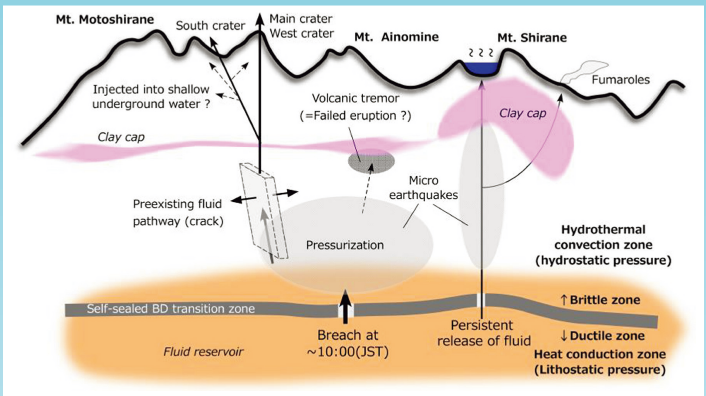
Earth, Planets and Space

Understanding Phreatic Eruptions
- Recent Observations of Kusatsu-Shirane Volcano and Equivalents -



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PREFACE

Open Access

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

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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

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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.

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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.

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All the authors have no competing interests.

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FRONTIER LETTER **Open Access**

A quest for unrest in multiparameter observations at Whakaari/White Island volcano, New Zealand 2007–2018

Corentin Caudron*, Társilo Girona, Arthur Jolly, Bruce Christenson, Martha Kane Savage, Roberto Carniel, Thomas Lecocq, Ben Kennedy, Ivan Lokmer, Alexander Yates, Ian Hamling, Iseul Park, Geoff Kilgour and Agnès Mazot

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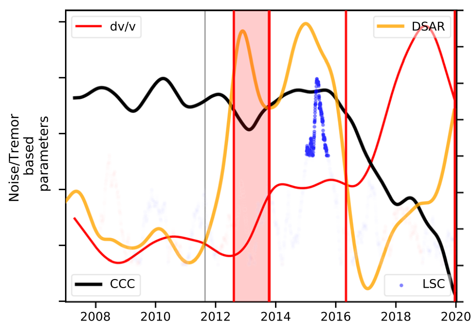
Abstract

The Whakaari/White Island volcano, located ~ 50 km off the east coast of the North Island in New Zealand, has experienced sequences of quiescence, unrest, magmatic and phreatic eruptions over the last decades. For the last 15 years, seismic data have been continuously archived providing potential insight into this frequently active volcano. Here we take advantage of this unusually long time series to retrospectively process the seismic data using ambient noise and tremor-based methodologies. We investigate the time (RSAM) and frequency (Power Spectral Density) evolution of the volcanic tremor, then estimate the changes in the shallow subsurface using the Displacement Seismic Amplitude Ratio (DSAR), relative seismic velocity (dv/v) and decorrelation, and the Luni-Seismic Correlation (LSC). By combining our new set of observations with the long-term evolution of earthquakes, deformation, visual observations and geochemistry, we review the activity of Whakaari/White Island between 2007 and the end of 2018. Our analysis reveals the existence of distinct patterns related to the volcano activity with periods of calm followed by cycles of pressurization and eruptions. We finally put these results in the wider context of forecasting phreatic eruptions using continuous seismic records.



Graphical abstract

Keywords: Volcanology, Monitoring, Phreatic eruption, Seismic noise, Tremor

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FULL PAPER **Open Access**

Oxidation during magma mixing recorded by symplectites at Kusatsu–Shirane Volcano, Central Japan

Kenta Ueki*, Mutsuko Inui, Kenta Matsunaga, Naoya Okamoto and Kazuki Oshio

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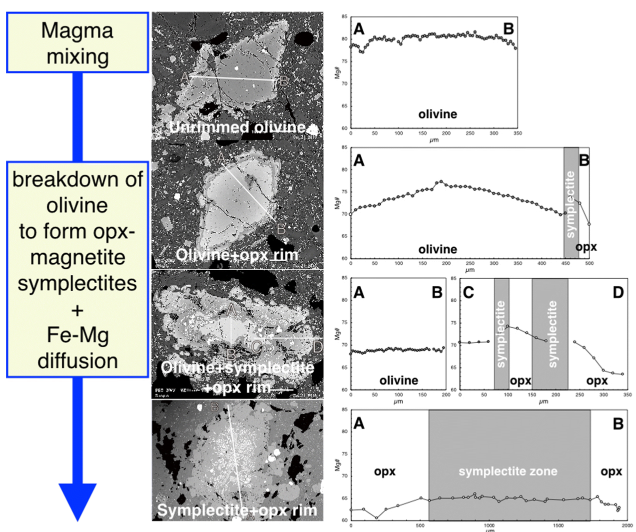
Abstract

Kusatsu–Shirane Volcano is an active Quaternary andesitic-to-dacitic volcano located in the Central Japan Arc. We conducted a detailed petrological investigation of orthopyroxene (opx)–magnetite (mt) symplectites associated with olivine in the Sessho lava, an andesitic lava flow from Kusatsu–Shirane. We concluded that the symplectites are pseudomorphs after olivine and were formed through the breakdown of olivine in a mafic magma as a result of oxidation during mixing with a felsic magma. Various olivines and opx–mt symplectites that show different stages of the progressive breakdown reaction of olivine coexist in a single lava flow. We suggest that basaltic recharge into the magma reservoir beneath Kusatsu–Shirane occurred repeatedly, leading to a hybrid andesite magma with different types of olivine and symplectite being erupted at Kusatsu–Shirane Volcano.



