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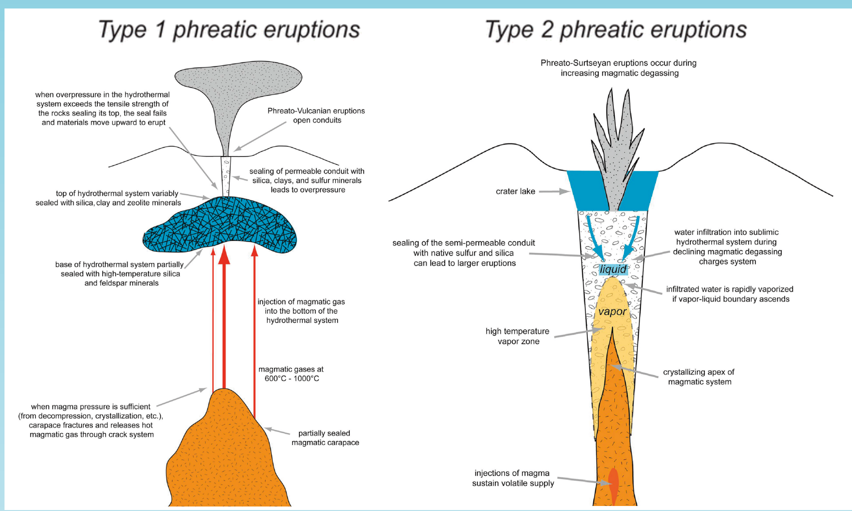
Towards forecasting phreatic eruptions: Examples from Hakone volcano and some global equivalents



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PREFACE

Open Access

Special issue "Towards forecasting phreatic eruptions: Examples from Hakone volcano and some global equivalents"

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Introduction

Volcanic eruptions are among the most spectacular natural phenomena on Earth and incandescent magmatic eruptions in particular have fascinated humans throughout history. Among the wide variety of volcanic eruptions, phreatic eruptions, which are non-magmatic and typically small in size, have received far less attention from researchers, and the number of research papers on phreatic eruptions has been far lower than those on magmatic eruptions. This does not mean phreatic eruption is a rare phenomenon—in fact, phreatic eruptions are common and may in fact outnumber magmatic eruptions.

A recent extensive review counted 116 phreatic eruptions of 36 volcanoes during the period from 1900 to 2015 (approximately one per year on average) in Japan, which has very detailed records of volcanic eruptions (Oikawa et al. 2018). However, few of these eruptions had interested volcanologists probably because limited ash dispersal and geophysical observations did not allow detailed analysis. The tragic eruption at Mt. Ontake in 2014, which killed 63 hikers, and the eruption (from an unexpected eruption center) at Mt. Kusatsu-Shirane in 2018, which killed a self-defense force personnel at drill seemed to change the mindsets of the volcanologists in Japan. Although detailed analysis of the 2018 eruption of Mt. Kusatsu-Shirane (Ogawa et al. 2018) is still ongoing, a special issue for the 2014 eruption of Mt. Ontake was organized in this journal, and compiled observations and models of preparatory process of this unexpected eruption, which resulted largest number of victims after World War II (Yamaoka et al. 2016).

The phreatic eruption of Hakone volcano, Japan, in 2015 was accompanied by a variety of intense precursors and mitigation measures, which included establishment of a no-entry zone by the municipal office and raising of the Volcano Alert Level by Japan Meteorological Agency. In contrast to Kusatsu-Shirane and Ontake, Hakone volcano is an 'urbanized' volcano, which enables researchers to access this potential eruption center frequently and to deploy geophysical instruments connected to electric and communication grids. The 2015 eruption of Hakone is thus an unprecedentedly well-monitored phreatic eruption. This special issue compiles a variety of papers that propose models of the hydro-magmatic system of Hakone and some global equivalents based on various observations.

Here, we review the contributions in the special issue with related papers published in other journals.

Content of the special issue

Modeling of phreatic eruptions

A phreatic eruption is an eruption without any eruption of juvenile magma. However, recent studies imply that subsurface injection of magma or magmatic fluid can trigger volcanic unrest and subsequent phreatic eruptions (e.g., Yamaoka et al. 2016). In this special issue, two contributions modeled the sequence from an event of magma or magmatic fluid injection at depth to a phreatic eruption through various precursory phenomena.

Stix and de Moor (2018) compiled recent studies of phreatic eruptions and proposed two endmembers for phreatic systems. Type 1 systems are characterized by a sealed hydrothermal system. Injection of magmatic fluids

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causes pressurization of the hydrothermal system and eventual rupture of the seal, generating ballistics, and fine ash. For a Type 2 system, input of magmatic fluids into a near-surface hydrothermal system vaporizes liquid water, promoting eruptions which emit wet ash, lahars, and/or ballistics. Since injection of magmatic fluids and rupture of hydrothermal seals are potentially seismogenic processes, they suggest that monitoring of broadband seismicity and gas ratios is useful approaches to forecasting phreatic eruptions.

Mannen et al. (2018) compiled geological and geophysical observations during the 2015 phreatic eruption of Hakone Volcano and its precursory unrest, and proposed that magma replenishment of a 10-km-deep magma chamber and subsequent pressurization of the hydrothermal system caused the volcanic unrest. The seismic activity reached its climax more than a month before the eruption; however, a pressure increase in the hydrothermal system continued even after the eruption. Since the eruption was caused by sudden formation of an open crack filled with hydrothermal fluid, short-term forecasting of a phreatic eruption was challenging.

Cap rock and sealing zone

A phreatic eruption is a phenomenon that releases hydrothermal fluids confined beneath a volcano. Such a confinement is seemingly attained by geological structures such as cap rock or sealing zone. To understand phreatic eruptions, the characterization of the properties of these structures, including their location, depth, and function in the context of the magma-hydrothermal system of the volcano is necessary. In the special issue, three contributions focused on investigations of cap rock and sealing zones (Ueda et al. 2018; Yoshimura et al. 2018; Ohba et al. 2019).

Yoshimura et al. (2018) conducted an audio-frequency magnetotelluric (AMT) survey at 39 sites, covering the whole of Hakone caldera before the eruption, and established a three-dimensional model of the resistivity structure of the volcano. The survey found a significant (< 10 Ωm) bell-shaped conductor beneath the center of the volcano. The apex of the bell-shaped conductor locates near the center of the volcano beneath the 2015 eruption vent. Beneath the conductor is a seismic zone which had been active during the previous periods of volcanic unrest. Since the previous study proposed that the seismic activity of the volcano had been triggered by pressure rise or fluid migration (Yukutake et al. 2011), the bell-shaped conductor is interpreted as the cap rock that confines a hydrothermal system.

Ohba et al. (2019) compiled long-term gas observations and developed a hydrothermal model of Hakone volcano in which a sealing zone just above the magma chamber controls volcanic unrest. In the model, the sealing zone has some permeability during background periods; however, a few months before the onset of volcanic unrest, changes in permeability of the zone began to restrict gas migration from the magma chamber to the hydrothermal system. The restriction allowed infiltration of atmospheric gases such as Ar and N_2 into the hydrothermal system. The increase in seismicity during volcanic unrest was triggered by breakage of the sealing zone, resulting in a transfer of confined pressure beneath the sealing zone into the hydrothermal system as indicated by the observed increase of CO_2/H_2O ratios.

Ueda et al. (2018) compiled geophysical and geological observations of a volcanic island named Ioto, which is also known as Iwo-jima for the fierce battle between Japan and the United States during World War II. At this volcano, phreatic eruptions with seismic precursors occur during intermittent uplift. This type of phreatic eruption is interpreted as a result of boiling of the hydrothermal reservoirs triggered by deep magma intrusion. The hydrothermal fluid reaches the surface through fault systems developed near the margin of hydrothermal reservoirs and these types of eruptions form craters along the fault zone. In contrast, phreatic eruptions at Ioto that occur without any precursors are small and similar to geyser eruptions.

Geological study

Phreatic eruptions are the smallest type of volcanic eruption in terms of erupted volume. Since the volume of erupted material is so small, the resulting deposits are washed out swiftly and it is very difficult to reconstruct an ancient phreatic eruption from study of the geologic record. Thus, detailed description and analysis of an eruption deposit soon after a phreatic eruption is critical to understand the eruption mechanism and to establish mitigation measures. For example, a detailed analysis of erupted material of the 2015 Hakone eruption implied the very shallow source of the explosion (Yaguchi et al. 2019). This special issue has four contributions documenting geological investigations immediately following phreatic eruptions (Geshi and Itoh 2018; Kataoka et al. 2018, 2019; Kilgour et al. 2019). In addition, Ikehata et al. (2019) is a rare but valuable contribution discussing the formation mechanism of sulfur deposits, which is a common but generally understudied volcanic deposit.

