japan
[2] National Central University, Taoyuan City, Taiwan
[3] National Institute of Geophysics and Volcanology, Bologna, Italy
[4] Kumamoto University, Kumamoto, Japan
[5] Kyushu University, Fukuoka, Japan

Volcanic groups with multiple edifices located close to each other are relatively common around the world. Understanding the magma supply system beneath such volcanic groups and the relationships between eruptive activities across different edifices is a subject of great interest. Mt. Kirishima, consisting of more than twenty isolated eruption centers forming small edifices, serves as a notable example. Shinmoe-dake, one of its active cones, produced a magmatic eruption in 2011. A variety of instruments were deployed around Shinmoe-dake to provide multidisciplinary observations of its eruptive activity, many of which were also used during the 2018 eruptions. Eruptions in 2018 occurred at two edifices—Shinmoe-dake and Iwo (Io)-yama. At Shinmoe-dake, an effusive eruption occurred following the explosive eruption in 2011 and small explosive events in 2017, accompanied by subsidiary Vulcanian eruptions. Iwo-yama experienced phreatic explosions, the first such activity since 1768. The extensive observational data and in-depth analysis of the 2018 eruptions present a significant opportunity to enhance our understanding of the magmatic system within the volcanic group. This special issue presents the latest insights into magma systems beneath volcanic groups and the mechanisms of associated eruptions using data from geophysical, geological, and geochemical investigations. The following results are presented:

New results were presented from the analyses of geophysical observation data. Kurihara and Kato (2022) presented a comprehensive study of deep low-frequency (DLF) earthquakes related to the 2018 eruptions at the Kirishima volcano group. Although the total DLF earthquake activity associated with the 2018 eruptions was much weaker than that for the 2011 eruptions, the temporal evolution of DLF earthquake activity was consistent with surface volcanic unrest and shallow deformation, similar to the observations during the 2011 eruptions. They interpreted that a deep magma supply influenced both eruptions, but the magma pathways might have been different in 2018 from 2011. Yukutake et al. (2023) applied a machine-learning approach to reexamine volcanic earthquakes at the Kirishima volcano over the past 12 years. They identified approximately 6.2 times more earthquakes than a conventional seismic catalog and obtained a high-resolution hypocenter distribution. They found earthquake events temporally and spatially consistent with recent eruptions and associated magma supply pathways that other multiparametric observations suggested. Konstantinou et al. (2022) studied seismic noise signatures before and after the 2011, 2017, and 2018 eruptions at Shinmoe-dake volcano, using a complexity metric called permutation entropy (PE). They found that the PE values decreased before each eruption and spiked just before the onset of all three eruptions. They inferred the PE variations indicated the interaction of the ascending magma with the aquifer or solidified magma plug at shallow depths. Yoshinaga et al. (2023) analyzed extensometer and tiltmeter data focusing on subsurface magma movement during the early stages of the 2018 Shinmoe-dake eruptions. They found that deep magmatic activity began at 14:00 on March 5, approximately 19 h earlier than previously thought. They discussed the magma ascent from ~ 11 km below sea level to the surface in the early and main phases of the 2018 eruptions. Kozono et al. (2023) investigated magma storage conditions before the 2011 and 2018 eruptions at Shinmoe-dake by analyzing the relationship between geodetic volume change and erupted magma volume. They concluded under the assumption of a spherical magma chamber that the chamber was filled with bubble-free magma, suggesting efficient gas segregation before the eruptions.

Studies on the erupted materials have also been reported. Maeno et al. (2023) studied the transition between explosive and effusive eruptions at Shinmoe-dake volcano in 2017 and 2018 by analyzing surface phenomena, whole-rock chemistry, and microtextural properties of erupted pumice, ballistics, and lava. Although samples of the ballistics or lava and pumice from Vulcanian explosions right after the lava emplacement were comparable with the Vulcanian ballistics and the subplinian pumice from the 2011 eruptions, respectively, pumice erupted during the hybrid activity with simultaneous small-scale explosions and lava dome formation, characteristic to the 2018 eruptions, exhibited textures that were not observed in 2011. They interpreted the results as showing that the transitions in the eruption styles were primarily controlled by the ascent rate of andesitic magma and the geological structure beneath the summit crater. Saito et al. (2023) studied magma ascent and degassing during the 2011 and 2017–2018 eruptions of Shinmoe-dake, analyzing the petrological characteristics and volatile content of the magmas. Their chemical analyses of the whole rock and crystals revealed that the 2018 magma was a remnant of the 2011 magma because both had similar compositions. They explained the effusive nature of the 2018 eruptions by the relatively low volatile content of the 2018 magma compared with the 2011 magma that led to subplinian eruptions.

Integrating the above findings reported in this special issue, information published elsewhere, and their own analyses of aerial photographs, satellite imagery, and seismo-acoustic data, Ichihara et al. (2023) provided a detailed sequence of events during the 2017–2018 eruptions at the Kirishima volcano group. They proposed that the eruptions of Shinmoe-dake in 2017 and 2018, as well as the 2018 eruption of Iwo-yama, were sequential events linked by the degassing of magma beneath Shinmoe-dake.

The continued surface activity at Shinmoe-dake and Iwo-yama after the main eruptions in 2018 made the Kirishima Volcano Group a natural laboratory for volcanologists. Ishii et al. (2023) developed a method to predict ash concentrations in volcanic ash clouds using the Himawari-8 satellite and an atmospheric transport model and tested it with the April 4, 2018, Shinmoe-dake eruption. They introduced a wind shear index and optimized its parameter to estimate ash cloud thickness immediately after an eruption. The proposed method will provide helpful information to assess safe areas and routes for airline operations. Miyabuchi et al. (2023) investigated the dispersal and grain size characteristics of the May 14, 2018, Shinmoe-dake eruption deposits immediately after the eruption. They demonstrated that the spatial and grain-size distributions of the tephra fall deposits can generally be explained by the eruption style and vertical wind profile over the source volcano but put forward the need to solve the inverse problem to accurately reconstruct the vertical profile of the volcanic ash plume in the atmosphere. Tanabe et al. (2023) performed multiparametric observations at Iwo-Yama's West Crater and explored the cause of cyclic hydrothermal water discharge. They proposed that the inflow of cold groundwater into the geyser conduit controls the cyclicity of hydrothermal water discharge by inhibiting boiling and building up pressure until discharge occurs. Yamakawa et al. (2023) conducted an experiment at Iwo-Yama using a very-small-aperture infrasonic array and a near-vent single microphone. They successfully resolved the two fumarolic sources and demonstrated the utility of their microphones and methods for volcanic monitoring.