Graphical abstract

Keywords: Kusatsu–Shirane, Andesite, Symplectite, Magma mixing, Olivine, Active volcano

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FULL PAPER Open Access

Classification of long-term very long period (VLP) volcanic earthquakes at Whakaari/White Island volcano, New Zealand

Iseul Park*, Arthur Jolly, Ivan Lokmer and Ben Kennedy

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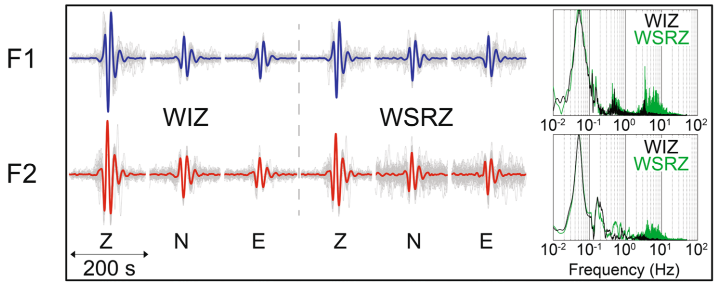
Abstract

We have observed very long period earthquakes (VLPs) over the period 2007 to the end of 2019 at Whakaari/White Island volcano, New Zealand. The earthquakes exhibit similitude between waveforms which suggests repeating source locations and processes. VLPs recorded at two permanent stations were detected using waveform semblance and were then classified into two main families (F1 and F2) using a clustering analysis. The two families are characterized by 'mirror image' reverse waveform polarity suggesting that they are genetically related, but occur during different evolutionary phases of volcanic activity. F1 events occurred throughout the observation period, while F2 events mainly occurred as swarms that mark the onset of volcanic unrest. A detailed cluster analysis reveals possible sub-families implying slight temporal evolutions within a family. Our results add to our understanding of the volcanic magma–hydrothermal system at Whakaari/White Island indicating that relatively stable VLP sources may be exploited to improve monitoring for future unrest.

Keywords: VLP, Earthquake family, Swarm, Volcanic unrest, Clustering analysis



Graphical abstract

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FULL PAPER Open Access

Identification of infrasonic and seismic components of tremors in single-station records: application to the 2013 and 2018 events at Ioto Island, Japan

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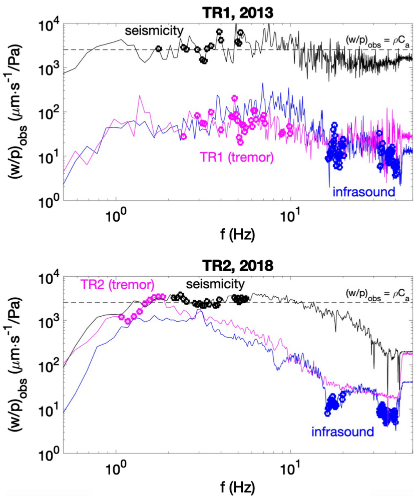
Abstract

Infrasonic stations are sparse at many volcanoes, especially those on remote islands and those with less frequent eruptions. When only a single infrasound station is available, the seismic–infrasonic cross-correlation method has been used to extract infrasound from wind noise. However, it does not work with intense seismicity and sometimes mistakes ground-to-atmosphere signals as infrasound. This paper proposes a complementary method to identify the seismic component and the infrasonic component using a single microphone and a seismometer. We applied the method to estimate the surface activity on Ioto Island. We focused on volcanic tremors during the phreatic eruption on April 11, 2013, and during an unconfirmed event on September 12, 2018. We used the spectral amplitude ratios of the vertical ground motion to the pressure oscillation and compared those for the tremors with those for known signals generated by volcano-tectonic earthquakes and airplanes flying over the station. We were able to identify the infrasound component in the part of the seismic tremor with the 2013 eruption. On the other hand, the tremor with the unconfirmed 2018 event was accompanied by no apparent infrasound. We interpreted the results that the infrasound with the 2013 event was excited by the vent opening or the ejection of ballistic rocks, and the 2018 event was not an explosive eruption either on the ground or in the shallow water. If there was any gas (and ash) emission, it might have occurred gently undersea. As the method uses the relative values of on-site records instead of the absolute values, it is available even if the instrument sensitivity and the station site effects are poorly calibrated.

Keywords: Volcanic tremor, Infrasound, Vertical ground motion, Spectral ratio, Ioto Island



Graphical abstract

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FULL PAPER **Open Access**

Locating hydrothermal fluid injection of the 2018 phreatic eruption at Kusatsu-Shirane volcano with volcanic tremor amplitude

Taishi Yamada*, Aika K. Kurokawa, Akihiko Terada, Wataru Kanda, Hideki Ueda, Hiroshi Aoyama, Takahiro Ohkura, Yasuo Ogawa and Toshikazu Tanada

Earth, Planets and Space 2021, **73**:14 DOI: 10.1186/s40623-020-01349-1
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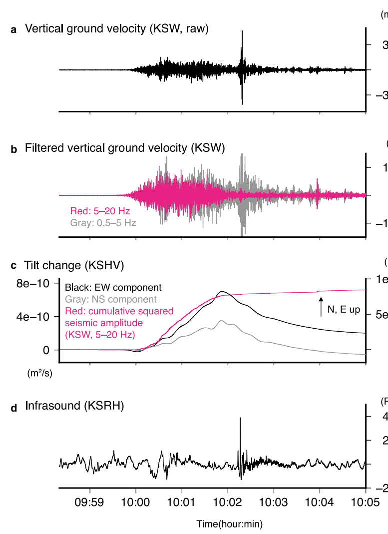
Abstract

Kusatsu-Shirane volcano hosts numerous thermal springs, fumaroles, and the crater lake of Yugama. Hence, it has been a particular study field for hydrothermal systems and phreatic eruptions. On 23 January 2018, a phreatic eruption occurred at the Motoshirane cone of Kusatsu-Shirane, where no considerable volcanic activity had been reported in observational and historical records. To understand the eruption process of this unique event, we analyzed seismic, tilt, and infrasound records. The onset of surface activity accompanied by infrasound signal was preceded by volcanic tremor and inflation of the volcano for ~2 min. Tremor signals with a frequency band of 5–20 Hz remarkably coincide with the rapid inflation. We apply an amplitude source location method to seismic signals in the 5–20 Hz band to estimate tremor source locations. Our analysis locates tremor sources at 1 km north of Motoshirane and at a depth of 0.5–1 km from the surface. Inferred source locations correspond to a conductive layer of impermeable cap-rock estimated by magnetotelluric investigations. An upper portion of the seismogenic region suggests hydrothermal activity hosted beneath the cap-rock. Examined seismic signals in the 5–20 Hz band are typically excited by volcano-tectonic events with faulting mechanism. Based on the above characteristics and background, we interpret that excitation of examined volcanic tremor reflects small shear fractures induced by sudden hydrothermal fluid injection to the cap-rock layer. The horizontal distance of 1 km between inferred tremor sources and Motoshirane implies lateral migration of the hydrothermal fluid, although direct evidence is not available. Kusatsu-Shirane has exhibited unrest at the Yugama lake since 2014. However, the inferred tremor source locations do not overlap active seismicity beneath Yugama. Therefore, our result suggests that the 2018 eruption was triggered by hydrothermal fluid injection through a different pathway from that has driven unrest activities at Yugama.