Kilgour et al. (2019) undertook a comprehensive surface investigation just after an eruption at White Island, New Zealand. They deployed drones to swiftly map the distribution of ballistic blocks. Based on the observed distribution and a simulation code named Ballista (Tsunematsu et al. 2014), they estimated the initial velocity of ballistics as 50–65 m/s, which is very low when compared to global equivalents. In addition, they revealed that topography around the eruption center significantly affects the distributions of surge deposits and ballistics.

Geshi and Itoh (2018) described a pyroclastic density current (PDC) formed during the 2015 phreatomagmatic eruption at Kuchinoerabu volcano in detail. The PDC was generated by partial collapse of an eruption column, which rose up to 9 km above sea level, and flowed along a valley to reach the coast of the island approximately 2.4 km away from the source crater. The estimated temperature of the PDC at Kuchinoerabu during this phreatic eruption was between 100 and 240–270 °C, which is less than that of typical magmatic PDC (> 300 °C). However, the PDC of Kuchinoerabu was still energetic and trees near the vent area were broken.

Kataoka et al. (2018) emphasizes that characteristics of post-eruptive lahars that occur after a single eruptive event can have significant differences depending on the trigger. After the 2014 Ontake eruption, two types of lahars occurred within 7 months: a rain-triggered type and a rain-on-snow type. The rain-triggered lahar, which took place during a rain storm 8 days after the eruption, deposited muddy and high-clay content sediment. In contrast, a rain-on-snow-type lahar, which is caused by heavy rain and snow melting, formed a fines-depleted sandy and gravelly deposit. Such a significant difference in post-eruptive lahars should be considered when implementing simulations and formulating mitigation plans.

Kataoka et al. (2019) monitored sediment transport by rivers running from the eruption center of the 2014 Ontake eruption and revealed that the influence of volcanic disturbance on the catchment continued for at least 10 months after the eruption and an additional 9 months until the end of the snowmelt season in 2016.

Simulation and analogue experiments

Simulations can examine the influence of a simple key mechanism on the subsequent complex behavior of the volcanic system. In this special issue, two contributions document simple-but-insightful simulation experiments (Noguchi et al. 2018; Tanaka et al. 2018).

Noguchi et al. (2018) focused on rootless eruptions caused by lava flows entering inland water or water-rich sediment. This type of eruption forms craters with significant explosion energy distal from the actual source vent; however, forecasting of these occurrences has remained difficult. Their unique analogue experiment using cooking ingredients such as syrup and baking powder shows a non-linear relationship between reaction efficiency and baking soda/poured heated syrup (= water/lava) proportion which may stem from a Rayleigh–Taylor instability occurring between lava and substrate water or sediment.

Tanaka et al. (2018) implemented a numerical simulation of a conduit system, through which hydrothermal fluid reaches the surface, and monitored crater temperature and pressure distribution of the edifice interior after changing the permeability of the conduit. The simulation showed how crater temperature can decrease before a phreatic eruption. They also showed the potential of their simulation to understand mechanisms of phreatic eruption with observations of crater temperature and ground deformation.

InSAR

InSAR (Interferometric Synthetic-Aperture Radar) presently plays a key role in volcano monitoring. During the 2015 Hakone eruption and unrest, InSAR data were critically important for planning mitigation measures (Mannen et al. 2018) and has to date resulted in three prominent literature contributions related to InSAR, two in this special issue (Doke et al. 2018; Kuraoka et al. 2018) and one in another journal (Kobayashi et al. 2018).

Doke et al. (2018) detected the open crack that was formed by the 2015 eruption by analysis of ground deformation observed by satellite InSAR. The eruption center was formed at the northern end of the open crack. Since old craters align on the ground surface just above the open crack, the 2015 eruption was interpreted as a reactivation of a pre-existing crack that was formed by earlier eruptions. The detailed analysis of Doke et al. (2018) detected a sill-like deflation source beneath the crack, which is considered the source of hydrothermal fluid that formed the open crack. The pre-eruptive pressurization of the hydrothermal system of the volcano was also detected as local uplift by the InSAR analysis.

Kuraoka et al. (2018) installed a ground-based InSAR (GBInSAR) 4 days before the 2015 eruption to monitor the local uplift observed by satellite InSAR. Fortunately, the 2015 eruption took place within the monitoring area and ground deformation associated with the eruption was recorded with high sampling rate (< 10 min). The 2015 eruption initiated crack intrusion at 7:32 and emission of highly pressurized fluid as inferred from infrasonic analysis (Yukutake et al. 2018). Curiously, the GBInSAR interferometry failed at the onset time and during the subsequent 46 min; however, ground deformation after the crack formation was still monitored in detail, and this successful observation implies significant potential of this technology for volcano monitoring and alerting.

Kobayashi et al. (2018) undertook a detailed analysis of InSAR and GNSS data and proposed two inflation sources: a deep spherical source at 4.5 km below sea level (BSL), interpreted as a potential magma chamber, and a shallow source (at approximately 150 m below the surface) which caused very local surface deformation detected by InSAR. Similar deformation sources are also deduced in papers in the special issue; however, the emphasis of Kobayashi et al. (2018) is on synchronization of the deformation rate changes of the two sources, which implies smooth fluid migration from deep to shallow. Kobayashi et al. (2018) also showed that subtle inflation of the two sources initiated in late 2014, long before the acceleration of inflation beginning in May 2015.

Signals emitted by phreatic eruption—location and source analysis

Phreatic eruptions emit various waveforms that are triggered by migration of hydrothermal fluid; thus, the location and depth of these signals are of primary importance for understanding the mechanism of the eruption. In addition, the interpretation and timing of seismic and acoustic events in the sequence of the eruption can help constrain eruption process. This special issue collected intriguing examples from White Island, Kawah Ijen, and Hakone (Yukutake et al. 2017, 2018; Caudron et al. 2018; Harada et al. 2018; Jolly et al. 2018; Walsh et al. 2019).

Walsh et al. (2019) located eruptive pulses emitted during a phreatic eruption that occurred at White Island on 27 April 2018 by a joint analysis combining acoustic and seismic data. The locations of the eruption vent were inferred using an amplitude source location method, and the depth of eruption pulses was inferred from volcanic acoustic–seismic ratios. After error analysis, the eruption sources are shown to conceivably come from a single vent with the eruption pulses gradually increasing in strength with time.

Jolly et al. (2018) focused on very-long-period (VLP) seismic events during the 2018 phreatic eruption of White Island volcano. The VLP was located through analysis of waveform semblance and the volumetric source of the largest VLP event was obtained by seismic waveform inversion. The pre-eruptive VLP seems to be linked to advection of gas from the VLP source location at the magmatic carapace, approximately 800 to 1000 m depth.

Caudron et al. (2018) carefully processed broadband seismic signals of VLP events from two similar volcanoes: Kawah Ijen (Indonesia) and White Island (New Zealand). The phreatic eruptions of both volcanoes initiated with a VLP seismic event at shallow levels beneath the crater region. The VLP events may be triggered by excitation of gas trapped behind a ductile magma carapace, followed by response of shallow hydrothermal system. Since signals emitted by these processes are long period and can be recorded only by broadband seismometers, the authors emphasize the importance of deploying broadband seismometers near active volcanic centers.

Yukutake et al. (2018) extracted infrasound signals emitted from the eruption center of the 2015 Hakone eruption from noisy (wind) data using the record of a co-located seismometer (Ichihara et al. 2012). Due to the poor visibility at the time of eruption, the exact timing of the eruption onset remains obscure and conventional geological observations only detected a lahar, which initiated in the late morning as the initial emission (Mannen et al. 2018). However, the extracted infrasound signal indicates an emission of highly pressurized fluid at 07:32 A.M. (JST), which is the timing of formation of the initial open crack that triggered the eruption (Honda et al. 2018).

Honda et al. (2018) observed a rapid tilt change at Hakone Volcano, which started 10 s before 07:33 A.M. (JST) and lasted for approximately 2 min. The tilt change, which occurred long before the initiation of ash dispersal at approximately 12:30 P.M. (JST), was observed not only by tiltmeters but also by broadband seismometers, which were temporarily deployed around the eruption center. The tilt change was considered to be caused by a crack intrusion, and analysis of the tilt record revealed the parameters of the crack, such as its location, depth, and opening. Since the opening of the crack is small (< 10 cm), it is highly unlikely that magma (as opposed to hydrothermal fluids) filled the crack.

