Ogawa *et al. Earth, Planets and Space (2022) 74:100*
https://doi.org/10.1186/s40623-022-01643-0

Earth, Planets and Space

PREFACE

Open Access

Special issue "Understanding phreatic eruptions - recent observations of Kusatsu-Shirane volcano and equivalents -"

Yasuo Ogawa[1*], Takeshi Ohba[2], Tobias P. Fischer[3], Mare Yamamoto[4] and Art Jolly[5,6]

Introduction

The phreatic eruption is one of the volcanic eruption styles triggered by the rapid vaporization of heated fluids at shallow depth without the involvement of juvenile magma (e.g., Stix and deMoor 2018). Although it is a relatively small-scale near-surface phenomenon, its precursors are difficult to detect. Thus, for the mitigation of volcanic risk, it is an important research topic. This special issue is dedicated to further understanding phreatic eruptions, notably the phreatic eruption of the Kusatsu-Shirane volcano in 2018. This issue also includes papers on the phreatic eruptions of similar volcanoes in Japan and the world.

Papers on the Kusatsu-Shirane volcano

Kusatsu-Shirane volcano is an active dacite-andesite Quaternary volcano located in Gunma Prefecture, Central Japan. From north to south, the volcano consists of three pyroclastic cones, Shirane, Ainomine, and Moto-Shirane. Since 1805, its volcanic activity has been characterized by phreatic eruptions, particularly around the Yugama crater of the Shirane pyroclastic cone (Terada 2018). Therefore, multi-disciplinary studies have been conducted around the most active Yugama crater to mitigate volcanic hazards using geochemical (Ohba et al. 1994, 2019; Terada et al. 2018), seismological (Nakano et al. 2003; Mori et al. 2006), and geomagnetic approaches (Nurhasan et al. 2006; Takahashi and Fujii 2014; Tseng et al. 2020).

In January 2018, an unexpected phreatic eruption (VEI = 1) took place at the three vents of the Moto-Shirane pyroclastic cone after 1500 years of dormancy. It occurred near the skiing slope in winter. One person was killed, and 11 people were injured. This event revealed the difficulty of the prediction of phreatic eruptions, in particular for dormant volcanoes, and motivated long-term and more regional-scale studies of the dormant volcanoes. This special issue includes past and ongoing research on the Kusatsu-Shirane volcano with various disciplines such as seismology, geodesy, geomagnetism, geochemistry, petrology, and risk assessment. We also included papers on other similar volcanoes with phreatic eruption activities. We hope these papers will have future impact on studies of short-term and long-term assessments of volcanic risk, particularly for phreatic eruptions, and will lead to mitigation of volcanic risk. We briefly introduce summaries of the contributed papers as follows.

Kametani et al. (2021) reported the total mass ejection from the 2018 phreatic eruption at the Moto-Shirane pyroclastic cone. They mapped the volcanic ejecta from the three craters which opened during the 2018 eruption. The volcanic blocks were distributed within 500 m from the new craters. On the other hand, the ash reached 25 km from the craters. The total ejected mass was estimated as 2.4×10^7–3.4×10^7 kg.

Sato (2021) reported that the three radars of the Japan Metrological Agency (JMA) captured the 2018 eruption. The radar echoes were detected in the lower and middle troposphere, the plume height was estimated

---

*Correspondence: oga@ksvo.titech.ac.jp

[1] Volcanic Fluid Research Center, Tokyo Institute of Technology, Tokyo, Japan
Full list of author information is available at the end of the article

as 5580 m, and the total ejected mass was estimated as 6.7×10^7–6.5×10^8 kg, depending on the chosen empirical models for magmatic eruptions.

After the unexpected eruption in winter, hazard assessment is needed to estimate the potential risk of snow-related lahars immediately. Kataoka et al. (2021) demonstrated numerical lahar flow simulations using the Titan2D by considering proximal tephra deposits and snow surveys. They made three lahar scenarios, including rain-on-snow, ice/snow slurry, and total snowmelt triggered by a new eruption, and showed the potential flow paths and travel distances.

The observed precursors for the 2018 Kusatsu-Shirane volcanic eruption were limited. One of the reasons might be that the seismic and geodetic networks were sparse for the dormant Moto-Shirane pyroclastic cone, compared with those around the active Yugama crater at Shirane pyroclastic cone. However, the seismic network detected the precursory signals just two minutes before the eruption. Yamada et al. (2021) investigated the temporal changes of the 5–20 Hz tremor amplitude observed by the seismic stations and located the tremor source. The result showed that the tremor source migrated for 1 km horizontally in two minutes before the eruption and finally reached the eruption place at 0.5–1 km depth from the surface. The pathway of tremor source differs from the known seismicity around the active Yugama crater, suggesting a unique migration of fluid movement.