Keywords: Kusatsu-shirane, Phreatic eruptions, Volcanic tremor, Hydrothermal system



Graphical abstract

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FULL PAPER **Open Access**

Volcanic unrest at Hakone volcano after the 2015 phreatic eruption: reactivation of a ruptured hydrothermal system?

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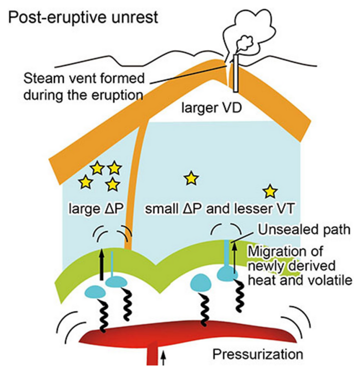
Earth, Planets and Space 2021, **73**:80 DOI: 10.1186/s40623-021-01387-3
Received: 28 September 2020, Accepted: 22 February 2021, Published: 26 March 2021

Abstract

Since the beginning of the twenty-first century, volcanic unrest has occurred every 2–5 years at Hakone volcano. After the 2015 eruption, unrest activity changed significantly in terms of seismicity and geochemistry. Like the pre- and co-eruptive unrest, each post-eruptive unrest episode was detected by deep inflation below the volcano (~10 km) and deep low frequency events, which can be interpreted as reflecting supply of magma or magmatic fluid from depth. The seismic activity during the post-eruptive unrest episodes also increased; however, seismic activity beneath the eruption center during the unrest episodes was significantly lower, especially in the shallow region (~2 km), while sporadic seismic swarms were observed beneath the caldera rim, ~3 km away from the center. This observation and a recent InSAR analysis imply that the hydrothermal system of the volcano could be composed of multiple sub-systems, each of which can host earthquake swarms and show independent volume changes. The 2015 eruption established routes for steam from the hydrothermal sub-system beneath the eruption center (≥150 m deep) to the surface through the cap-rock, allowing emission of super-heated steam (~160 ºC). This steam showed an increase in magmatic/hydrothermal gas ratios (SO_2/H_2S and HCl/H_2S) in the 2019 unrest episode; however, no magma supply was indicated by seismic and geodetic observations. Net SO_2 emission during the post-eruptive unrest episodes, which remained within the usual range of the post-eruptive period, is also inconsistent with shallow intrusion. We consider that the post-eruptive unrest episodes were also triggered by newly derived magma or magmatic fluid from depth; however, the breached cap-rock was unable to allow subsequent pressurization and intensive seismic activity within the hydrothermal sub-system beneath the eruption center. The heat released from the newly derived magma or fluid dried the vapor-dominated portion of the hydrothermal system and inhibited scrubbing of SO_2 and HCl to allow a higher magmatic/hydrothermal gas ratio. The 2015 eruption could have also breached the sealing zone near the brittle–ductile transition and the subsequent self-sealing process seems not to have completed based on the observations during the post-eruptive unrest episodes.

Keywords: Hakone volcano, Phreatic eruption, Hydrothermal system, Sealing zone, Cap-rock, Volcanic unrest, Scrubbing of magmatic gas



Graphical abstract

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FULL PAPER Open Access

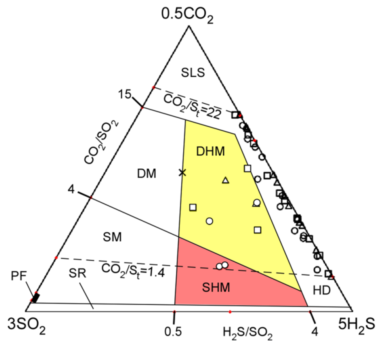
Behavior of magmatic components in fumarolic gases related to the 2018 phreatic eruption at Ebinokogen Ioyama volcano, Kirishima Volcanic Group, Kyushu, Japan

Takeshi Ohba*, Muga Yaguchi, Urumu Tsunogai, Masanori Ito and Ryo Shingubara

Earth, Planets and Space 2021, **73**:81 DOI: 10.1186/s40623-021-01405-4
Received: 12 January 2021, Accepted: 24 March 2021, Published: 31 March 2021

Abstract

Direct sampling and analysis of fumarolic gas was conducted at Ebinokogen Ioyama volcano, Japan, between December 2015 and July 2020. Notable changes in the chemical composition of gases related to volcanic activity included a sharp increase in SO_2 and H_2 concentrations in May 2017 and March 2018. The analyses in March 2018 immediately preceded the April 2018 eruption at Ioyama volcano. The isotopic ratios of H_2O in fumarolic gas revealed the process of formation. Up to 49% high-enthalpy magmatic vapor mixed with 51% of cold local meteoric water to generate coexisting vapor and liquid phases at 100–160 °C. Portions of the vapor and liquid phases were discharged as fumarolic gases and hot spring water, respectively. The CO_2/SO_2 ratio of the fumarolic gas was higher than that estimated for magmatic vapor due to SO_2 hydrolysis during the formation of the vapor phase. When the flux of the magmatic vapor was high, effects of hydrolysis were small resulting in low CO_2/SO_2 ratios in fumarolic gases. The high apparent equilibrium temperature defined for reactions involving SO_2, H_2S, H_2 and H_2O, together with low CO_2/SO_2 and H_2S /SO_2 ratios were regarded to be precursor signals to the phreatic eruption at Ioyama volcano. The apparent equilibrium temperature increased rapidly in May 2017 and March 2018 suggesting an increased flux of magmatic vapor. Between September 2017 and January 2018, the apparent equilibrium temperature was low suggesting the suppression of magmatic vapor flux. During this period, magmatic eruptions took place at Shinmoedake volcano 5 km away from Ioyama volcano. We conclude that magma sealing and transport to Shinmoedake volcano occurred simultaneously in the magma chamber beneath Ioyama volcano.