Harada et al. (2018) monitored the rate of inflation of Hakone volcano using GNSS, beginning when precursory unrest started approximately 3 months before the 2015 eruption, and modeled the inflation sources. The deep source at 6.5 km BSL, which is interpreted as a magma chamber, first started inflating at the end of March, then the shallow open crack at approximately 800 m ASL started inflating in mid-May. Interestingly, both sources continued inflating even after the eruption on Jun. 29 and until early August. This observation implies that the phreatic eruption did not relieve the pressure in the hydrothermal system significantly.

Yukutake et al. (2017) estimated the source location of the continuous volcanic tremor observed during the 2015 Hakone eruption using a cross-correlation analysis of waveform envelopes. The source of the tremor is determined to be near the vent of the eruption. The amplitude of the tremor increased coincident with the occurrence of impulsive infrasonic waves and the largest amplitude was observed at the end of the eruption. The analysis suggests that both seismic and infrasonic waves were generated when a gas slug bursts at the surface of the vent.

Conclusion

This special issue is a collection of the latest studies on phreatic eruptions from various aspects. We expect that this timely special issue will help further advances in understanding of phreatic eruptions, towards the goal of forecasting their occurrence.

Abbreviations

GBInSAR: Ground-Based Interferometric Synthetic-Aperture Radar; GNSS: Global Navigation Satellite System; InSAR: Interferometric Synthetic-Aperture Radar; JST: Japan Standard Time; PDC: pyroclastic density current; VLP: very long period.

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The authors declare that they have no competing interests.

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Publisher's Note

FRONTIER LETTER Open Access

Understanding and forecasting phreatic eruptions driven by magmatic degassing

John Stix* and J. Maarten de Moor

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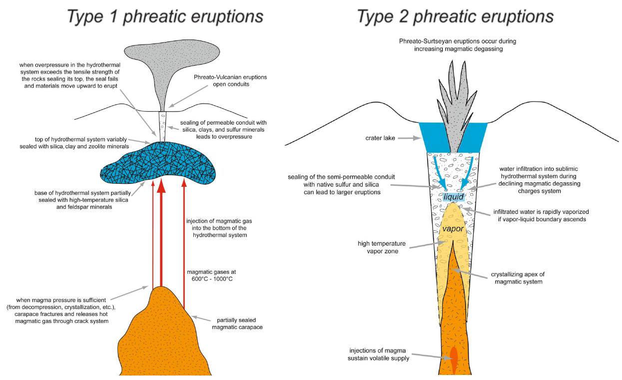
Abstract

This paper examines phreatic eruptions which are driven by inputs of magma and magmatic gas. We synthesize data from several significant phreatic systems, including two in Costa Rica (Turrialba and Poás) which are currently highly active and hazardous. We define two endmember types of phreatic eruptions, the first (type 1) in which a deeper hydrothermal system fed by magmatic gases is sealed and produces overpressure sufficient to drive explosive eruptions, and the second (type 2) where magmatic gases are supplied via open-vent degassing to a near-surface hydrothermal system, vaporizing liquid water which drives the phreatic eruptions. The surficial source of type 2 eruptions is characteristic, while the source depth of type 1 eruptions is commonly greater. Hence, type 1 eruptions tend to be more energetic than type 2 eruptions. The first type of eruption we term "phreato-vulcanian", and the second we term "phreato-surtseyan". Some systems (e.g., Ruapehu, Poás) can produce both type 1 and type 2 eruptions, and all systems can undergo sealing at various timescales. We examine a number of precursory signals which appear to be important in understanding and forecasting phreatic eruptions; these include very long period events, banded tremor, and gas ratios, in particular H_2S/SO_2 and CO_2/SO_2. We propose that if these datasets are carefully integrated during a monitoring program, it may be possible to accurately forecast phreatic eruptions.

Keywords: Phreatic eruptions, Magmatic inputs, Overpressure, Sealing, Vaporization, Forecasting



Graphical abstract

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Pyroclastic density currents associated with the 2015 phreatomagmatic eruption of the Kuchinoerabujima volcano

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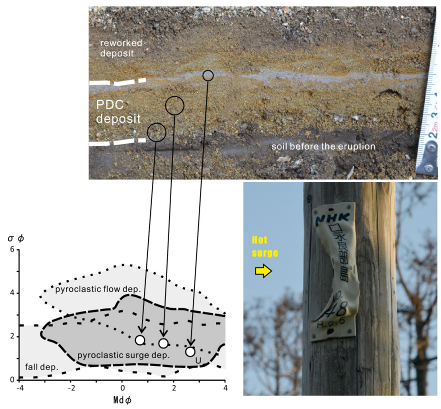
Abstract

A pyroclastic density current (PDC) was observed with the phreatomagmatic eruption of the Kuchinoerabujima volcano, southern Japan, on May 29, 2015. The PDC flowed down in all direction from the source crater, forming three major branches. The PDC reached the western coast of the island and the edge of the habitation area, which is ~2.4 km away from the source crater. The average speed of PDC along the Mukaehama River was estimated as 42 m/s. The PDC involved both surge and block-and-ash flow. Pyroclastic surge left thin layer of volcanic ash, though no remarkable signature of the lateral transportation was found in the surge deposit. The surge deposit occupies ~85% of the area covered with the PDC. Block-and-ash flow deposits were also recognized, but their distribution was limited mainly at the foot of the steep slope of the edifice of Shindake. The erupted materials from the May 29, 2015 eruption were estimated to be $\sim 1.3 \times 10^9$ kg, including 2.4×10^8 kg of the PDC deposit and $\sim 1.1 \times 10^9$ kg of the fallout deposit in proximal and distal area. The PDC deposit consisted of rock fragments with various degrees of hydrothermal alteration. The least-altered glassy blocks of andesite, which was the candidate for the juvenile materials, occupied less than 10% of the deposit. The area covered by the PDC was damaged by both mechanical and thermal effects. The dynamic pressure of the PDC damaged the forest in the inner portion of the area covered with the PDC. The thermal influence of the PDC caused dieback of the vegetation and deformation of some plastic materials. The absence of carbonization of wood in PDC indicates that the temperature was below the ignition temperature of wood. These observations suggest that the temperature of the PDC was between 100 and 240–270 °C.

Keywords: Pyroclastic density current, Pyroclastic surge, Phreatomagmatic eruption, Kuchinoerabujima volcano



Graphical abstract

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FULL PAPER **Open Access**

Analyzing the continuous volcanic tremors detected during the 2015 phreatic eruption of the Hakone volcano

Yohei Yukutake*, Ryou Honda, Masatake Harada, Ryosuke Doke, Tatsuhiko Saito, Tomotake Ueno, Shin'ichi Sakai and Yuichi Morita

Earth, Planets and Space 2017, **69**:164 DOI:10.1186/s40623-017-0751-y
Received: 12 July 2017, Accepted: 27 November 2017, Published: 6 December 2017

Abstract

In the present study, we analyze the seismic signals from a continuous volcanic tremor that occurred during a small phreatic eruption of the Hakone volcano, in the Owakudani geothermal region of central Japan, on June 29, 2015. The signals were detected for 2 days, from June 29 to July 1, at stations near the vents. The frequency component of the volcanic tremors showed a broad peak within 1–6 Hz. The characteristics of the frequency component did not vary with time and were independent of the amplitude of the tremor. The largest amplitude was observed at the end of the tremor activity, 2 days after the onset of the eruption. We estimated the location of the source using a cross-correlation analysis of waveform envelopes. The locations of volcanic tremors are determined near the vents of eruption and the surface, with the area of the upper extent of an open crack estimated using changes in the tilt. The duration-amplitude distribution of the volcanic tremor was consistent with the exponential scaling law rather than the power law, suggesting a scale-bound source process. This result suggests that the volcanic tremor originated from a similar physical process occurring practically in the same place. The increment of the tremor amplitude was coincident with the occurrence of impulsive infrasonic waves and vent formations. High-amplitude seismic phases were observed prior to the infrasonic onsets. The time difference between the seismic and infrasonic onsets can be explained assuming a common source located at the vent. This result suggests that both seismic and infrasonic waves are generated when a gas slug bursts at that location. The frequency components of the seismic phases observed just before the infrasonic onset were generally consistent with those of the tremor signals without infrasonic waves. The burst of a gas slug at the surface vent may be a reasonable model for the generation mechanism of the volcanic tremor and the occurrence of impulsive infrasonic signals.