The Special Issue also includes studies on similar phenomena at other volcanoes. Massaro et al. (2022) reconstructed the evolution of discharge rates at the Santiaguito lava dome complex in Guatemala from 1922 to 2021, combining new satellite thermal data. They identified three key periodicities: (i) long-term cycles lasting approximately 10 years, (ii) intermediate-term cycles lasting around 3.5 years, and (iii) short-term cycles ranging from 1 year to 3 months. These periodicities were similar to those observed in other lava dome eruptions at calc-alkaline volcanoes. Shinmoe-dake exhibited more sporadic lava effusions, and each of the 2011 and 2018 effusion events lasted a few days. Petrelli et al. (2023) reviewed pre-eruptive dynamics and open-system behavior in the volcanic plumbing system beneath Campi Flegrei Caldera in Italy, focusing on magma ascent and mixing-to-eruption timescales. They suggested that explosive eruptions could occur with minimal warning, as magma ascent could be fast and mixing timescales could be as short as minutes to hours. The recent studies included those in this special issue reported new observations indicating magma movement before the Shinmoe-dake eruptions (Ichihara et al. 2023; Konstantinou et al. 2022; Kurihara and Kato 2022; Yoshinaga et al. 2023; Yukutake et al. 2023), the magma mixing timescales at Shinmoe-dake have not been constrained, yet. The simultaneous activation of the DLF at tens of kilometers deep and the shallow and surface phenomena was one of the unique observations at the Kirishima Volcano Group (Kurihara and Kato 2022). Yukutake et al. (2022) reported a deep harmonic volcanic tremor event related to DLF earthquakes at Hakone volcano. They estimated the tremor source as deep as 40 km beneath the volcano, in the extension of the DLF earthquake hypocenters near the Moho discontinuity. The DLFs activated immediately before the tremor onset and continued for several months. Ozaki et al. (2023) updated a nonlinear flow-induced tremor model. Combining the model solution with the Green's function, they successfully reproduced the observed deep tremor waveforms at the Hakone volcano. Their results supported Yukutake et al. (2023) that the tremor signified the migration of magmatic fluid in the volcano's deep region.

As summarized above, this special issue compiles a diverse range of findings from the 2017–2018 activities of the Kirishima volcano group, as well as similar cases worldwide. A key takeaway from these studies is that the subsurface structure and magma plumbing system beneath a volcanic group with multiple edifices are highly complex, emphasizing the need for further research to deepen our understanding. Fortunately, the observation network at the Kirishima volcano group has been consistently maintained at a high level since the 2017–2018 eruption. In addition, several campaign observations, including electromagnetic surveys and high-density seismic array studies, have been conducted. It is expected that, by analyzing the data collected, we will gain a more accurate understanding of the magma systems beneath volcanic groups and the associated eruption mechanisms. The findings presented in this issue will serve as a solid foundation for future research in this field.

Author contributions
All authors of this article served as guest editors for this special issue. TK drafted the manuscript. All authors read and approved the final manuscript.

Availability of data
Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

FULL PAPER **Open Access**

Detecting multiscale periodicity from the secular effusive activity at Santiaguito lava dome complex (Guatemala)

Silvia Massaro*, Antonio Costa, Roberto Sulpizio, Diego Coppola and Anatoly Soloviev

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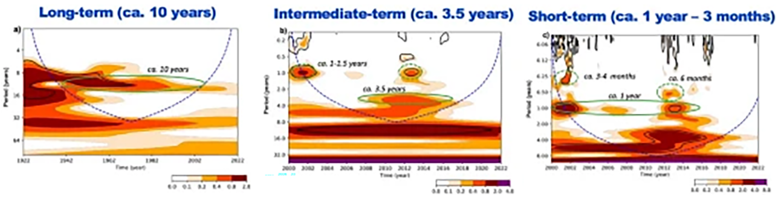
Abstract

Santiaguito, Guatemala, represents one of the best cases of active lava dome complex in the world, producing lava flow effusion, weak explosive activity, and cycles of lava dome extrusion over varying timescales. Since the inception in 1922, it has shown a remarkable constant eruptive activity, characterized by effusion of blocky domes and lava flows punctuated by moderate explosions of gas-and-ash and pyroclastic flows. In this study, we reconstruct the time evolution of discharge rates of Santiaguito across one entire century, from 1922 to 2021, combining, for the more recent activity, new satellite thermal data. By using discrete Fourier transform (DFT) and Morlet wavelet analyses, we identify three fundamental periodicities in subsets of the 1922–2021 time-series: (i) long term (ca. 10 years), (ii) intermediate term (ca. 3.5 years), and (iii) short term (from ca. 1 year to ca. 3 months), which are comparable with those observed at other lava dome eruptions at calc-alkaline volcanoes. Such inferred periodicities provide a powerful tool for the interpretation of the non-linear eruptive behaviour and represent a pivotal benchmark for numerical modelling aimed to reconstruct the dynamics of the magma feeding system based on a time-averaged discharge rate dataset.

Keywords: Wavelet analysis, Magma feeding system, Secular eruptive time-series, Santiaguito



Graphical abstract

*Corresponding author: Silvia Massaro, silvia.massaro@uniba.it

FULL PAPER **Open Access**

Permutation entropy variations in seismic noise before and after eruptive activity at Shinmoedake volcano, Kirishima complex, Japan

K. I. Konstantinou*, D. A. Rahmalia, I. Nurfitriana and M. Ichihara

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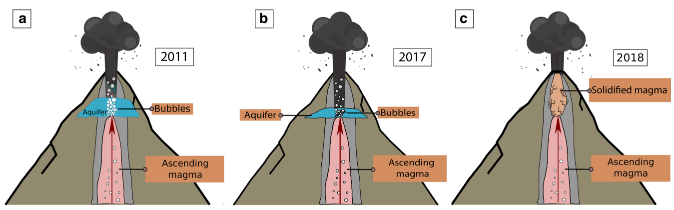
Abstract

Permutation entropy (PE) is a complexity metric that encodes a time series into sequences of symbols and can be used to decipher between deterministic and stochastic behavior. This study investigates PE variations in seismic noise during three eruption cycles in 2011, 2017, and 2018 at Shinmoedake volcano, Japan. The volcano is monitored by a dedicated seismic network and by infrasound microphones that recorded continuously during the aforementioned eruptions. The frequency range 1–7 Hz was used in order to infer temporal changes of PE in seismic noise and minimize any human contributions. The results showed that PE values decreased before the occurrence of each eruption. By combining these results with other observations we can attribute this decrease in PE to two reasons: first, to the occurrence of volcanic tremor that is a deterministic signal, and second, to magma migration at shallower depth beneath Shinmoedake which can attenuate high-frequency seismic waves and thus result in a less stochastic signal. PE also exhibited a spike-like increase just before the onset of the three eruptions. In 2011 and 2017, this feature was probably associated with bubble growth and collapse due to the interaction between the aquifer and high temperature magma. In 2018 the aquifer had mostly evaporated; hence, the spike in PE values was likely generated by fracturing of solidified magma within the conduit as fresh magma was pushing its way upwards. These results show that PE is a potentially useful tool for monitoring seismic noise at volcanoes and can contribute toward forecasting volcanic eruptions in conjunction with other widely used methodologies.