Graphical abstract

Keywords: Phreatic eruption, Volcanic gas, Fumarole, Hydrothermal reservoir, Magmatic vapor

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FULL PAPER Open Access

Response of a hydrothermal system to escalating phreatic unrest: the case of Turrialba and Irazú in Costa Rica (2007–2012)

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Earth, Planets and Space 2021, **73**:142 DOI: 10.1186/s40623-021-01471-8
Received: 30 December 2020, Accepted: 24 June 2021, Published: 12 July 2021

Abstract

This study presents the first hydrogeochemical model of the hydrothermal systems of Turrialba and Irazú volcanoes in central Costa Rica, manifested as thermal springs, summit crater lakes, and fumarolic degassing at both volcanoes. Our period of observations (2007–2012) coincides with the pre- and early syn-phreatic eruption stages of Turrialba volcano that resumed volcanic unrest since 2004, after almost 140 years of quiescence. Peculiarly, the generally stable Irazú crater lake dropped its level during this reawakening of Turrialba. The isotopic composition of all the discharged fluids reveals their Caribbean meteoric origin. Four groups of thermal springs drain the northern flanks of Turrialba and Irazú volcanoes into two main rivers. Río Sucio (i.e. "dirty river") is a major rock remover on the North flank of Irazú, mainly fed by the San Cayetano spring group. Instead, one group of thermal springs discharges towards the south of Irazú. All thermal spring waters are of SO_4-type (i.e. steam-heated waters), none of the springs has, however, a common hydrothermal end-member. A water mass budget for thermal springs results in an estimated total output flux of 187 ± 37 L/s, with 100 ± 20 L/s accounted for by the San Cayetano springs. Thermal energy release is estimated at 110 ± 22 MW (83.9 ± 16.8 MW by San Cayetano), whereas the total rock mass removal rate by chemical leaching is ~3000 m^3/year (~2400 m^3/year by San Cayetano-Río Sucio). Despite Irazú being the currently less active volcano, it is a highly efficient rock remover, which, on the long term can have effects on the stability of the volcanic edifice with potentially hazardous consequences (e.g. flank collapse, landslides, phreatic eruptions). Moreover, the vapor output flux from the Turrialba fumaroles after the onset of phreatic eruptions on 5 January 2010 showed an increase of at least ~260 L/s above pre-eruptive background fumarolic vapor fluxes. This extra vapor loss implies that the drying of the summit hydrothermal system of Turrialba could tap deeper than previously thought, and could explain the coincidental disappearance of Irazú's crater lake in April 2010.

Fig. 4

Keywords: Irazú and Turrialba volcanoes, Phreatic eruptions, Thermal springs, Fluid geochemistry, Crater lake disappearance, Water budget analysis, Hazard assessment

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FULL PAPER **Open Access**

Magma reservoir beneath Azumayama Volcano, NE Japan, as inferred from a three-dimensional electrical resistivity model explored by means of magnetotelluric method

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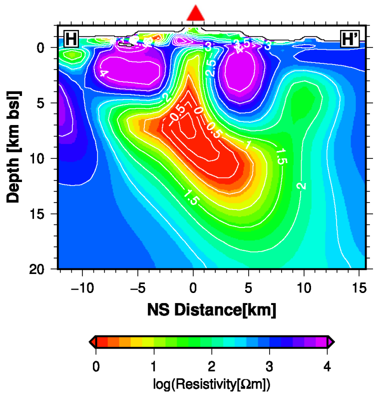
Received: 29 December 2020, Accepted: 5 June 2021, Published: 27 July 2021

Abstract

An electrical resistivity model beneath Azumayama Volcano, NE Japan, is explored using magnetotelluric method to probe the magma/hydrothermal fluid distribution. Azumayama is one of the most concerning active volcanoes capable of producing a potential eruption triggered by the 2011 Tohoku-Oki Earthquake. The three-dimensional resistivity model reveals a conductive magma reservoir (< 3 Ωm) at depths of 3–15 km below sea level (bsl). The 67% and 90% confidence intervals of resistivity are 0.2–5 Ωm and 0.02–70 Ωm, respectively, for the magma reservoir. We assumed dacitic melt + rock at a shallow depth of 4 km bsl and andesitic melt + rock at a greater depth of 9 km bsl. The confidence interval of resistivity cannot be explained by using dacitic melt + rock condition at a depth of 4 km bsl. This suggests that very conductive hydrothermal fluids coexist with dacitic melt and rock in the shallow part of the magma reservoir. For the depth of 9 km bsl, the 67% confidence interval of resistivity is interpreted as water-saturated (8.0 weight %) andesitic melt–mafic rock complex with melt volume fractions greater than 4 volume %, while the shear wave velocity requires the fluid and/or melt volume fraction of 6–7 volume % at that depth. Considering the fluid and/or melt volume fraction of 6–7 volume %, the conductive hydrous phase is likewise required to explain the wide range of the 67% confidence interval of resistivity. The Mogi inflation source determined from geodetic data lies on the resistive side near the top boundary of the conductive magma reservoir at a depth of 2.7 or 3.7 km bsl. Assuming that the resistivity of the inflation source region is above the upper bound of the confidence interval of resistivity for the conductive magma reservoir and that the source region is composed of hydrothermal fluid + rock, the resistivity of the source region is explained by a hydrothermal fluid volume fraction below 5 volume %, which is the percolation threshold porosity in an effusive eruption. This indicates that the percolation threshold characterizes the inflation source region.