Keywords: Volcanic tremor, Phreatic eruption, Duration-amplitude distribution, Hakone volcano

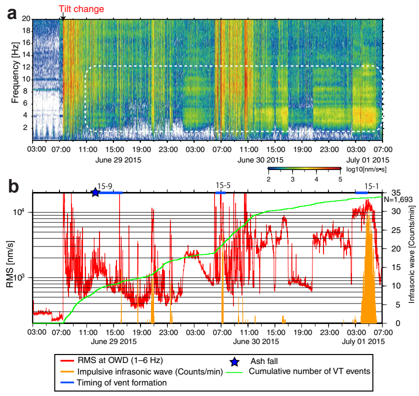

Fig. 3

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FULL PAPER **Open Access**

Phreatic eruptions and deformation of Ioto Island (Iwo-jima), Japan, triggered by deep magma injection

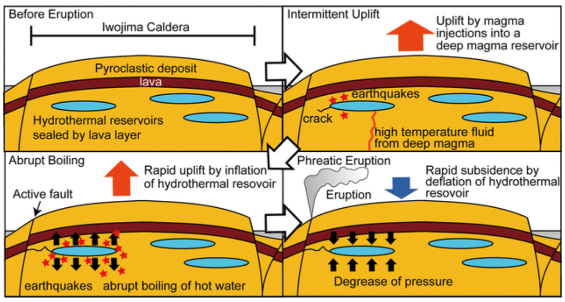
Hideki Ueda*, Masashi Nagai and Toshikazu Tanada

Earth, Planets and Space 2018, **70**:38 DOI:10.1186/s40623-018-0811-y
Received: 18 December 2017, Accepted: 27 February 2018, Published: 12 March 2018

Abstract

On Ioto Island (Iwo-jima), 44 phreatic eruptions have been recorded since 1889, when people began to settle there. Four of these eruptions, after the beginning of continuous observation by seismometers in 1976, were accompanied by intense seismic activity and rapid crustal deformation beforehand. Other eruptions on Ioto were without obvious crustal activities. In this paper, we discuss the mechanisms of phreatic eruptions on Ioto. Regular geodetic surveys and continuous GNSS observations show that Ioto intermittently uplifts at an abnormally high rate. All of the four eruptions accompanied by the precursors took place during intermittent uplifts. The crustal deformation before and after one of these eruptions revealed that a sill-like deformation source in the shallow part of Motoyama rapidly inflated before and deflated after the beginning of the eruption. From the results of a seismic array and a borehole survey, it is estimated that there is a layer of lava at a depth of about 100–200 m, and there is a tuff layer about 200–500 m beneath it. The eruptions accompanied by the precursors probably occurred due to abrupt boiling of hot water in hydrothermal reservoirs in the tuff layer, sealed by the lava layer and triggered by intermittent uplift. For the eruptions without precursors, the hydrothermal systems are weakly sealed by clay or probably occurred on the same principle as a geyser because phreatic eruptions had occurred beforehand and hydrostatic pressure is applied to the hydrothermal reservoirs.

Keywords: Phreatic eruption, Caldera, Earthquake, Crustal deformation, Precursor, Transient deformation



Graphical abstract

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FULL PAPER **Open Access**

InSAR analysis for detecting the route of hydrothermal fluid to the surface during the 2015 phreatic eruption of Hakone Volcano, Japan

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Earth, Planets and Space 2018, **70**:63 DOI:10.1186/s40623-018-0834-4
Received: 4 October 2017, Accepted: 5 April 2018, Published: 18 April 2018

Abstract

Although the 2015 Hakone Volcano eruption was a small-scale phreatic eruption with a discharged mass of only about 100 tons, interferometric synthetic aperture radar successfully detected surface deformations related to the eruption. Inversion model of the underground hydrothermal system based on measured ground displacements by ALOS-2/PALSAR-2 images showed that a crack opened at an elevation of about 530–830 m, probably at the time of the eruption. A geomorphological analysis detected several old NW–SE trending fissures, and the open crack was located just beneath one of the fissures. Thus, the crack that opened during the 2015 eruption could have been a preexisting crack that formed during a more voluminous hydrothermal eruption. In addition, the inversion model implies that a sill deflation occurred at an elevation of about 225 m, probably at the time of the eruption. The deflation of sill-like body represents a preexisting hydrothermal reservoir at an elevation of 100–400 m, which intruded fluid in the open crack prior to eruption. The volume changes of the open crack and the sill were calculated to be 1.14×10^5 m^3 (inflation) and 0.49×10^5 m^3 (deflation), respectively. A very local swelling (about 200 m in diameter) was also detected at the eruption center 2 months before the eruption. The local swelling, whose rate in satellite line-of-sight was 0.7–0.9 cm/day during May 2015 and declined in June, had been monitored until the time of the eruption, when its uplift halted. This was modeled as a point pressure source at an elevation of about 900 m (at a depth of about 80–90 m from the ground surface) and is considered to be a minor hydrothermal reservoir just beneath the fumarolic field. Our analysis shows that the northernmost tip of the open crack reached within 200 m of the surface. Thus, it is reasonable to assume that the hydrothermal fluid in the open crack found a way to the surface and formed the eruption.

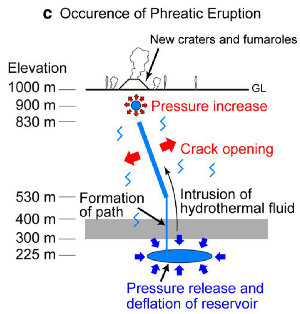

Fig. 10

Keywords: Phreatic eruption, Hakone Volcano, InSAR, ALOS-2/PALSAR-2, Open crack, Hydrothermal fluid

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FULL PAPER **Open Access**

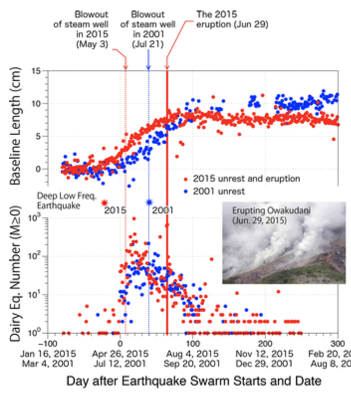
Chronology of the 2015 eruption of Hakone volcano, Japan: geological background, mechanism of volcanic unrest and disaster mitigation measures during the crisis

Kazutaka Mannen*, Yohei Yukutake, George Kikugawa, Masatake Harada, Kazuhiro Itadera and Jun Takenaka

Earth, Planets and Space 2018, **70**:68 DOI:10.1186/s40623-018-0844-2
Received: 10 November 2017, Accepted: 18 April 2018, Published: 26 April 2018

Abstract

The 2015 eruption of Hakone volcano was a very small phreatic eruption, with total erupted ash estimated to be in the order of only 10^2 m^3 and ballistic blocks reaching less than 30 m from the vent. Precursors, however, had been recognized at least 2 months before the eruption and mitigation measures were taken by the local governments well in advance. In this paper, the course of precursors, the eruption and the post-eruptive volcanic activity are reviewed, and a preliminary model for the magma-hydrothermal process that caused the unrest and eruption is proposed. Also, mitigation measures taken during the unrest and eruption are summarized and discussed. The first precursors observed were an inflation of the deep source and deep low-frequency earthquakes in early April 2015; an earthquake swarm then started in late April. On May 3, steam wells in Owakudani, the largest fumarolic area on the volcano, started to blowout. Seismicity reached its maximum in mid-May and gradually decreased; however, at 7:32 local time on June 29, a shallow open crack was formed just beneath Owakudani as inferred from sudden tilt change and InSAR analysis. The same day mud flows and/or debris flows likely started before 11:00 and ash emission began at about 12:30. The volcanic unrest and the eruption of 2015 can be interpreted as a pressure increase in the hydrothermal system, which was triggered by magma replenishment to a deep magma chamber. Such a pressure increase was also inferred from the 2001 unrest and other minor unrests of Hakone volcano during the twenty-first century. In fact, monitoring of repeated periods of unrest enabled alerting prior to the 2015 eruption. However, since open crack formation seems to occur haphazardly, eruption prediction remains impossible and evacuation in the early phase of volcanic unrest is the only way to mitigate volcanic hazard.