Keywords: Permutation Entropy, Shinmoedake, Japan, Volcanic tremor, Eruption, Seismic noise



Graphical abstract

*Corresponding author: K. I. Konstantinou, kkonst@cc.ncu.edu.tw

FULL PAPER **Open Access**

Pre-eruptive dynamics at the Campi Flegrei Caldera: from evidence of magma mixing to timescales estimates

Maurizio Petrelli*, Mónica Ágreda López, Alessandro Pisello and Diego Perugini

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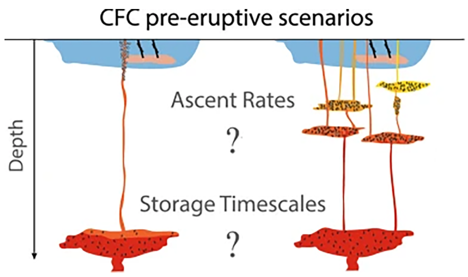
Abstract

We review pre-eruptive dynamics and evidence of open-system behavior in the volcanic plumbing system beneath Campi Flegrei Caldera, together with estimates of magma residence time, magma ascent, and mixing-to-eruption timescales. In detail, we compile pre- and syn-eruptive dynamics reported in the literature for (a) the Campanian Ignimbrite ~ 40 ka, (b) the Neapolitan Yellow Tuff (~ 15 ka), and (c) the recent activity within the Phlegrean area. We first summarize geochemical and textural evidence (e.g., magma mixing, crystal disequilibria, vertical zonings, and isotopic records) of open-system behavior for the pyroclasts erupted in the last 40 ky at Campi Flegrei Caldera. We show that the fingerprint of open-system dynamics is ubiquitous in the deposits associated with the volcanic activity at the Campi Flegrei Caldera in the last 40 ky. Then, we describe the results of geophysical and petrological investigations that allow us to hypothesize the structure of the magma feeding system. We point to a trans-crustal magmatic feeding system characterized by a main storage reservoir hosted at ~ 9 km that feeds and interacts with shallow reservoirs, mainly placed at 2–4 km. Finally, we define a scenario depicting pre-eruptive dynamics of a possible future eruption and provide new constraints on timescales of magma ascent with a physical model based on magma-driven ascending dyke theory. Results show that considerably fast ascent velocities (i.e., of the order of m/s) can be easily achieved for eruptions fed by both shallow (i.e., 3–4 km) and deep (i.e., ~ 9 km) reservoirs. Comparing the results from experimental and numerical methods, it emerges that mixing-to-eruption timescales occurring at shallow reservoirs could be on the order of minutes to hours. Finally, we highlight the volcanological implications of our timescale estimates for magma ascent and mixing to eruption. In particular, explosive eruptions could begin with little physical 'warning', of the order of days to months. In this case, the onset of volatile saturation might provide pre-eruptive indicators.

Keywords: Campi Flegrei Caldera, Pre-eruptive dynamics, Volcanic plumbing system, Mixing-to-eruption timescales, Magma ascent velocity



Graphical abstract

*Corresponding author: Maurizio Petrelli, maurizio.petrelli@unipg.it

FULL PAPER **Open Access**

Experiment to distinguish two fumaroles consistently emanating infrasound at Kirishima Iwo-Yama

Kazuya Yamakawa*, Mie Ichihara, Dan Muramatsu, Takeshi Matsushima, Hidetoshi Takahashi, Ruka Wada and Isao Shimoyama

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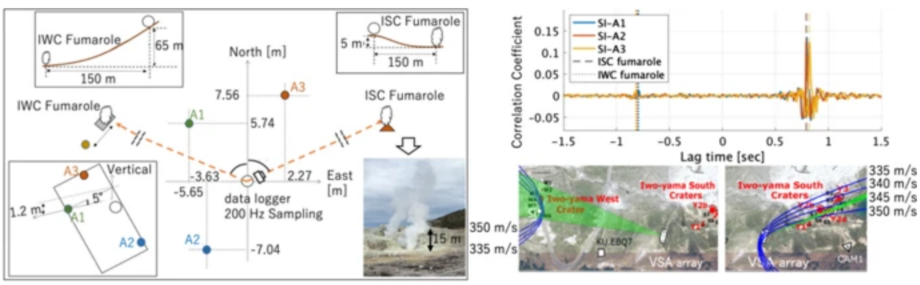
Abstract

In the infrasonic observation of a fumarolic field, distinguishing multiple fumarolic sources is challenging. The array technique effectively estimates the source locations and identifies the target signal from other signals and noise. We conducted an experiment at Kirishima Iwo-Yama, Japan, where two active fumarolic areas were separated by ~ 450 m. A three-element array with an aperture of ~ 20 m was installed between the two fumarolic areas. In addition, a single microphone was installed near one of the fumaroles. The array combined with the waveform correlation analysis estimated the most prominent source but failed to estimate the other weak source. A joint analysis of the array and the single microphone effectively resolved the two sources. It was also confirmed that newly developed power-saving MEMS microphones were useful for observing the fumaroles. This paper presents the instrumentation and analytical method that would be beneficial for monitoring volcanoes that have multiple hydrothermally active vents.