Graphical abstract

Keywords: Magnetotellurics, Electrical resistivity, Shear wave velocity, Magma reservoir, Melt fraction, Permeability, Percolation threshold, Hydrothermal fluid, Mogi inflation source

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FULL PAPER **Open Access**

The 2018 phreatic eruption at Mt. Motoshirane of Kusatsu–Shirane volcano, Japan: eruption and intrusion of hydrothermal fluid observed by a borehole tiltmeter network

Akihiko Terada*, Wataru Kanda, Yasuo Ogawa, Taishi Yamada, Mare Yamamoto, Takahiro Ohkura, Hiroshi Aoyama, Tomoki Tsutsui and Shin'ya Onizawa

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Abstract

We estimate the mass and energy budgets for the 2018 phreatic eruption of Mt. Motoshirane on Kusatsu–Shirane volcano, Japan, based on data obtained from a network of eight tiltmeters and weather radar echoes. The tilt records can be explained by a subvertical crack model. Small craters that were formed by previous eruptions are aligned WNW–ESE, which is consistent with the strike of the crack modeled in this study. The direction of maximum compressive stress in this region is horizontal and oriented WNW–ESE, allowing fluid to intrude from depth through a crack with this orientation. Based on the crack model, hypocenter distribution, and MT resistivity structure, we infer that fluid from a hydrothermal reservoir at a depth of 2 km below Kusatsu–Shirane volcano has repeatedly ascended through a pre-existing subvertical crack. The inflation and deflation volumes during the 2018 eruption are estimated to have been 5.1×10^5 and 3.6×10^5 m^3, respectively, meaning that 1.5×10^5 m^3 of expanded volume formed underground. The total heat associated with the expanded volume is estimated to have been $\geq 10^{14}$ J, similar to or exceeding the annual heat released from Yugama Crater Lake of Mt. Shirane and that from the largest eruption during the past 130 year. Although the ejecta mass of the 2018 phreatic eruption was small, the eruption at Mt. Motoshirane was not negligible in terms of the energy budget of Kusatsu–Shirane volcano. A water mass of 0.1–2.0 × 10^7 kg was discharged as a volcanic cloud, based on weather radar echoes, which is smaller than the mass associated with the deflation. We suggest that underground water acted as a buffer against the sudden intrusion of hydrothermal fluids, absorbing some of the fluid that ascended through the crack.

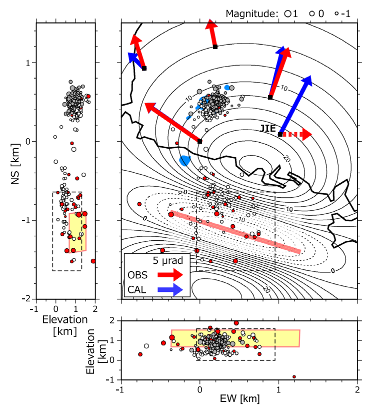

Fig. 5

Keywords: Phreatic eruption, Tiltmeter, Kusatsu–Shirane volcano, Hydrothermal system, Tensile crack, Brittle–ductile transition zone

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FULL PAPER **Open Access**

Modeling long-term volcanic deformation at Kusatsu-Shirane and Asama volcanoes, Japan, using the GNSS coordinate time series

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Earth, Planets and Space 2021, **73**:192 DOI: 10.1186/s40623-021-01512-2
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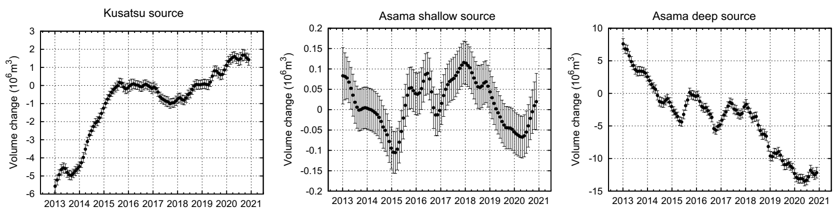
Abstract

Long-term deformation of Kusatsu-Shirane and Asama volcanoes in central Japan were investigated using Global Navigation Satellite System (GNSS) measurements. Large postseismic deformation caused by the 2011 Tohoku earthquake—which obscures the long-term volcanic deformation—was effectively removed by approximating the postseismic and other recent tectonic deformation in terms of quadrature of the geographical eastings/northings. Subsequently, deformation source parameters were estimated by the Markov Chain Monte Carlo (MCMC) method and linear inversion, employing an analytical model that calculates the deformation from an arbitrary oriented prolate/oblate spheroid. The deformation source of Kusatsu-Shirane volcano was found to be a sill-like oblate spheroid located a few kilometers northwest of the Yugama crater at a depth of approximately 4 km, while that of Asama was also estimated to be a sill-like oblate spheroid beneath the western flank of the edifice at a depth of approximately 12 km, along with the previously reported shallow east–west striking dike at a depth of approximately 1 km. It was revealed that (1) volume changes of the Kusatsu-Shirane deformation source and the shallow deformation source of Asama were correlated with the volcanic activities of the corresponding volcanoes, and (2) the Asama deep source has been steadily losing volume, which may indicate that the volcano will experience fewer eruptions in the near future.

Keywords: Kusatsu-Shirane volcano, Asama volcano, Global Navigation Satellite System, Crustal deformation, Oblate spheroid



Graphical abstract

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FULL PAPER **Open Access**

Crisis hazard assessment for snow-related lahars from an unforeseen new vent eruption: the 2018 eruption of Kusatsu-Shirane volcano, Japan

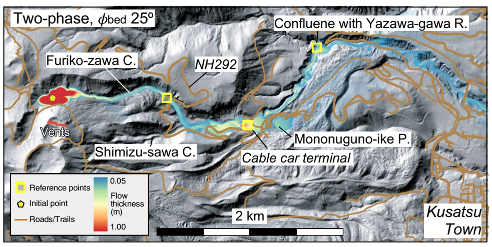
Kyoko S. Kataoka*, Kae Tsunematsu, Takane Matsumoto, Atsushi Urabe and Katsuhisa Kawashima

Earth, Planets and Space 2021, **73**:220 DOI: 10.1186/s40623-021-01522-0
Received: 17 June 2021, Accepted: 18 September 2021, Published: 11 December 2021