Graphical abstract

Keywords: Hakone, Phreatic eruption, Lahar, Debris flow, Ash fall, Fumarole

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FULL PAPER **Open Access**

Contention between supply of hydrothermal fluid and conduit obstruction: inferences from numerical simulations

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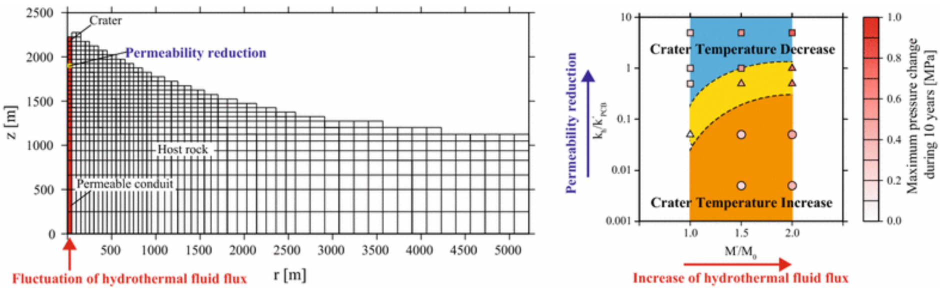
Earth, Planets and Space 2018, **70**:72 DOI:10.1186/s40623-018-0840-6
Received: 29 December 2017, Accepted: 14 April 2018, Published: 4 May 2018

Abstract

We investigate a volcanic hydrothermal system using numerical simulations, focusing on change in crater temperature. Both increases and decreases in crater temperature have been observed before phreatic eruptions. We follow the system's response for up to a decade after hydrothermal fluid flux from the deep part of the system is increased and permeability is reduced at a certain depth in a conduit. Our numerical simulations demonstrate that: (1) changes in crater temperature are controlled by the magnitude of the increase in hydrothermal fluid flux and the degree of permeability reduction; (2) significant increases in hydrothermal flux with decreases in permeability induce substantial pressure changes in shallow depths in the edifice and decreases in crater temperature; (3) the location of maximum pressure change differs between the mechanisms. The results of this study imply that it is difficult to predict eruptions by crater temperature change alone. One should be as wary of large eruptions when crater temperature decreases as when crater temperature increases. It is possible to clarify the implications of changes in crater temperature with simultaneous observation of ground deformation.



Graphical abstract

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FULL PAPER **Open Access**

Lahar characteristics as a function of triggering mechanism at a seasonally snow-clad volcano: contrasting lahars following the 2014 phreatic eruption of Ontake Volcano, Japan

Kyoko S. Kataoka*, Takane Matsumoto, Takeshi Saito, Katsuhisa Kawashima, Yoshitaka Nagahashi, Tsutomu Iyobe, Akihiko Sasaki and Keisuke Suzuki

Earth, Planets and Space 2018, **70**:113 DOI:10.1186/s40623-018-0873-x
Received: 27 February 2018, Accepted: 12 June 2018, Published: 5 July 2018

Abstract

In association with the September 2014 phreatic eruption (VEI 1–2) at Ontake Volcano, a syn-eruptive and two post-eruptive lahars occurred in the Akagawa–Nigorigawa River, southern flank of the volcano. The present contribution describes and discusses the contrasting features of the two post-eruptive lahars, which caused a major impact on downstream river morphology, and re-examines the description of the syn-eruptive lahar in the previous study. The first post-eruptive lahar occurred 8 days after the eruption by the rainstorm (October 5, 2014, before the snowy season), and the second lahar was associated with the rain-on-snow (ROS) event on April 20, 2015, in the early spring of the snowmelt season. The October rain-triggered lahar, which can be interpreted as a cohesive debris flow, reached at least ~ 11 km downstream and left muddy matrix-rich sediments with high clay content (10–20 wt% of clay in matrix). The lahar deposits contain hydrothermally altered rock fragments, sulfide/sulfate minerals, and clay minerals and show extremely high total sulfur content (10–14 wt%) in matrix part, indicating source material from the September phreatic eruption deposits. The presence of "rain-triggered" clay-rich lahar and deposits originating from a single small phreatic eruption is important because usually such clay-rich lahars are known to occur in association with large-scale sector collapse and debris avalanches. The April ROS-triggered lahar was caused by the heavy rain and accompanying snow melting. The lahar was dilute and partly erosional and evolved into hyperconcentrated flow, which left fines-depleted sandy and gravelly deposits. Despite these lahars that originated from the same volcanic source and occurring within a 7-month period, the flow and resulting depositional characteristics are totally different. These different types of lahars after a single eruptive event need different simulations and mitigation of lahar hazards with timing (season) of the lahar onset. In comparison with rainfall intensity, snow-melting rate, and the contrasting lahars occurred in 2014/2015, it is postulated that the generation, size, and types of lahars can vary with the timing of eruption, whether it happens during the pre-snow season, snow season, or rainy season.

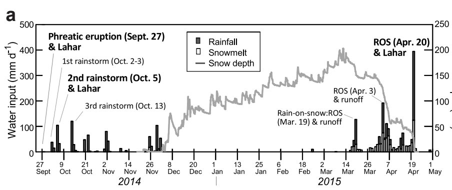

Fig. 2

Keywords: Ontake Volcano, 2014 eruption, Phreatic eruption, Clay-rich lahar, Rain-on-snow, Cohesive debris flow

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FULL PAPER Open Access

Precursory tilt changes associated with a phreatic eruption of the Hakone volcano and the corresponding source model

Ryou Honda*, Yohei Yukutake, Yuichi Morita, Shin'ichi Sakai, Kazuhiro Itadera and Kazuya Kokubo

Earth, Planets and Space 2018, **70**:117 DOI:10.1186/s40623-018-0887-4
Received: 14 January 2018, Accepted: 27 June 2018, Published: 11 July 2018

Abstract

The 2015 unrest of the Hakone volcano in Japan, which began on April 26, generated earthquake swarms accompanied by long-term deformation. The earthquake swarm activity reached its maximum in mid-May and gradually calmed down; however, it increased again on the morning of June 29, 2015. Simultaneously with the earthquake increase, rapid tilt changes started 10 s before 07:33 (JST) and they lasted for approximately 2 min. The rapid tilt changes likely reflected opening of a shallow crack that was formed near the eruption center prior to the phreatic eruption on that day. In this study, we modeled the pressure source beneath the eruption center based on static tilt changes determined using both tilt meters and broadband seismometers. In the best-fit model, the source depth was 854 m above sea level, and its orientation (N316°E) agreed with the direction of maximum compression estimated based on focal mechanism and *S*-wave splitting data. The extent of the crack opening was estimated to be 4.6 cm, while the volume change was approximately 1.6×10^5 m^3. The top of the crack reached to approximately 150 m below the eruption center. Because the crack was too thin to be penetrated by magma, the crack opening was attributed to the intrusion of hydrothermal water. This intrusion of hydrothermal water may have triggered the phreatic eruption. Reverse polarity motion with respect to that expected from crack opening was recognized in 1 Hz tilt records during the first 20 s of the intrusion of hydrothermal water. This motion, not the subsidence of volcanic edifice, was responsible for the observed displacement.

Keywords: Hakone volcano, Broadband seismogram, Tilt change, Pressure source model

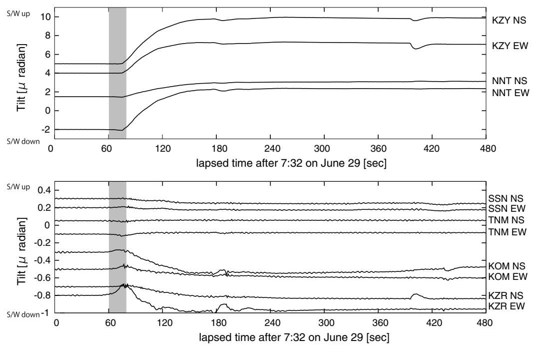

Fig. 3

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FULL PAPER Open Access

Anatomy of phreatic eruptions

Corentin Caudron*, Benoit Taisne, Jurgen Neuberg, Arthur D. Jolly, Bruce Christenson, Thomas Lecocq, Suparjan, Devy Syahbana and Gede Suantika

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Received: 10 April 2018, Accepted: 6 October 2018, Published: 24 October 2018

Abstract

This study investigates phreatic eruptions at two similar volcanoes, Kawah Ijen (Indonesia) and White Island (New Zealand). By carefully processing broadband seismic signals, we reveal seismic signatures and characteristics of these eruptions. At both volcanoes, the phreatic eruptions are initiated by a very-long-period (VLP) seismic event located at shallow depths between 700 and 900 m below the crater region, and may be triggered by excitation of gas trapped behind a ductile magma carapace. The shallow hydrothermal systems respond in different ways. At Kawah Ijen, the stress change induced by VLPs directly triggers an eigenoscillation of the hyperacidic lake. This so-called seiche is characterized by long-lasting, long-period oscillations with frequencies governed by the dimensions of the crater lake. A progressive lateral rupture of a seal below the crater lake and/or fluids migrating toward the surface is seismically recorded ~ 15 min later as high-frequency bursts superimposed to tilt signals. At White Island, the hydrothermal system later (~ 25 min) responds by radiating harmonic tremor at a fixed location that could be generated through eddy-shedding. These seismic signals shed light on several aspects of phreatic eruptions, their generation and timeline. They are mostly recorded at periods longer than tens of seconds further emphasizing the need to deploy broadband seismic equipment close to active volcanic activity.