Keywords: Infrasound, Volcano, Fumarole, Array observation



Graphical abstract

*Corresponding author: Kazuya Yamakawa, yamakawa@mfri.pref.yamanashi.jp

FULL PAPER Open Access

Multi-parametric observations of intermittent hydrothermal water discharge in West Crater of Iwo-Yama volcano, Kirishima Volcanic Complex, Japan

Harutou Tanabe*, Takeshi Matsushima, Koki Aizawa and Dan Muramatsu

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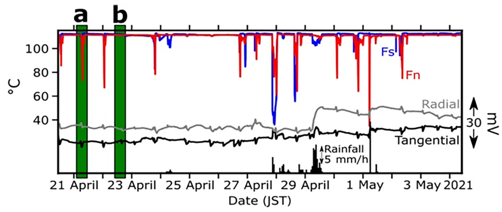
Abstract

From April to July 2021, West Crater at Iwo-Yama, Kirishima Volcanic Complex, Japan, was repeatedly filled with hydrothermal water and subsequently evacuated. The overall cycle lasted 14–70 h, and the course of a single cycle followed this sequence of phases: (i) steam effusion disappeared 20–40 min before hydrothermal water discharge; (ii) hydrothermal water discharge occurred, generating a hydrothermal water pool; (iii) steam effusion resumed and gradually increased; and (iv) drain-back (evacuation) of the hydrothermal water occurred 1–1.5 h before the onset of the next hydrothermal water discharge. We used multi-parametric observations (optical camera, thermometer, electric self-potential (SP) electrodes, seismometer, acoustic sensor, and tiltmeter) to investigate the cause of the cyclic hydrothermal water discharge. A change in SP data occurred approximately 2 h before the onset of hydrothermal water discharge. However, the change in SP was small when hydrothermal water discharge did not occur. The temporal change in SP is inferred to have been caused by groundwater flow through the region below West Crater, implying that groundwater flow was occurring 2 h before hydrothermal water discharge. The polarity of SP change suggests that groundwater flowed toward the region underlying the vents. Seismic signals in the frequency range of < 20 Hz decreased 15–45 min after the onset of change in SP. This seismic signal pattern is inferred to have been caused by bubble activity in boiling fluid. We interpret that the inflow of cold groundwater inhibited boiling activity in the conduit, which in turn caused the cessation of both steam effusion and seismic activity. SP data suggest that the inflow of cold groundwater gradually decreased before hydrothermal water discharge. Pressurization sufficient to force the water in the upper part of the conduit to ascend could have built up in the lower part of the conduit owing to a decrease in the input of groundwater into the upper part of the conduit and the continuing supply of steam bubbles and hot water. This increase in pressure finally led to hydrothermal water discharge at the surface. We suggest that the inflow of cold groundwater into the geyser conduit was the key control on the occurrence and cyclicity of hydrothermal water discharge in West Crater at Iwo-Yama.

Keywords: Geyser, Electric self-potential, Electric field, Multi-parametric observations



Graphical abstract

*Corresponding author: Harutou Tanabe, haruto_tanabe@kyudai.jp

FULL PAPER Open Access

Eruption style transition during the 2017–2018 eruptive activity at the Shinmoedake volcano, Kirishima, Japan: surface phenomena and eruptive products

Fukashi Maeno*, Sayaka Shohata, Yuki Suzuki, Natsumi Hokanishi, Atsushi Yasuda, Yuya Ikenaga, Takayuki Kaneko and Setsuya Nakada

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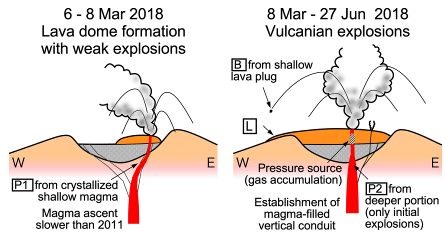
Abstract

Recent eruptions of the Shinmoedake volcano, Japan, have provided a valuable opportunity to investigate the transition between explosive and effusive eruptions. In October 2017, phreatic/phreatomagmatic explosions occurred. They were followed in March 2018 by a phase of hybrid activity with simultaneous explosions and lava flows and then a transition to intermittent, Vulcanian-style explosions. Evolution of surface phenomena, temporal variations of whole-rock chemical compositions from representative eruptive material samples, and rock microtextural properties, such as the crystallinity and crystal size distribution of juvenile products, are analyzed to characterize the eruption style transition, the conduit location, and the shallow magma conditions of the volcanic edifice. The 2017–2018 eruptive event is also compared with the preceding 2011 explosive–effusive eruption. The chemical and textural properties of the 2018 products (two types of pumice, ballistically ejected lava blocks, and massive lava) are representative of distinct cooling and magma ascent processes. The initial pumice, erupted during lava dome formation, has a groundmass crystallinity of up to 45% and the highest plagioclase number density of all products (1.9×10^6/mm^3). Conversely, pumice that erupted later has the lowest plagioclase number density (1.2×10^5/mm^3) and the highest nucleation density (23/mm^4 in natural logarithm). This 2018 pumice is similar to the 2011 subplinian pumice. Therefore, it was likely produced by undegassed magma with a high discharge rate. Ballistics and massive lava in 2018 are comparable to the 2011 Vulcanian ballistics. Conversely, the high plagioclase number density pumice that occurred in 2018 was not observed during the 2011 eruption. Thus, such pumice might be specific to hybrid eruptions defined by small-scale explosions and lava dome formation with low magma discharge. The observed transitions and temporal variations of the activities and eruption style during the 2017–2018 Shinmoedake eruptions were primarily influenced by the ascent rate of andesitic magma and the geological structure beneath the summit crater.

Keywords: Lava dome, Phreatic, Phreatomagmatic, Effusive, Explosive, Subplinian, Number density, Shinmoedake



Graphical abstract

*Corresponding author: Fukashi Maeno, fmaeno@eri.u-tokyo.ac.jp

FULL PAPER **Open Access**

Magma ascent and degassing processes of the 2011 and 2017–18 eruptions of Shinmoedake in Kirishima volcano group, Japan, based on petrological characteristics and volatile content of magmas

Genji Saito*, Teruki Oikawa and Osamu Ishizuka

Earth, Planets and Space 2023, **75**:89 DOI: 10.1186/s40623-023-01836-1
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Abstract

The eruption activity of Shinmoedake in the Kirishima volcanic group of Japan resumed in 2017–18, following a quiet period during 2011–17. Subplinian eruptions preceded lava effusion in 2011; however, no subplinian eruption occurred during 2017–18. Petrological studies and melt inclusion analyses were conducted to investigate the ascent and degassing of the magma to understand the cause of the different eruption styles. Chemical analysis of the melt inclusions from the 2011 eruption indicates that mafic magma with high volatile content (6.2 wt% H_2O, 0.25–1.4 wt% CO_2) ascended into the shallow felsic magma (1.9–3.7 wt% H_2O, 0.025–0.048 wt% CO_2) at depths of 5–6 km. Calculations indicate that the mafic magmas were of lower density (1717–1835 kg m^{-3}) than the felsic magma (2264–2496 kg m^{-3}) at 125 MPa and that the two magmas were mixed. The 2011 mixed magma with high volatile content (4.0 wt% H_2O, 0.14–0.70 wt% CO_2) had a bubble volume of approximately 50 vol% at 50 MPa, which is likely to have caused the subplinian eruption. The whole-rock and chemical compositions of the plagioclase, clinopyroxene, and orthopyroxene phenocryst cores from 2018 and 2011 were similar, suggesting that the 2018 magma was a remnant of the 2011 magma. Chemical analyses of the groundmass from 2018 and the MELTS calculation indicate that the magma approached chemical equilibrium during 2011–18. Melt inclusion analyses and volcanic gas observation noted a lower bulk volatile content in the 2018 magma (2.1–3.0 wt% H_2O, 0.087–0.10 wt% CO_2) than that in the 2011 magma. Comparison of the degassed-magma volumes estimated from the S and Cl contents of the melt inclusions, SO_2 flux and volcanic gas composition, and erupted-magma volume indicates that excess degassing has been occurring in the magma due to convection since February 2011, which may have decreased the volatile content of the magma. The relatively low volatile content meant that the 2018 magma could not erupt explosively and lava was instead erupted via effusion.