Abstract

Two-thirds of the 111 active volcanoes in Japan are covered with snow for several months during winter and demonstrate high hazard and risk potentials associated with snow-related lahars during and after eruptions. On 23 January 2018, a sudden phreatic eruption occurred at the ski field on Kusatsu-Shirane (Mt. Motoshirane) volcano, Japan. This new vent eruption from the snow-clad pyroclastic cone required forecasting of future snow-related lahars and crisis hazards zonation of downslope areas including Kusatsu town, a popular tourist site for skiing and hot springs. In order to achieve a prompt hazard assessment for snow-related lahars, a multidisciplinary approach was carried out involving characterization of proximal tephra deposits, snow surveys, and numerical lahar flow simulations using the Titan2D model. To determine the input parameters for the flow model, the consideration of snow water equivalent (SWE) immediately after the eruption (on 29 January) and in the post-eruptive period (on 12 March), was significant. In the case of Kusatsu-Shirane volcano during the winter of 2018, linear relationships between altitude and SWE, obtained at different elevations, were used to estimate the snow volume around the new vents. Several scenarios incorporating snow and snowmelt (water), with or without the occurrence of a new eruption, were simulated for the prediction of future lahars. Three lahar scenarios were simulated, including A) rain-on-snow triggered, B) ice/snow slurry, and C) full snowmelt triggered by a new eruption, and indicated the flow paths (inundation areas) and travel distances. These were useful for lahar hazard zonation and identification of potential high-risk areas. Since the input parameters required for the Titan2D flow model can be relatively easily determined, the model was suitable for the 2018 eruption at Motoshirane where historical and geological lahar records are not available for calibration. The procedure used in the study will enable rapid lahar prediction and hazard zonation at snow-clad volcanoes. Further consideration for simulating a cohesive-type flow, which was predicted by the primary deposits containing large amounts of clay minerals and could not be expressed in the Titan2D flow model, is necessary.

Keywords: Lahar, Flow simulation, Titan2D, Snow-clad volcano, Snow survey, Crisis hazard map, Kusatsu-Shirane volcano



Graphical abstract

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EXPRESS LETTER **Open Access**

Coeruptive and posteruptive crustal deformation associated with the 2018 Kusatsu-Shirane phreatic eruption based on PALSAR-2 time series analysis

Yuji Himematsu*, Taku Ozawa and Yosuke Aoki

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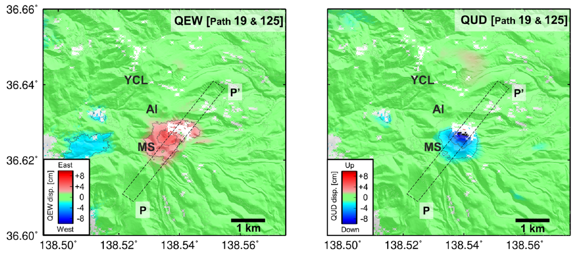
Received: 20 May 2020, Accepted: 1 August 2020, Published: 10 August 2020

Abstract

Coeruptive deformation helps to interpret physical processes associated with volcanic eruptions. Because phreatic eruptions cause small, localized coeruptive deformation, we sometimes fail to identify plausible deformation signals. Satellite synthetic aperture radar (SAR) data allow us to identify extensive deformation fields with high spatial resolutions. Herein, we report coeruptive crustal deformation associated with the 2018 Kusatsu-Shirane phreatic eruption detected by time series analyses of L-band satellite SAR (ALOS-2/PALSAR-2) data. Cumulative deformation maps derived from SAR time series analyses show that subsidence and eastward displacement dominate the southwestern side of an eruptive crater with a spatial extent of approximately 2 km in diameter. Although we were unable to identify any significant deformation signals before the 2018 eruption, posteruptive deformation on the southwestern side of the crater has been ongoing until the end of 2019. This prolonged deformation implies the progression of posteruptive physical processes within a confined hydrothermal system, such as volcanic fluid discharge, similar to the processes observed during the 2014 Ontake eruption. Although accumulated snow and dense vegetation hinder the detection of deformation signals on Kusatsu-Shirane volcano using conventional InSAR data, L-band SAR with various temporal baselines allowed us to successfully extract both coeruptive and posteruptive deformation signals. The extracted cumulative deformation is well explained by a combination of normal faulting with a left-lateral slip component along a southwest-dipping fault plane and an isotropic deflation. Based on the geological background in which the shallow hydrothermal system develops across Kusatsu-Shirane volcano, the inferred dislocation plane can be considered as a degassing pathway from the shallow hydrothermal system to the surface due to the phreatic eruption. We reconfirmed that SAR data are a robust tool for detecting coeruptive and posteruptive deformations, which are helpful for understanding shallow physical processes associated with phreatic eruptions at active volcanoes.

Keywords: Satellite SAR, Phreatic eruption, Hydrothermal system, Kusatsu-Shirane volcano, Crustal deformation, ALOS-2/PALSAR-2



Graphical abstract

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EXPRESS LETTER **Open Access**

On data reduction methods for volcanic tremor characterization: the 2012 eruption of Copahue volcano, Southern Andes

Ivan Melchor*, Javier Almendros, Roberto Carniel, Kostas I. Konstantinou, Marcia Hantusch and Alberto Caselli

Earth, Planets and Space 2020, **72**:134 DOI: 10.1186/s40623-020-01270-7
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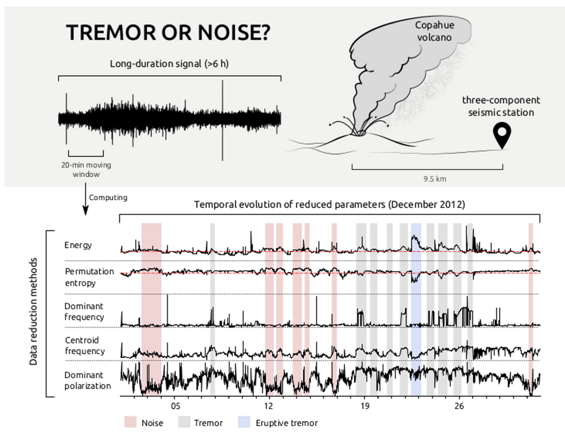
Abstract

Improving the ability to detect and characterize long-duration volcanic tremor is crucial to understand the long-term dynamics and unrest of volcanic systems. We have applied data reduction methods (permutation entropy and polarization degree, among others) to characterize the seismic wave field near Copahue volcano (Southern Andes) between June 2012 and January 2013, when phreatomagmatic episodes occurred. During the selected period, a total of 52 long-duration events with energy above the background occurred. Among them, 32 were classified as volcanic tremors and the remaining as noise bursts. Characterizing each event by averaging its reduced parameters, allowed us to study the range of variability of the different events types. We found that, compared to noise burst, tremors have lower permutation entropies and higher dominant polarization degrees. This characterization is a suitable tool for detecting long-duration volcanic tremors in the ambient seismic wave field, even if the SNR is low.