Himematsu et al. (2020) analyzed the L-band satellite synthetic aperture radar (SAR) data, pertaining to the 2018 Kusatsu-Shirane volcanic eruption, searching for precursory signals of phreatic eruptions. They could find no precursors, but they detected co- and post-eruptive deformations around the new craters. They detected combinations of normal faulting and left-lateral slip for co-eruptive deformation followed by an isotropic deflation. They interpreted that the co-eruptive fault plane can be a pathway of volcanic fluid from the reservoir imaged by magnetotellurics (Matsunaga et al. 2020).

Terada et al. (2021) analyzed tilt data obtained at the three borehole stations surrounding the Yugama crater during the 2018 Moto-Shirane cone eruption. The tilt record showed inflation stating two minutes prior to the eruption, which is consistent with the initiation of the tremor. Deflation was recorded after the eruption. The tilt data were modeled using a sub-vertical crack for inflation and deflation phases. Inflation/deflation volume was estimated as 5.1×10^5 and 3.6×10^5 m^3, respectively. The total heat discharge was estimated as $> 10^{14}$ J, equivalent to annual heat discharge from the active Yugama crater.

Munekane (2021) reported long-term volcanic deformation using GNSS data around the Kusatsu-Shirane volcano. After carefully removing the regional-scale post-deformation due to the 2011 Tohoku earthquake, the deformation around the Kusatsu-Shirane volcano was inferred and modeled as a spheroidal pressure source model located at 4 km below the surface. A volume change of the spheroid expressed the long-term deformation. The 2014 unrest at Yugama crater and the 2018 eruption at Moto-Shirane cone were characterized by sharp increases in the spheroid volume, implying an increase of magmatic input. This study was successful in detecting long-term precursory volcanic activity.

For a further general understanding of the Kusatsu-Shirane volcano system, magnetotelluric surveys have been undertaken. Tseng et al. (2020) reported the three-dimensional resistivity structure surrounding the Yugama crater. They imaged a conductive clay cap layer that forms an impermeable seal for the geothermal system under the Yugama crater. This capping structure can explain the upper limit of the micro-seismicity, demagnetization source locations, and the 2014 inflation source locations. They also found a deep conductor which implies high-salinity supercritical fluid below the micro-seismicity cutoff, presumably capped by a silica seal .

Koyama et al. (2021) reported the aeromagnetic survey over the Kusatsu-Shirane volcano after the 2018 eruption using an unmanned helicopter. The equipment has an advantage for the high spatial resolution because of the data acquisition at the low altitude from the surface and the safe measurement when the volcanic target is difficult to access. They modeled the three-dimensional distribution of magnetic intensity. The recent volcanic deposits showed the surface positive magnetic intensity, and the underlying negative intensity was interpreted as an older lava flow. This measurement can be baseline data for future repeat measurements for detection of temporal temperature change of the volcano.

Ueki et al. (2020) reported the petrological investigations on the orthopyroxene and magnetite symplectites associated with olivine in the Sessho lava, which erupted about 3000 years ago (e.g., Terada 2018). The varieties of the symplectites suggest that the recharge of the basaltic magma into the existing magma reservoir repeatedly occurred under the Kusatsu-Shirane volcano.

Papers on similar volcanoes in Japan and the world

This special issue also includes studies on phreatic eruptions at other volcanoes in Japan, New Zealand, and Costa Rica, and the summaries are described below.

Ichiki et al. (2021) obtained wideband magnetotelluric data around the Azumayama volcano, northeastern Japan, and imaged the magmatic-hydrothermal system from the three-dimensional inversion. They detected a conductor (less than 3 Ωm) at 3–15 km below sea level. The conductors imply the hydrothermal fluid and the water-saturated andesitic melt. The fact that the location of the Mogi inflation source coincides with the top of the conductor implies that the percolation threshold governs the inflation.

Mannen et al. (2021) describe the recent reactivation of the Hakone volcano after the 2015 phreatic eruption (Mannen et al. 2018). After the eruption, they also see deep inflation at 10 km depth, and deep low-frequency earthquakes, which are interpreted as the re-supply of magma and magmatic fluids. While the 2015 eruption center appears to have lower seismicity at present, the seismic swarm area has shifted to the rim of the caldera. The post-eruption activity suggests that the system has again sealed and phreatic eruptions are possible.