Keywords: Kirishima volcano, Shinmoedake, Eruption, Petrology, Magma mixing, Magma ascent, Degassing, Melt inclusions, Volatile content, Bubble volume

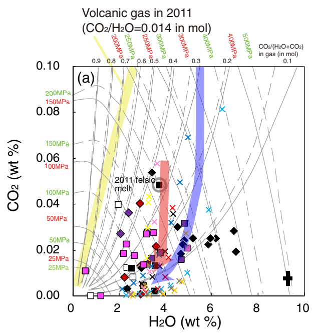


Fig. 8

*Corresponding author: Genji Saito, saito-g@aist.go.jp

FULL PAPER **Open Access**

Constraints on magma storage conditions based on geodetic volume change and erupted magma volume and application to the 2011 and 2018 eruptions at Kirishima Shinmoe-dake volcano, Japan

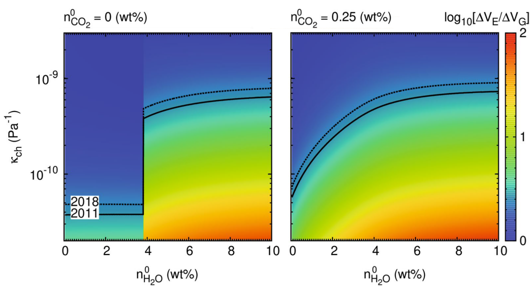
Tomofumi Kozono*, Takehiro Koyaguchi, Hideki Ueda, Taku Ozawa and Tadashi Yamasaki

Earth, Planets and Space 2023, **75**:100 DOI: 10.1186/s40623-023-01851-2
Received: 16 September 2022, Accepted: 26 May 2023, Published: 20 June 2023

Abstract

We investigated magma storage conditions prior to the 2011 and 2018 eruptions at Kirishima Shinmoe-dake volcano in Japan based on the relationship between geodetic volume change of magma chamber and erupted magma volume. We derived an analytical expression for the ratio of the erupted magma volume to the geodetic volume change ("volume ratio"), which was formulated as a function of parameters related to the magma storage conditions. This expression shows that the volume ratio is strongly dependent on the effective compressibility of the magma chamber, which in turn depends on the rigidity of surrounding host rocks and shape of the chamber. For the Shinmoe-dake eruptions, the magnitude of the volume change (i.e., deflation) of a spherical magma chamber associated with lava effusion was estimated based on geodetic observations. The erupted magma volume was estimated from a SAR image analysis of the lava accumulation inside the summit crater. Based on these observations, we estimated that the volume ratio in 2011 and 2018 was 2.69 and 2.33, respectively. Substituting the estimated volume ratio into the analytical expression revealed that the observed geodetic data and volume ratio can be explained only when the magma chamber, which was assumed to be spherical, is filled with bubble-free magma. This result suggests that efficient gas segregation from the chamber occurred prior to the eruptions. Our results indicate that combining multi-observation data based on the volume ratio provides valuable information about the magma storage process, such as the behavior of the gas phase in the magma chamber.

Keywords: Volcanic eruption, Magma chamber, Magma dynamics, Geodetic observation



Graphical abstract

*Corresponding author: Tomofumi Kozono, kozono@bosai.go.jp

FULL PAPER Open Access

Linking the flow-induced tremor model to the seismological observation: application to the deep harmonic tremor at Hakone volcano, Japan

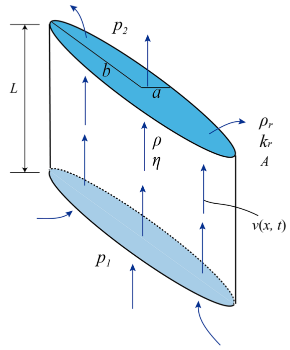
Tomonori Ozaki, Yohei Yukutake and Mie Ichihara*

Earth, Planets and Space 2023, **75**:111 DOI: 10.1186/s40623-023-01865-w
Received: 27 December 2022, Accepted: 28 June 2023, Published: 17 July 2023

Abstract

Decades ago, Julian (J Volcanol Geotherm Res 101:19–26, 1994. https://doi.org/10.1029/93JB03129) proposed the lumped parameter model of non-linear excitation of an elastic channel vibration by fluid flow as a mechanism of volcanic harmonic tremor. Since then, his model and similar flow-induced oscillation models have been applied or considered to explain volcanic tremors and low-frequency earthquakes. Here we extended Julian's model to allow quantitative comparison with observation data and applied it to deep harmonic tremor observed at Hakone volcano, Japan. We formulated the model in terms of the channel volume and linked the solution to the volumetric moment tensor. We also incorporated the turbulent flow effect to deal with both magma and super-critical fluid as the working fluid. Assuming the realistic material parameters at the tremor source depth (~ 30 km) beneath Hakone, we searched for the conditions in which tremor was generated at an observed frequency (~ 1 Hz). It is shown that both magma and super-critical fluids can generate realistic tremors with similar channel sizes of several-meter long and several-centimeter wide. We convolved the model solution with the Green's function at each seismic station to compare the model with the data. The result showed that Julian's model could produce synthetic tremor waveforms very close to the observed ones. Although the source waveform had only a single peak at each cycle, the convolved waveform exhibited an apparent secondary peak, like the observed waveforms. While the previous models generated such waveforms exhibiting alternative large and small peaks by a non-linear effect of period-doubling before the chaos, our model did not show such transitions, at least with the investigated parameters. Although most of the parameters and physical values of the solutions were in the realistic ranges, the only problem was the presumed low elasticity of the channel as small as 10^5 Pa to generate oscillation at ~ 1 Hz. We proposed that not the rock property alone but the channel structure consisting of rock and compressible fluids could generate the low effective elasticity. To fully validate our model, the mechanism of such small elasticity should be identified, which is our future work.