Keywords: Volcanic monitoring, Phreatic eruption, Volcanic lake, Broadband seismology

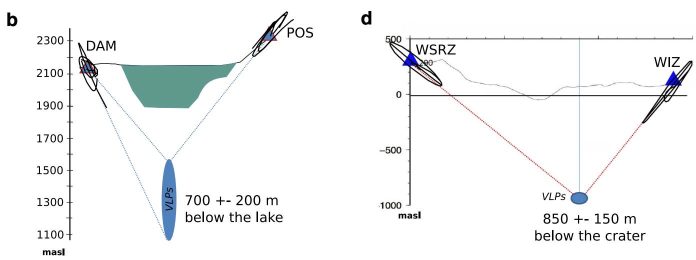

Fig. 7

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FULL PAPER Open Access

Relating gas ascent to eruption triggering for the April 27, 2016, White Island (Whakaari), New Zealand eruption sequence

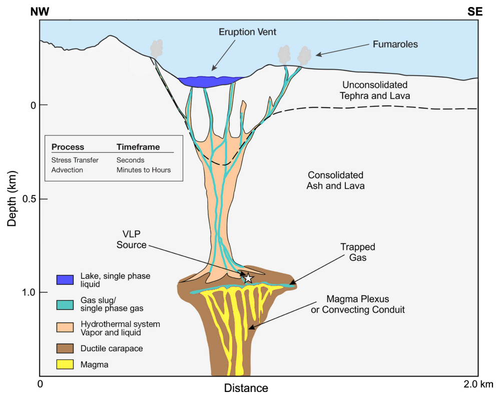
Arthur Jolly*, Ivan Lokmer, Bruce Christenson and Johannes Thun

Earth, Planets and Space 2018, **70**:177 DOI:10.1186/s40623-018-0948-8
Received: 10 April 2018, Accepted: 30 October 2018, Published: 13 November 2018

Abstract

The April 27, 2016 eruption sequence at White Island was comprised of 6 discrete eruptive events that occurred over a 35-min period. Seismicity included three episodes of VLP activity: the first occurring ~ 2 h and a second occurring 10 min prior to the first eruption. A third larger VLP event occurred just prior to the fourth eruption. A VLP source depth of 800–1000 m below the vent is obtained from an analysis of the waveform semblance, and a volumetric source is obtained from waveform inversion of the largest VLP event. Lag times between VLP occurrence and eruption onsets provide an opportunity to examine gas migration and stress transfer models as potential triggers to the eruptive activity. Plausible lag times for a deep gas pulse to the surface are obtained by application of a TOUGH2 computational model which suggests propagation times of 0.25–1.9 m/s and are informed by previously measured White Island rock porosities and permeabilities. Results suggest that pre-eruption VLP may be plausibly linked to advection of gas from the VLP source at a magmatic carapace located ~ 800–1000 m depth. Alternatively, the large VLP that occurred just prior to the fourth eruption may be linked to a quasi-dynamic or quasi-static stress perturbation.

Keywords: VLP earthquake, Gas ascent velocity, Dynamic stress, Static stress, TOUGH2 modeling



Graphical abstract

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FULL PAPER Open Access

Geophysical examination of the 27 April 2016 Whakaari/White Island, New Zealand, eruption and its implications for vent physiognomies and eruptive dynamics

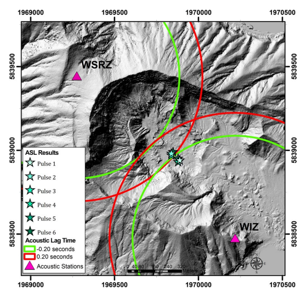
Braden Walsh*, Jonathan Procter, Ivan Lokmer, Johannes Thun, Tony Hurst, Bruce Christenson and Arthur Jolly

Earth, Planets and Space 2019, **71**:25 DOI:10.1186/s40623-019-1003-0
Received: 3 April 2018, Accepted: 17 February 2019, Published: 28 February 2019

Abstract

At approximately 09:36 UTC on 27 April 2016, a phreatic eruption occurred on Whakaari Island (White Island) producing an eruption sequence that contained multiple eruptive pulses determined to have occurred over the first 30 min, with a continuing tremor signal lasting ~ 2 h after the pulsing sequence. To investigate the eruption dynamics, we used a combination of cross-correlation and coherence methods with acoustic data. To estimate locations for the eruptive pulses, seismic data were collected and eruption vent locations were inferred through the use of an amplitude source location method. We also investigated volcanic acoustic–seismic ratios for comparing inferred initiation depths of each pulse. Initial results show vent locations for the eruptive pulses were found to have possibly come from two separate locations only ~ 50 m apart. These results compare favorably with acoustic lag time analysis. After error analysis, eruption sources are shown to conceivably come from a single vent, and differences in vent locations may not be constrained. Both vent location scenarios show that the eruption pulses gradually increase in strength with time, and that pulses 1, 3, 4, and 5 possibly came from a deeper source than pulses 2 and 6. We show herein that the characteristics and locations of volcanic eruptions can be better understood through joint analysis combining data from several data sources.

Keywords: Amplitude source location, Infrasound, Source migration, Volcanic acoustic–seismic ratio, White Island



Graphical abstract

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FULL PAPER **Open Access**

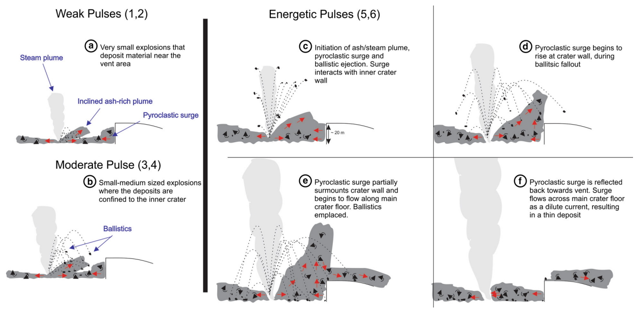
Phreatic eruption dynamics derived from deposit analysis: a case study from a small, phreatic eruption from Whakāri/White Island, New Zealand

Geoff Kilgour*, Stephanie Gates, Ben Kennedy, Aaron Farquhar, Ame McSporran and Cameron Asher

Earth, Planets and Space 2019, **71**:36 DOI:10.1186/s40623-019-1008-8
RReceived: 12 June 2018, Accepted: 25 February 2019, Published: 1 April 2019

Abstract

On 27 April 2016, White Island erupted in a multi-pulse, phreatic event that lasted for ~40 min. Six, variably sized pulses generated three ballistic ejections and at least one pyroclastic surge out of the inner crater and onto the main crater floor. Deposit mapping of the pyroclastic surge and directed ballistic ejecta, combined with numerical modelling, is used to constrain the volume of the ejecta and the energetics of the eruption. Vent locations and directionality of the eruption are constrained by the ballistic modelling, suggesting that the vent/s were angled towards the east. Using these data, a model is developed that comports with the field and geophysical data. One of the main factors modifying the dispersal of the eruption deposits is the inner crater wall, which is ~20 m high. This wall prevents some of the pyroclastic surge and ballistic ejecta from being deposited onto the main crater floor but also promotes significant inflation of the surge, generating a semi-buoyant plume that deposits ash high on the crater walls. While the eruption is small volume, the complexity determined from the deposits provides a case study with which to assess the relatively frequent hazards posed by active volcanoes that host hydrothermal systems. The deposits of this and similar eruptions are readily eroded, and for complete understanding of volcanic hazards, it is necessary to make observations and collect samples soon after these events.