Ohba et al. (2021) analyzed the fumarolic gases at Kirishima volcano, Kyushu, Japan, during the 2018 Ebinokogen Ioyama eruption. Sharp increases of SO_2 and H_2 concentrations were observed in 2017 and 2018 prior to the phreatic eruption of April 2018. Oxygen and hydrogen isotope studies reveal the mixing of magmatic gases and meteoric water. Furthermore, they found that the high apparent equilibrium temperature from SO_2, H_2S, H_2, and H_2O, together with low CO_2/SO_2 and H_2S/SO_2 ratios, can be used as precursor signals to the phreatic eruption.

Muramatsu et al. (2021) installed two infrasound records and cameras near the two craters at Kirishima volcano during the 2018 Ebinokogen Ioyama eruption. They identified the intense eruption with low-frequency infrasonic signals several hours after the onset of the phreatic eruption.

Kurokawa and Ichihara (2020) measured infrasound and seismic tremor at a single station during the 2013 and 2018 events at the Ioto island, an active volcano located 1200 km south of Tokyo in the Izu–Bonin arc. They could successfully identify the phreatic eruption of the 2013 events by using spectral amplitude ratios of the vertical ground motion to the pressure oscillation. However, for the 2018 event, the phreatic event was not clear. These differences imply that the differences of the explosive nature may depend on whether the eruption took place on land or underwater.

Caudron et al. (2021) reviewed the 15-year-long seismic data of the Whakaari White Island volcano, a frequently active volcano located 50 km off the northern coast of the North Island in New Zealand. They focused on the ambient noises and tremors for the different activity periods of quiescence, unrest, magmatic and phreatic eruptions. Time and frequency evolution of the volcanic tremor was monitored for 15 years by Displacement Seismic Amplitude Ratio (DSAR), relative seismic velocity (dv/v), decorrelation, and the Luni-Seismic Correlation (LSC). They finally proposed a general scheme for forecasting phreatic eruptions using data from the continuous seismic records.

Park et al. (2020) analyzed very long-period earthquakes (VLPs) from 2007 to the end of 2019 at Whakaari/White Island volcano, New Zealand. The waveform shows similitudes, implying that the source locations and the mechanism do not change. From the semblance analyses, two families are detected and characterized by the mirror image, but they occur in a different stage of volcanic activities. The one is stable over the whole period, while the other occurs as swarms that mark the onset of phreatic activity.

Melchor et al. (2020) analyzed volcanic tremors during the 2012 and 2013 phreatic eruptions at Copahue volcano, southern Andes. They could discriminate the tremor signals from the noise by the lower permutation entropies and higher degrees of polarizations even if the signal-to-noise level is low.

Rouwet (2021) presented the first geochemical model of the Turrialba and the Irazú volcanoes in Costa Rica. The Turrialba volcano became active in 2004 after 140 years of dormancy. After the onset of the 2010 phreatic eruption of the Turrialba volcano, the underlying geothermal system changed as seen from the significant increase in the fumarole output at the Turrialba volcano. At the same time, the crater lake at the inactive Irazú volcano disappeared.

Concluding remarks

The short-term prediction of phreatic eruptions remains challenging because of the typically subtle and short-term precursors. As an example, the 2018 Kusatsu-Shirane volcanic eruption at Moto-Shirane cone had precursory tremor and simultaneous tilt changes just two minutes prior to eruption after 1500 years of dormancy. There are successful studies on long-term assessment of phreatic eruptions, using seismology, geodesy, and geochemistry, as shown in the papers in this issue. Predicting phreatic eruptions needs a basic understanding of the architecture and the dynamics of magma–hydrothermal systems over multiple timescales, understanding that requires the use of dense near-field milti-disciplinary monitoring.

The guest editors hope that the special issue papers will promote further studies on phreatic eruptions toward the mitigation of phreatic eruption risk.

Acknowledgements
We acknowledge all the contributing authors and reviewers. We also thank Stephanie Prejean and Takeshi Sagiya for reviewing this preface article.

Author contributions

YO drafted the manuscript, and all the co-authors contributed to the editing. All agreed with the contents. All authors read and approved the final manuscript.

Funding
Some of the published papers were supported by KAKENHI 17K20141 and 20H01992.

Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

All the authors have no competing interests.