Keywords: Volcanic tremor, Flow induced oscillation, Non-linear oscillation



Graphical abstract

*Corresponding author: Mie Ichihara, ichihara@eri.u-tokyo.ac.jp

FULL PAPER Open Access

Subsurface magma movement inferred from extensometer and tiltmeter records during the early stage of the 2018 Shinmoe-dake eruptions, Japan

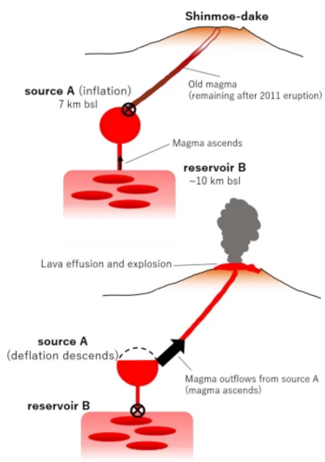
Koki Yoshinaga*, Takeshi Matsushima, Hiroshi Shimizu, Yusuke Yamashita, Ken'ichi Yamazaki, Shintaro Komatsu and Satoshi Fujiwara

Earth, Planets and Space 2023, **75**:143 DOI: 10.1186/s40623-023-01895-4
Received: 14 February 2023, Accepted: 4 September 2023, Published: 20 September 2023

Abstract

We infer the temporal changes in the pressure sources that induced crustal deformation during the 2018 Shinmoe-dake eruption using strain and tilt observations and discern that the deep magmatic activity associated with the early stage of this eruption began approximately 19 h earlier than the previously defined onset of magmatic activity. Distinct tilt changes were observed from around 09:00 on 6 March to 12:00 on 8 March 2018 (JST), coincident with observed lava outflow into the crater and lava dome formation. Existing studies have attributed this tilt change to the onset of the deflation of a spherical pressure source located at ~ 7 km bsl (below sea level) to the northwest of Shinmoe-dake. Here we examine strain and tilt data that were acquired in the Kirishima volcanic group, and we find that the distinct changes in the measured strain at Isa-Yoshimatsu Observatory began at around 14:00 on 5 March. This change can be explained by the deflation of a spherical pressure source, thereby suggesting that the onset of magma ascent was earlier than previously thought. The time variation in the spherical pressure source is estimated using the time-dependent inversion of the Ensemble Kalman Filter; the deflation source ascended from ~ 11 to 7 km bsl during Phase 1 (14:00 on 5 March to 06:00 on 6 March) and descended from 7 to 8 km bsl during Phase 2 (06:00 on 6 March to 12:00 on 8 March). Interferometric synthetic aperture radar analysis suggests that a dike intrusion had occurred just below Shinmoe-dake crater until 5 March, and this inflatable crustal deformation is attributed to the emplacement of residual volcanic fluids from the 2011 eruption. It is also known that the surface eruptive activity increased during Phase 1, including an increase in ash venting from the night of 5 March. These strain and tilt observations, therefore, suggest that magma ascended from ~ 11 km bsl to the magma reservoir at 7 km bsl during Phase 1, followed by a deflation of the magma reservoir during Phase 2 due to the large magma supply to the surface.

Keywords: 2018 Shinmoe-dake eruption, Strain, Tilt, Time-dependent inversion, Magma plumbing system, Extensometer, Magma effusion, Ensemble Kalman Filter, Subsurface magma movement



Graphical abstract

*Corresponding author: Koki Yoshinaga, yoshinaga.koki@sevo.kyushu-u.ac.jp

FULL PAPER **Open Access**

The sequence of the 2017–2018 eruptions and seismo-acoustic activity at Kirishima volcano group

Mie Ichihara*, Tsukasa Kobayashi, Fukashi Maeno, Takao Ohminato, Atsushi Watanabe, Setsuya Nakada and Takayuki Kaneko

Earth, Planets and Space 2023, **75**:144 DOI: 10.1186/s40623-023-01883-8
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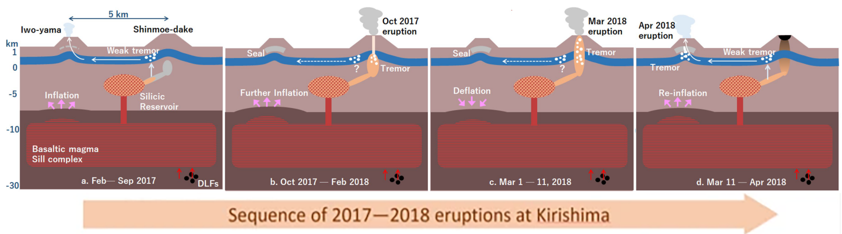
Abstract

Kirishima volcano consists of more than 20 eruptive centers. Among them, Shinmoe-dake had magmatic eruptions in October 2017 and March 2018. Subsequently, another active cone, Iwo-yama, had phreatic eruptions in April 2018. These events were unique in that the 2018 eruption was the first effusion-dominated eruption of Shinmoe-dake and the first simultaneous activity of two cones of the Kirishima volcanic group ever documented. We report the detailed sequence of the events by combining areal photos, satellite images, and seismo-acoustic data analyses with the other published information. The seismo-acoustic data clarify the eruption onset and the transitions of the behaviors in three stages for each of the 2017 and 2018 eruptions. For both eruptions, we present regularly repeated tremors or 'drumbeat' earthquakes in the second stage, which interpret as gas separation from magma, leading to the ash-poor plume in the 2017 eruption or the effusive eruption in the 2018 event. We also propose that the 2017 and 2018 eruptions of Shinmoe-dake and the 2018 eruption of Iwo-yama are sequential events linked by the degassing of magma beneath Shinmoe-dake. An eruption like the 2017–2018 eruptions of Shinmoe-dake would leave few geological records and could be captured only by modern techniques. Although Shinmoe-dake has been believed to be an example of less-frequent eruptions, effusive eruptions like the 2018 case might have occurred more frequently in the past , but the following eruptions had obscured their records. The timelines summarized in this study will be useful in future studies of Kirishima volcanoes and world equivalences.