Graphical abstract

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FULL PAPER **Open Access**

Time variations in the chemical and isotopic composition of fumarolic gases at Hakone volcano, Honshu Island, Japan, over the earthquake swarm and eruption in 2015, interpreted by magma sealing model

Takeshi Ohba*, Muga Yaguchi, Kana Nishino, Nozomi Numanami, Yasushi Daita, Chiho Sukigara, Masanori Ito and Urumu Tsunogai

Earth, Planets and Space 2019, **71**:48 DOI:10.1186/s40623-019-1027-5
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Abstract

Definite increases in the components ratios of CO_2/H_2O, CO_2/H_2S, CO_2/CH_4 and He/CH_4 were observed at the fumarolic gases from Owakudani geothermal area located at the center of Hakone volcanic caldera (Honshu Island, Japan), synchronized with the earthquake swarm in 2015. Such variations were due to the dominance of a magmatic component over a hydrothermal component, suggesting the earthquake swarm was produced by the injection of magmatic gases into the hydrothermal system. The CO_2/H_2O ratio of magmatic gas was estimated to be 0.0045 before the earthquake swarm, which increased up to 0.013 during the earthquake swarm, likely produced by the pressurization of magma as a result of magma sealing where the pressure increment in magma was estimated to be 3% to the lithostatic pressure. The H_2O and CO_2 concentration in magma were estimated to be 6.3 wt% and 20 wt ppm, respectively, assuming a temperature 900 °C and a rhyolitic composition. In May 2015, a few months prior to the earthquake swarm in May 2015, a sharp increase in the Ar/CO_2 and N_2/He ratios and a decrease in the isotopic ratio of H_2O were observed at the fumarolic gas. The invasion of air into the hydrothermal system increased the Ar/CO_2 and N_2/He ratios. The decrease in the isotopic ratio of H_2O was induced by partial condensation of H_2O vapor.

Keywords: Active volcano, Fumarolic gas, Earthquake swarm, Phreatic eruption, Mt. Hakone, Magma degassing, Magma sealing

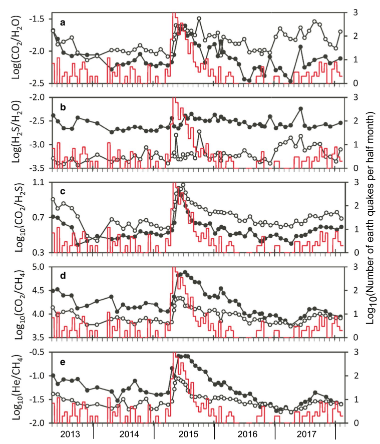

Fig. 2

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EXPRESS LETTER **Open Access**

Infrasonic wave accompanying a crack opening during the 2015 Hakone eruption

Yohei Yukutake*, Mie Ichihara and Ryou Honda

Earth, Planets and Space 2018, **70**:53 DOI:10.1186/s40623-018-0820-x
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Abstract

To understand the initial process of the phreatic eruption of the Hakone volcano from June 29 to July 01, 2015, we analyzed infrasound data using the cross-correlation between infrasound and vertical ground velocity and compared the results of our analysis to the crustal deformation detected by tiltmeters and broadband seismometers. An infrasound signal and vertical ground motion due to an infrasound wave coupled to the ground were detected simultaneously with the opening of a crack source beneath the Owakudani geothermal region during the 2-min time period after 07:32 JST on June 29, 2015 (JST = UTC + 8 h). Given that the upper end of the open crack was approximately 150 m beneath the surface, the time for the direct emission of highly pressurized fluid from the upper end of the open crack to the surface should have exceeded the duration of the inflation owing to the hydraulic diffusivity in the porous media. Therefore, the infrasound signal coincident with the opening of the crack may reflect a sudden emission of volcanic gas resulting from the rapid vaporization of pre-existing groundwater beneath Owakudani because of the transfer of the volumetric strain change from the deformation source. We also noticed a correlation pattern corresponding to discrete impulsive infrasound signals during vent formation, which occurred several hours to 2 days after the opening of the crack. In particular, we noted that the sudden emission of vapor coincided with the inflation of the shallow pressure source, whereas the eruptive burst events accompanied by the largest vent formation were delayed by approximately 2 days. Furthermore, we demonstrated that the correlation method is a useful tool in detecting small infrasound signals and provides important information regarding the initial processes of the eruption.

Keywords: Infrasound signal, Vertical ground motion, Correlation, Monitoring, Volcanic activity, Phreatic eruption

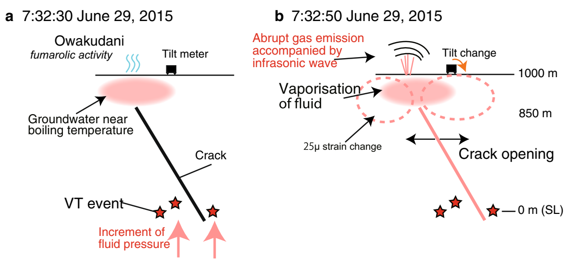

Fig. 5

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EXPRESS LETTER **Open Access**

Resistivity characterisation of Hakone volcano, Central Japan, by three-dimensional magnetotelluric inversion

Ryokei Yoshimura*, Yasuo Ogawa, Yohei Yukutake, Wataru Kanda, Shogo Komori, Hideaki Hase, Tada-nori Goto, Ryou Honda, Masatake Harada, Tomoya Yamazaki, Masato Kamo, Shingo Kawasaki, Tetsuya Higa, Takeshi Suzuki, Yojiro Yasuda, Masanori Tani and Yoshiya Usui

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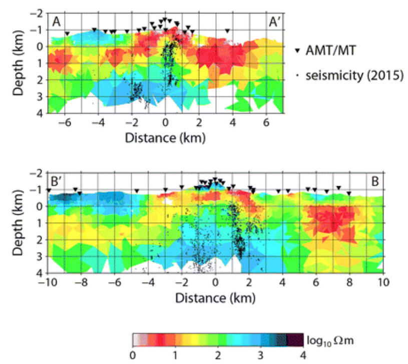
Abstract

On 29 June 2015, a small phreatic eruption occurred at Hakone volcano, Central Japan, forming several vents in the Owakudani geothermal area on the northern slope of the central cones. Intense earthquake swarm activity and geodetic signals corresponding to the 2015 eruption were also observed within the Hakone caldera. To complement these observations and to characterise the shallow resistivity structure of Hakone caldera, we carried out a three-dimensional inversion of magnetotelluric measurement data acquired at 64 sites across the region. We utilised an unstructured tetrahedral mesh for the inversion code of the edge-based finite element method to account for the steep topography of the region during the inversion process. The main features of the best-fit three-dimensional model are a bell-shaped conductor, the bottom of which shows good agreement with the upper limit of seismicity, beneath the central cones and the Owakudani geothermal area, and several buried bowl-shaped conductive zones beneath the Gora and Kojiri areas. We infer that the main bell-shaped conductor represents a hydrothermally altered zone that acts as a cap or seal to resist the upwelling of volcanic fluids. Enhanced volcanic activity may cause volcanic fluids to pass through the resistive body surrounded by the altered zone and thus promote brittle failure within the resistive body. The overlapping locations of the bowl-shaped conductors, the buried caldera structures and the presence of sodium-chloride-rich hot springs indicate that the conductors represent porous media saturated by high-salinity hot spring waters. The linear clusters of earthquake swarms beneath the Kojiri area may indicate several weak zones that formed due to these structural contrasts.

Keywords: Hakone volcano, Magnetotellurics, Resistivity structure, Three-dimensional inversion



Graphical abstract

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EXPRESS LETTER Open Access

Temporal changes in inflation sources during the 2015 unrest and eruption of Hakone volcano, Japan

Masatake Harada*, Ryosuke Doke, Kazutaka Mannen, Kazuhiro Itadera and Mikio Satomura

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Abstract

Global navigation satellite system data from Hakone volcano, central Japan, together with GEONET data from the Geospatial Information Authority of Japan, were used to investigate the processes associated with the volcanic activity in 2015, which culminated in a small phreatic eruption in late June 2015. Three deep and shallow sources, namely spherical, open crack, and sill, were employed to elucidate the volcanic processes using the observed GNSS displacements, and the MaGCAP-V software was used to estimate the volumetric changes of these sources. Our detailed analysis shows that a deep inflation source at 6.5 km below sea level started to inflate in late March 2015 at a rate of ~ 9.3×10^4 m^3/day until mid-June. The inflation rate then slowed to ~ 2.1×10^4 m^3/day and ceased at the end of August 2015. A shallow open crack at 0.8 km above sea level started to inflate in May 2015 at a rate of 1.7×10^3 m^3/day. There was no significant volumetric change in the shallow sill source during the volcanic unrest, which is evident from interferometric synthetic aperture radar analysis. The inflation of the deep source continued even after the eruption without a significant slowdown in inflation rate. The inflation stopped in August 2015, approximately 1 month after the eruption ceased. This observation implies that the transportation of magmatic fluid to a deep inflation source (6.5 km) triggered the 2015 unrest. The magmatic fluid may have then migrated from the deep source to the shallow open crack. The phreatic eruption was then caused by the formation of a crack that extended to the surface. However, steam emissions from the vent area during and after the eruption were apparently insufficient to mitigate the internal pressure of the shallow open crack.