Keywords: Volcanic tremor, Phreatic eruption, Data reduction method, Polarization degree, Permutation entropy, Copahue volcano



Graphical abstract

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EXPRESS LETTER Open Access

Anatomy of active volcanic edifice at the Kusatsu–Shirane volcano, Japan, by magnetotellurics: hydrothermal implications for volcanic unrests

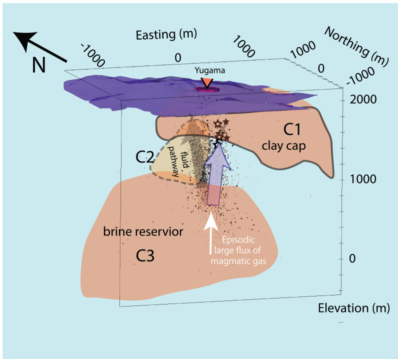
Kuo Hsuan Tseng, Yasuo Ogawa*, Nurhasan, Sabri Bülent Tank, Naoto Ujihara, Yoshimori Honkura, Akihiko Terada, Yoshiya Usui and Wataru Kanda

Earth, Planets and Space 2020, **72**:161 DOI: 10.1186/s40623-020-01283-2
Received: 15 February 2020, Accepted: 28 September 2020, Published: 23 October 2020

Abstract

We aimed to perform three-dimensional imaging of the underlying geothermal system to a depth of 2 km using magnetotellurics (MT) at around the Yugama crater, the Kusatsu–Shirane Volcano, Japan, which is known to have frequent phreatic eruptions. We deployed 91 MT sites focusing around the peak area of 2 km × 2 km with typical spacings of 200 m. The full tensor impedances and the magnetic transfer functions were inverted, using an unstructured tetrahedral finite element code to include the topographic effect. The final model showed (1) low-permeability bell-shaped clay cap (C1) as the near-surface conductor, (2) brine reservoir as a deep conductor (C3) at a depth of 1.5 km from the surface, and (3) a vertical conductor (C2) connecting the deep conductor to the clay cap which implies an established fluid path. The columnar high-seismicity distribution to the east of the C2 conductor implies that the flushed vapor and magmatic gas was released from the brine reservoir by breaking the silica cap at the brittle–ductile transition. The past magnetization/demagnetization sources and the inflation source of the 2014 unrest are located just below the clay cap, consistent with the clay capped geothermal model underlain by brine reservoir. The resistivity model showed the architecture of the magmatic–hydrothermal system, which can explain the episodic volcanic unrest.

Keywords: Phreatic eruption, Magnetotelluric method, Clay cap, Brine, Unrest



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EXPRESS LETTER Open Access

Reconstructing surface eruptive sequence of 2018 small phreatic eruption of Iwo-yama volcano, Kirishima Volcanic Complex, Japan, by infrasound cross-correlation analysis

Dan Muramatsu*, Takeshi Matsushima and Mie Ichihara

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Abstract

The Iwo-yama volcano of the Kirishima Volcanic Complex in Japan had a small phreatic eruption in April 2018, which newly formed multiple vents. The activity was recorded by two infrasound sensors and two monitoring cameras, which had been installed within 1 km of the vents. This study identified infrasonic signals from the multiple vents by a cross-correlation analysis between the two infrasound sensors. The analysis successfully revealed the signals from two main eruption craters and constrained the infrasound onsets at the individual vents in the two craters. We combined the infrasound results with the images from the cameras and reconstructed the sequence of the small phreatic eruption of Iwo-yama. At each of the two craters, the intense eruption, which was depicted by the evident infrasound signals, occurred several hours after the eruption onset. This study provides a sequence of the activities of the multiple vents in a phreatic eruption, which will be useful for understanding the phreatic eruption and hazard assessments.

Keywords: Volcano infrasound, Phreatic eruption, Multiple-vent activities, Cross-correlation analysis, Iwo-yama volcano, Monitoring

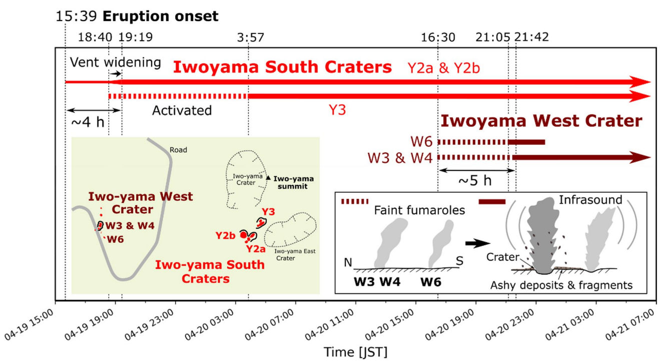

Fig. 5

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EXPRESS LETTER **Open Access**

Kusatsu-Shirane volcano eruption on January 23, 2018, observed using JMA operational weather radars