Keywords: Eruption sequence, Volcanic group, Volcanic tremor, Eruption types, Volcano monitoring



Graphical abstract

*Corresponding author: Mie Ichihara, ichihara@eri.u-tokyo.ac.jp

FULL PAPER **Open Access**

Dispersal and grain size characteristics of the May 14, 2018 Shinmoedake eruption deposit, Kirishima Volcano, Japan, based on post-eruption field survey and meteorological datasets

Yasuo Miyabuchi* and Eiichi Sato

Earth, Planets and Space 2023, **75**:182 DOI: 10.1186/s40623-023-01907-3
Received: 2 April 2023, Accepted: 23 September 2023, Published: 5 December 2023

Abstract

This study describes the dispersal and grain size characteristics of the May 14, 2018 Shinmoedake eruption deposits of Kirishima Volcano in southern Kyushu, southwestern Japan. We discuss the eruption sequence, including the temporal variations in the behavior of the plume, by combining field and meteorological datasets. Following a magmatic activity in 2011 characterized by a substantial change in the eruption style (from subplinian eruptions to lava effusion) and subsequent vulcanian explosions, the Shinmoedake crater experienced intermittent eruptions in 2018. The May 14, 2018 eruption began at 14:44 with a vulcanian eruption, with the eruption plume rising 4500 m above the crater rim. Thereafter, it transitioned to an ash eruption; the plume height decreased gradually until the eruption ceased at 16:10. The tephra fall deposits were distributed more than 27 km to the southeast of the source crater; the mass of the tephra fall deposit was approximately 2.1×10^7 kg, calculated based on an isomass map. The deposit incidence differed between the east and west sides of the major dispersal axis. The deposits found east of the main dispersal axis were primarily composed of coarse to medium sand-sized particles with no fine fraction (fine sand to silt in size). In contrast, the deposits west of the axis were finer-grained than those east of the axis. We analyzed photographs of the eruption plume, along with the regional meteorological data and the dispersal and grain-size characteristics of the deposits, and reached the following conclusion: during the May 14, 2018 eruption, the wind directions above the Shinmoedake crater fluctuated across altitudes. The westerly winds dispersed the eruption plume that rose to a higher altitude, containing coarser tephra associated with the initial vulcanian eruption, further to the east rather than along the main axis. In contrast, a lower-altitude ash eruption plume that was rich in fine materials was dispersed westward rather than along the main axis, which was influenced by northerly winds. The findings of this study can support the analysis of similar volcanic events.

Keywords: Dispersal characteristics, Erupted mass, Eruption plume, Grain size, Kirishima Volcano, Meteorological conditions, Shinmoedake, Tephra fall

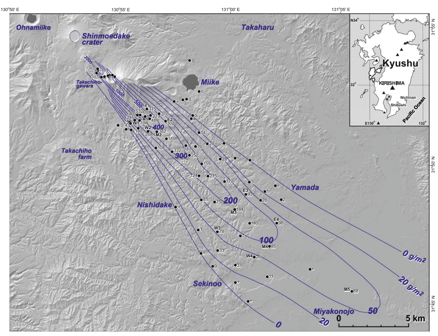


Fig. 2

*Corresponding author: Yasuo Miyabuchi, miyabuchi@gmail.com

FULL PAPER Open Access

Reappraisal of volcanic seismicity at the Kirishima volcano using machine learning

Yohei Yukutake*, Ahyi Kim and Takao Ohminato

Earth, Planets and Space 2023, **75**:183 DOI: 10.1186/s40623-023-01939-9
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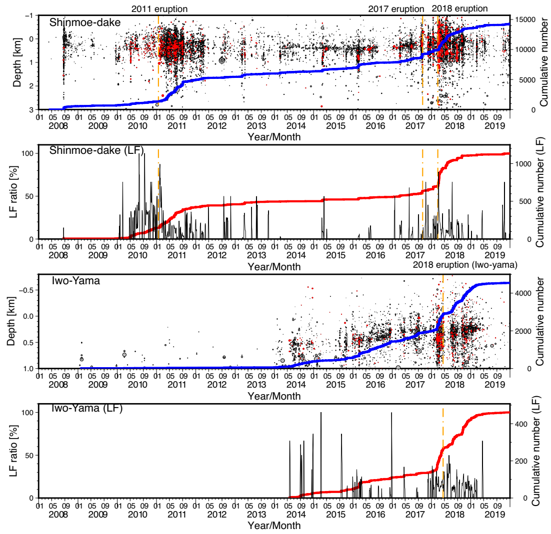
Abstract

Volcanic earthquakes provide essential information for evaluating volcanic activity. Because volcanic earthquakes are often characterized by swarm-like features, conventional methods using manual picking require considerable time to construct seismic catalogs. In this study, using a machine learning framework and a trained model from a volcanic earthquake catalog, we obtained a detailed picture of volcanic earthquakes during the past 12 years at the Kirishima volcano, southwestern Japan. We detected ~6.2 times as many earthquakes as a conventional seismic catalog and obtained a high-resolution hypocenter distribution through waveform correlation analysis. Earthquake clusters were estimated below the craters, where magmatic or phreatic eruptions occurred in recent years. Increases in seismic activities, *b* values, and the number low-frequency earthquakes were detected before the eruptions. The process can be conducted in real time, and monitoring volcanic earthquakes through machine learning methods contributes to understanding the changes in volcanic activity and improving eruption predictions.

Keywords: Volcanic earthquake, Machine learning, Phase picking, Kirishima volcano



Graphical abstract

*Corresponding author: Yohei Yukutake, yukutake@eri.u-tokyo.ac.jp

EXPRESS LETTER Open Access

Harmonic tremor from the deep part of Hakone volcano

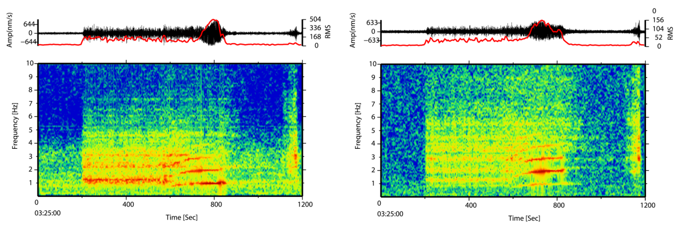
Yohei Yukutake*, Ryou Honda, Motoo Ukawa and Kei Kurita

Earth, Planets and Space 2022, **74**:144 DOI: 10.1186/s40623-022-01700-8
Received: 14 June 2022, Accepted: 29 August 2022, Published: 21 September 2022

Abstract

The feeding system of magmatic fluid from the volcanic root to a shallow magma reservoir remains a poorly understood issue. Seismic events, including volcanic tremors and low-frequency earthquakes, in a deep part beneath volcanos are key observations for understanding the feeding system at the depth. Although deep low-frequency (DLF) earthquakes beneath volcanos have been recognized universally through dense seismic observations, volcanic tremors with harmonic frequency components originating at volcanic roots have rarely been observed. Here, we report the observation of a harmonic volcanic tremor event that occurred beneath the Hakone volcano on May 26, 2019. The tremor signal continued for approximately 10 min and was recognized at seismic stations 90 km away from the Hakone volcano. The apparent velocity of the tremor wave train is 5 km/s, corresponding to the S-wave velocity of the lower crust beneath the Hakone volcano. The frequency components varied with time. In the initial part of the tremor signal, a spectrum had a broad peak of around 1.2 Hz, whereas the tremor became harmonic with a sharp fundamental peak at 0.98 Hz in the latter part, increasing its amplitude. We estimated the source location of the volcanic tremor using the relative arrival times of the waveform envelope. The optimal source locations were estimated at a deep extension of the hypocenter distribution of the DLF earthquakes beneath the Hakone volcano, around the depth level of Moho discontinuity. The DLF earthquakes were activated immediately before the onset time of the volcanic tremor and continued for several months. The harmonic volcanic tremor may have been generated by the migration of magmatic fluid in the volcano's deep region.