Keywords: GNSS, Magma chamber, Hydrothermal system, Open crack, Phreatic eruption, Hakone

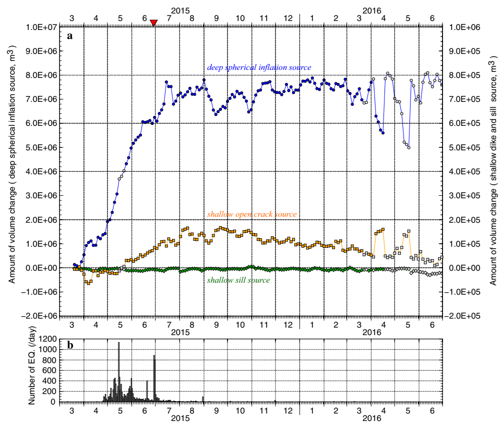

Fig. 4

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EXPRESS LETTER Open Access

Monitoring ground deformation of eruption center by ground-based interferometric synthetic aperture radar (GB-InSAR): a case study during the 2015 phreatic eruption of Hakone volcano

Senro Kuraoka*, Yuichi Nakashima, Ryosuke Doke and Kazutaka Mannen

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Abstract

We successfully monitored the ground deformation of an eruption center during the 2015 phreatic eruption of Hakone volcano, Japan, using ground-based interferometric synthetic aperture radar (GB-InSAR). GB-InSAR has been developed and applied over the past two decades and enables the frequent (< 10 min) aerial monitoring of surficial deformation of structures and slopes. We installed a GB-InSAR 4 days before the eruption of Hakone volcano on June 29, 2015, and monitored the ground deformation of an area where uplift was detected by a satellite InSAR. The ground deformation observed by the GB-InSAR began suddenly on the morning of June 29 almost coincident with the intrusion of hydrothermal fluid that was inferred by other geophysical observations. The hydrothermal crack is considered to have caused the eruption, which was known by an ash fall 5 h later. The GB-InSAR results indicated a significant uplifted area which is approximately 100 m in diameter, and new craters and fumaroles were created by the eruption in and around the area. The displacement reached up to a total of 45 mm until the evening of June 29 and continued at least until the morning of July 1. During our observation, the displacement rate decreased twice, and the timing of each decrease seemed to correspond to the formation of new conduits as implied from geophysical observations.

Keywords: GB-InSAR, Hakone volcano, Ground deformation, Phreatic eruption, Hydrothermal fluid

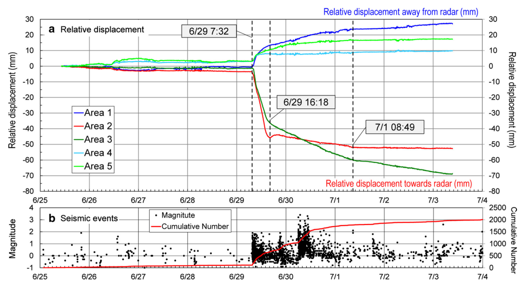

Fig. 4

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EXPRESS LETTER **Open Access**

Experimental approach to rootless eruptions using kitchen materials

Rina Noguchi*, Ai Hamada, Ayako I. Suzuki and Kei Kurita

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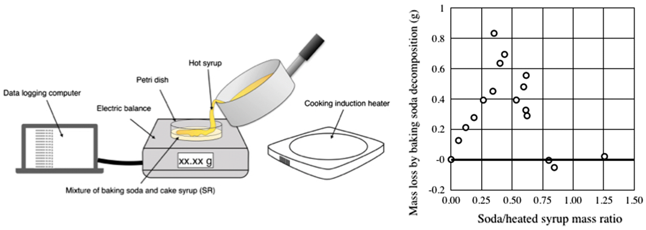
Abstract

Rootless eruption is caused by lava flow entering inland water or wet sediment and forms craters and cones far from the actual vent. Since the rootless eruption can be significantly explosive, the possibility of rootless eruption is critical for hazard management; however, forecasting occurrence and explosiveness of a rootless eruption remains difficult because explosiveness is considered to correlate nonlinearly with the mass ratio of hot lava and water. Here, we show the nonlinear nature of this type of eruption roots from the nonlinearly determined area between lava and underlying wet sediment as a function of water content within the wet sediment by a series of analog experiments can be implemented in a kitchen. In our analog experiment, lava and wet sediment were replaced by heated syrup and mixture of baking soda (sodium bicarbonate) and cake syrup. From measurements of mass loss due to CO_2 gas emission during the heat-induced decomposition of baking soda, we estimated the reaction efficiency for various proportions of baking soda and cake syrup in the substrate. We observed a nonlinear dependence of CO_2 emission; the peak efficiency was achieved for the substrate with 15 and 35 g of baking soda and cake syrup, respectively. Considering physical properties such as density and viscosity, we found that the Rayleigh–Taylor instability between the poured heated syrup and the substrate can explain the observed nonlinear dependence of CO_2 emission. For natural settings, the results of this study suggest that both the availability of water and rheological properties of the substrate affect the occurrence and stability of hydrovolcanic eruptions.

Keywords: Rootless eruption, Lava–water interaction, Kitchen earth experiment, Syrup, Soda



Graphical abstract

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EXPRESS LETTER **Open Access**

Suspended sediment transport diversity in river catchments following the 2014 phreatic eruption at Ontake Volcano, Japan

Kyoko S. Kataoka*, Takane Matsumoto, Takeshi Saito, Yoshitaka Nagahashi and Tsutomu Iyobe

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Abstract

The present contribution investigates the temporal changes in volcaniclastic sediment transport over the 2-year period after the 2014 eruption of Ontake Volcano in two small drainage basins where increased turbidity was observed immediately after the eruption. Two similar-sized catchments on the southern flank of the volcano, the Akagawa River (~4.4 km^2) and the Shirakawa River (~2.9 km^2) catchments, exhibited contrasting sediment delivery patterns and river water characteristics such as acidity and electric conductivity (EC). Increased turbidity, a high rate of suspended sediment supply, and elevated EC values were observed only in the Akagawa River, which hosts volcanic vents in its proximal part. The mineral assemblages and chemical characteristics of suspended sediment from the Akagawa River clearly indicate that the turbidity was derived from the erosion and reworking of primary eruptive material and lahar deposits. Previous airborne and remote surveys suggested the presence of primary ashfall and pyroclastic density currents in the upslope areas and valley heads of both the Akagawa and Shirakawa rivers. However, the river water characteristics and sediment transportation data of the present study clarify that the initial volcanic disturbance of the Shirakawa catchment was minor and limited. The influence of volcanic disturbance on the Akagawa River catchment continued for at least 10 months after the eruption and was also observed for an additional 9 months until the end of the snowmelt season in 2016. In the Akagawa River valley, two post-eruptive lahars that occurred during a 7-month period may have enhanced the removal of volcaniclastic deposits, and this remobilization may have resulted in diminished sediment delivery in the river after the lahar events. The results of this study provide information about the timing of the decline of suspended sediment delivery associated with small-scale eruptive activity, and such information may prove useful for evaluating the effects of other eruptions similar in size and character to the 2014 Ontake eruption. In addition, the approach adopted for monitoring rivers at downstream sites is clearly of utility for evaluating primary pyroclastic deposition and volcanic disturbance near inaccessible vent areas.

Keywords: Ontake Volcano, 2014 eruption, Phreatic eruption, Suspended sediment supply, Volcanic disturbance, Water characteristics

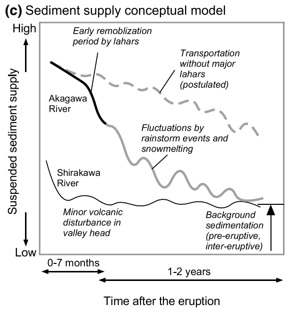

Fig. 2

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