Eiichi Sato

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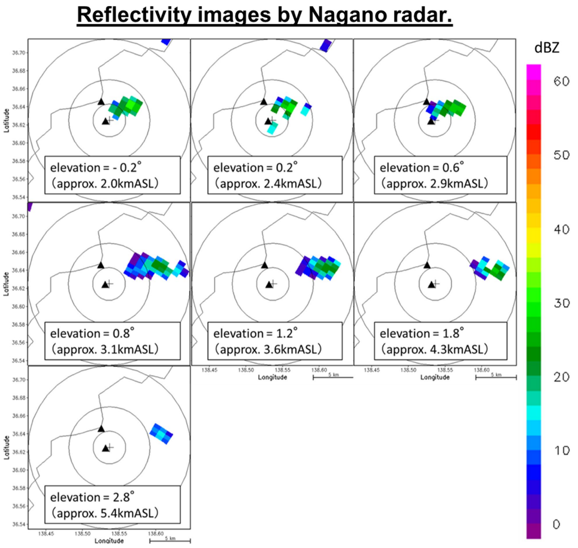
Abstract

A phreatic eruption suddenly occurred at Motoshirane (Kusatsu-Shirane volcano, Japan) at 10:02 JST on January 23, 2018. A member of the Japan Self-Defense Force was killed by volcanic blocks during training in Motoshirane, and 11 people were injured by volcanic blocks or fragments of broken glass. According to a field survey, ash fall was confirmed in Minakami, about 40 km east-northeast from Motoshirane. Although the eruption was not captured by a distant camera, the eruption plume/cloud was captured by three of the Japan Meteorological Agency's operational weather radars. These radars observed the echo propagated to the northeast in the lower troposphere, and to the east in the middle troposphere. This is generally consistent with the observed ash fall distribution. Using the modified probabilistic estimation method, the maximum plume height was estimated to be about 5580 ± 506 m (1σ) above sea level. Estimates of the erupted mass based on the range of plume heights from radar observations and the duration of volcanic tremor during the eruption (about 8 min) do not match that obtained from a field survey (3.0–5.0 × 10^7 kg). This discrepancy confirms that estimates of erupted mass based on plume heights must account for eruption style parametrically, which can only be constrained by case studies of varied eruption styles.

Keywords: Weather radar, Remote sensing, Volcanic plume, Eruption cloud, Kusatsu-shirane volcano



Graphical abstract

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EXPRESS LETTER **Open Access**

Aeromagnetic survey in Kusatsu-Shirane volcano, central Japan, by using an unmanned helicopter

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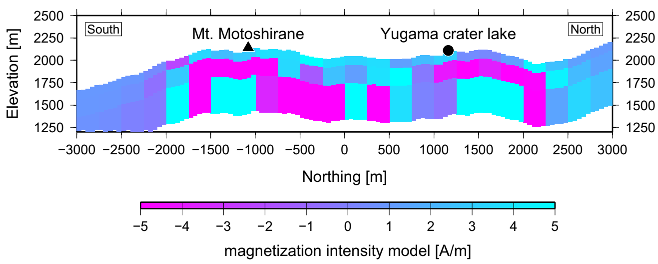
Abstract

Kusatsu-Shirane volcano is one of the active volcanoes in Japan. Phreatic explosions occurred in Mt. Shirane in 1983 and most recently, in 2018, in Mt. Motoshirane. Information on the subsurface structure is crucial for understanding the activity of volcanoes with well-developed hydrothermal systems where phreatic eruptions occur. Here, we report aeromagnetic surveys conducted at low altitudes using an unmanned helicopter. The survey aimed to obtain magnetic data at a high spatial resolution to map the magnetic anomaly and infer the magnetization intensity distribution in the region immediately after the 2018 Mt. Motoshirane eruption. The helicopter used in the survey was YAMAHA FAZER R G2, an autonomously driven model which can fly along a precisely programmed course. The flight height above the ground and a measurement line spacing were set to ~ 150 m and ~ 100 m, respectively, and the total flight distance was 191 km. The measured geomagnetic total intensity was found to vary by ~ 1000 nT peak-to-peak. The estimated magnetization intensity derived from measured data showed a 100 m thick magnetized surface layer with normal polarity, composed of volcanic deposits of recent activities. Underneath, a reverse-polarity magnetization was found, probably corresponding to the Takai lava flow in the Early Quaternary period (~ 1 Ma) mapped in the region. Our results demonstrate the cost-effectiveness and accuracy of using drone magnetometers for mapping the rugged terrain of volcanoes.

Keywords: Kusatsu-Shirane volcano, Aeromagnetic survey, Unmanned helicopter



Graphical abstract

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Earth, Planets and Space

EXPRESS LETTER Open Access

Total mass estimate of the January 23, 2018, phreatic eruption of Kusatsu-Shirane Volcano, central Japan

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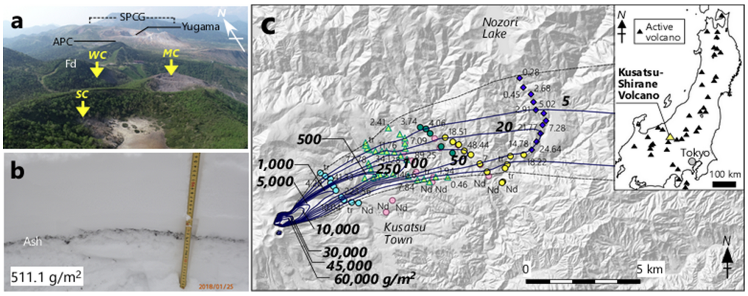
Abstract

On January 23, 2018, a small phreatic eruption (VEI = 1) occurred at the Motoshirane Pyroclastic Cone Group in the southern part of Kusatsu-Shirane Volcano in central Japan. The eruption ejected ash, lapillus, and volcanic blocks from three newly opened craters: the main crater (MC), west crater (WC), and south crater (SC). Volcanic blocks were deposited up to 0.5 km from each crater. In contrast, the ash released during this eruption fell up to 25 km ENE of the volcano. The total mass of the fall deposit generated by the eruption was estimated using two methods, yielding total masses of 3.4×10^4 t (segment integration method) and 2.4×10^4 t (Weibull fitting method). The calculations indicate that approximately 70% of the fall deposit was located within 0.5 km of the craters, which was mainly attributed to the low height of the eruption plume.

Keywords: Kusatsu-Shirane Volcano, Phreatic eruption, Fall deposit, Isomass contour map, Mass estimate



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