Keywords: Harmonic tremor, Hakone volcano, Root of a volcano, Deep low-frequency earthquake



Graphical abstract

*Corresponding author: Yohei Yukutake, yukutake@eri.u-tokyo.ac.jp

EXPRESS LETTER **Open Access**

Deep low-frequency earthquake activity associated with the 2018 eruptions in the Kirishima volcanic complex, Japan

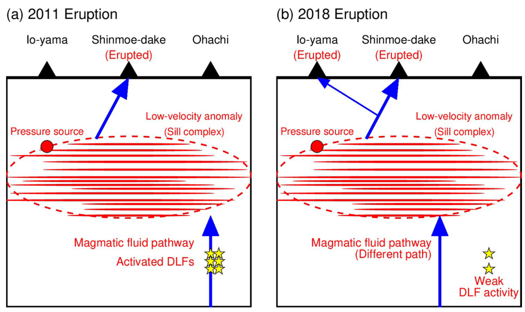
Ryo Kurihara* and Aitaro Kato

Earth, Planets and Space 2022, **74**:174 DOI: 10.1186/s40623-022-01723-1
Received: 7 August 2022, Accepted: 16 October 2022, Published: 30 November 2022

Abstract

Deep low-frequency (DLF) earthquakes have occurred at depths of 10–30 km in the Kirishima volcanic complex, Japan. Here, we investigate the DLF earthquake activity that was associated with the 2018 eruptions, compare these DLF earthquakes with those associated with the 2011 eruptions, and provide inferences on magmatic fluid ascension during these two eruptions. We apply a new matched-filter method to the continuous waveform data from the 2017–2018 period to comprehensively detect the DLF earthquake activity surrounding the 2018 eruptions. This new method can detect microearthquakes using a single seismic station based on an index that is computed as the product of mutual information and the correlation coefficient to measure the similarity between the template and target waveforms. We perform the same analysis using the 2010–2011 waveform data for comparison with the DLF earthquake activity associated with the 2011 eruptions. We detect 75 DLF earthquakes at approximately 25 km depth during the 2017–2018 period, whereas we detect 1302 DLF earthquakes at similar depths during the 2010–2011 period. Although the number of detected 2017–2018 events is small, we identify two swarms of DLF earthquake activity in March and July 2017. The March 2017 swarm coincides with the appearance of mud pots and jet fumaroles at the surface, and the July 2017 swarm coincides with the initiation of crustal deformation, which indicates the inflation of a deep magma reservoir. Furthermore, the occurrence rate of DLF earthquakes increased slightly after the March 2018 eruptions. Although the occurrence rate of DLF earthquakes associated with the 2018 eruptions was much lower than that associated with the 2011 eruptions, the slight increase in DLF earthquakes during the 2018 eruptions implies a connection between the deep magmatic fluid ascension and shallow volcanic unrest in 2018, which is similar to that observed during the 2011 eruptions. Such a close temporal relationship between the DLF earthquakes and surface volcanic activity suggests that the pressure disturbance within volcanic conduits propagates rapidly from depth.

Keywords: Matched-filter technique, Low-frequency earthquakes, Mutual information, Kirishima Volcanic complex



Graphical abstract

*Corresponding author: Ryo Kurihara, kurihara@onken.odawara.kanagawa.jp

EXPRESS LETTER **Open Access**

Prediction of volcanic ash concentrations in ash clouds from explosive eruptions based on an atmospheric transport model and the Japanese meteorological satellite Himawari-8: a case study for the Kirishima-Shinmoedake eruption on April 4th 2018

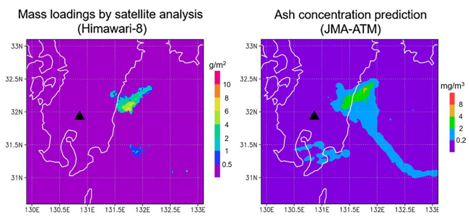
Kensuke Ishii*, Masahiro Hayashi, Hiroshi Ishimoto and Toshiki Shimbori

Earth, Planets and Space 2023, **75**:37 DOI: 10.1186/s40623-023-01790-y
Received: 26 June 2022, Accepted: 23 February 2023, Published: 13 March 2023

Abstract

Prediction of ash concentrations in volcanic ash clouds for the Kirishima-Shinmoedake eruption on April 4th, 2018 is performed on the basis of an atmospheric transport model and the Japanese meteorological satellite Himawari-8. The retrieval algorithm for Himawari-8 (referred to as the "Optimal Volcanic Ash Algorithm", OVAA) provides two-dimensional properties of volcanic ash clouds, such as cloud heights and total column mass loading, whereas it does not provide ash cloud thickness which is required to make an initial condition for the atmospheric transport model. To estimate ash cloud thickness immediately after an eruption, here, a wind shear index is introduced. The wind shear index includes an empirical constant parameter T_c; a small value of T_c leads to thick ash clouds, whereas a large value of T_c leads to thin ash clouds. In this study, the value of T_c is optimized empirically in the following two ways: (1) a comparison between the total column mass loadings in the prediction and that in the OVAA estimation and (2) a comparison between the estimated ash cloud thickness and the observed ash cloud thickness by lidar measurements. These two comparisons suggest the optimal value of T_c is 0.5–0.6, and then, the uncertainty of the ash clouds thickness estimation to be ~700 m. In an operation, this estimation of T_c can be used as a fixed value to estimate the ash cloud thickness for a future eruption. In this case, the ash concentration predictions can be obtained immediately after the OVAA estimation. The ash concentrations prediction for T_c=0.6 provides areas of high contamination (>4 mg/m^3) and low contamination (<2 mg/m^3). This classification of ash concentration in ash clouds has been required by the aviation industry, and is helpful information to assess safe areas and routes for airline operations.

Keywords: Volcanic ash cloud, Atmospheric transport model, Volcanic ash prediction, Tephra dispersal, Meteorological satellite, Japanese Meteorological Satellite Himawari-8, Optimal Volcanic Ash Algorithm, OVAA



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*Corresponding author: Kensuke Ishii, kishii@mri-jma.go.jp

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