Author details
[1]Volcanic Fluid Research Center, Tokyo Institute of Technology, Tokyo, Japan. [2]Department of Chemistry, School of Science, Tokai University, Hiratsuka, Japan. [3]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, USA. [4]Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Sendai, Japan. [5]GNS Science, Lower Hutt, New Zealand. [6]Present Address: US Geological Survey, Hawaiian Volcano Observatory, Hawaii 96720, USA.

Received: 22 April 2022 Accepted: 22 April 2022

References

Caudron C, Girona T, Jolly A et al (2021) A quest for unrest in multiparameter observations at Whakaari/White Island volcano, New Zealand 2007–2018. Earth Planets Space 73:195. https://doi.org/10.1186/s40623-021-01506-0
Himematsu Y, Ozawa T, Aoki Y (2020) Coeruptive and posteruptive crustal deformation associated with the 2018 Kusatsu-Shirane phreatic eruption based on PALSAR-2 time series analysis. Earth Planets Space 72:116. https://doi.org/10.1186/s40623-020-01247-6
Ichiki M, Kaida T, Nakayama T et al (2021) Magma reservoir beneath Azumayama Volcano, NE Japan, as inferred from a three-dimensional electrical resistivity model explored by means of magnetotelluric method. Earth Planets Space 73:150. https://doi.org/10.1186/s40623-021-01451-y
Kametani N, Ishizaki Y, Yoshimoto M et al (2021) Total mass estimate of the January 23, 2018, phreatic eruption of Kusatsu-Shirane volcano, central Japan. Earth Planets Space 73:141. https://doi.org/10.1186/s40623-021-01468-3
Kataoka KS, Tsunematsu K, Matsumoto T et al (2021) Crisis hazard assessment for snow-related lahars from an unforeseen new vent eruption: the 2018 eruption of Kusatsu-Shirane volcano, Japan. Earth Planets Space 73:220. https://doi.org/10.1186/s40623-021-01522-0
Koyama T, Kanda W, Utsugi M et al (2021) Aeromagnetic survey in Kusatsu-Shirane volcano, central Japan, by using an unmanned helicopter. Earth Planets Space 73:139. https://doi.org/10.1186/s40623-021-01466-5
Kurokawa AK, Ichihara M (2020) Identification of infrasonic and seismic components of tremors in single-station records: application to the 2013 and 2018 events at Ioto Island, Japan. Earth Planets Space 72:171. https://doi.org/10.1186/s40623-020-01302-2
Mannen K, Abe Y, Daita Y et al (2021) Volcanic unrest at Hakone volcano after the 2015 phreatic eruption: reactivation of a ruptured hydrothermal system? Earth Planets Space 73:80. https://doi.org/10.1186/s40623-021-01387-3
Mannen K, Yukutake Y, Kikugawa G, Harada M, Itadera K, Takenaka J (2018) Chronology of the 2015 eruption of Hakone volcano Japan: geological background mechanism of volcanic unrest and disaster mitigation measures during the crisis. Earth Planets Space 70:68. https://doi.org/10.1186/s40623-018-0844-2
Matsunaga Y, Kanda W, Takakura S, Koyama T, Saito Z, Seki K, Suzuki A, Kishita T, Kinoshita Y, Ogawa Y (2020) Magmatic hydrothermal system inferred from the resistivity structure of Kusatsu-Shirane Volcano. J Volcanol Geotherm Res 390:106742. https://doi.org/10.1016/j.jvolgeores.2019.106742
Melchor I, Almendros J, Carniel R et al (2020) On data reduction methods for volcanic tremor characterization: the 2012 eruption of Copahue volcano, Southern Andes. Earth Planets Space 72:134. https://doi.org/10.1186/s40623-020-01270-7
Mori T, Hirabayashi J, Nogami K, Onizawa S (2006) A new seismic observation system at the Kusatsu-Shirane volcano. Bull Volcanol Soc Japan Ser 2(51):41–47 (**in Japanese with English abstract**)
Munekane H (2021) Modeling long-term volcanic deformation at Kusatsu-Shirane and Asama volcanoes, Japan, using the GNSS coordinate time series. Earth Planets Space 73:192. https://doi.org/10.1186/s40623-021-01512-2
Muramatsu D, Matsushima T, Ichihara M (2021) Reconstructing surface eruptive sequence of 2018 small phreatic eruption of Iwo-yama volcano, Kirishima Volcanic complex, Japan, by infrasound cross-correlation analysis. Earth Planets Space 73:8. https://doi.org/10.1186/s40623-020-01344-6
Nakano M, Kumagai H, Chouet BA (2003) Source mechanism of long-period events at Kusatsu-Shirane volcano, Japan, inferred from waveform inversion of the effective excitation functions. J Volcanol Geotherm Res 122:149–164. https://doi.org/10.1016/S0377-0273(02)00499-7
Nurhasan, Ogawa Y, Ujihara N, Tank SB, Honkura Y, Onizawa S, Mori T, Makino M (2006) Two electrical conductors beneath Kusatsu-Shirane volcano, Japan, imaged by audiomagnetotellurics, and their implications for the hydrothermal system. Earth Planets Space 58:1053–1059. https://doi.org/10.1186/BF03352610
Ohba T, Hirabayashi J, Nogami K (1994) Water, heat and chloride budgets of the crater lake, Yugama at Kusatsu-Shirane volcano, Japan. Geochem J 28:217–231. https://doi.org/10.2343/geochemj.28.217
Ohba T, Yaguchi M, Nishino K et al (2019) Time variation in the chemical and isotopic composition of fumarolic gasses at Kusatsu-Shirane volcano, Japan. Front Earth Sci 7:249. https://doi.org/10.3389/feart.2019.00249
Ohba T, Yaguchi M, Tsunogai U et al (2021) Behavior of magmatic components in fumarolic gases related to the 2018 phreatic eruption at Ebinokogen Ioyama volcano, Kirishima Volcanic Group, Kyushu, Japan. Earth Planets Space 73:81. https://doi.org/10.1186/s40623-021-01405-4
Park I, Jolly A, Lokmer I, Kennedy B (2020) Classification of long-term very long period (VLP) volcanic earthquakes at Whakaari/White Island volcano, New Zealand. Earth Planets Space 72:92. https://doi.org/10.1186/s40623-020-01224-z
Rouwet D, Mora-Amador R, Ramírez C et al (2021) Response of a hydrothermal system to escalating phreatic unrest: the case of Turrialba and Irazú in Costa Rica (2007–2012). Earth Planets Space 73:142. https://doi.org/10.1186/s40623-021-01471-8
Sato E (2021) Kusatsu-Shirane volcano eruption on January 23, 2018, observed using JMA operational weather radars. Earth Planets Space 73:117. https://doi.org/10.1186/s40623-021-01445-w
Stix J, de Moor JM (2018) Understanding and forecasting phreatic eruptions driven by magmatic degassing. Earth Planets Space 70:83. https://doi.org/10.1186/s40623-018-0855-z
Takahashi K, Fujii I (2014) Long-term thermal activity revealed by magnetic measurements at Kusatsu-Shirane volcano, Japan. J Volcanol Geotherm Res 285:180–194. https://doi.org/10.1016/j.jvolgeores.2014.08.014
Terada A (2018) Kusatsu-Shirane volcano as a site of phreatic eruptions. J Geol Soc Japan 124:251–270. https://doi.org/10.5575/geosoc.2017.0060
Terada A, Morita Y, Hashimoto T, Mori T, Ohba T, Yaguchi M, Kanda W (2018) Water sampling using a drone at Yugama crater lake, Kusatsu-Shirane volcano, Japan. Earth Planets Space 70:64. https://doi.org/10.1186/s40623-018-0835-3
Terada A, Kanda W, Ogawa Y et al (2021) The 2018 phreatic eruption at Mt. Motoshirane of Kusatsu-Shirane volcano, Japan: eruption and intrusion of hydrothermal fluid observed by a borehole tiltmeter network. Earth Planets Space 73:157. https://doi.org/10.1186/s40623-021-01475-4
Tseng KH, Ogawa Y, Nurhasan et al (2020) Anatomy of active volcanic edifice at the Kusatsu-Shirane volcano, Japan, by magnetotellurics: hydrothermal implications for volcanic unrests. Earth Planets Space 72:161. https://doi.org/10.1186/s40623-020-01283-2
Ueki K, Inui M, Matsunaga K et al (2020) Oxidation during magma mixing recorded by symplectites at Kusatsu-Shirane Volcano, Central Japan. Earth Planets Space 72:68. https://doi.org/10.1186/s40623-020-01192-4
Yamada T, Kurokawa AK, Terada A et al (2021) Locating hydrothermal fluid injection of the 2018 phreatic eruption at Kusatsu-Shirane volcano with

volcanic tremor amplitude. Earth Planets Space 73:14. https://doi.org/10.1186/s40623-020-01349-1

Publisher's Note