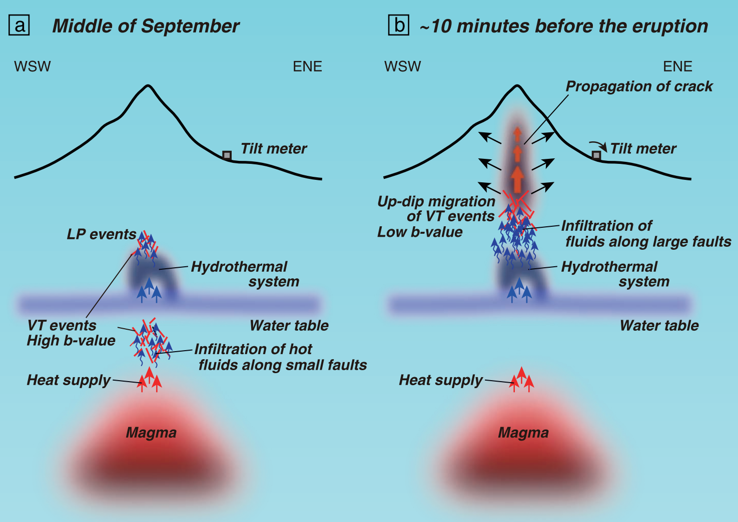
Earth, Planets and Space

The Phreatic Eruption of Mt. Ontake Volcano in 2014



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PREFACE

Open Access

Special issue "The phreatic eruption of Mt. Ontake volcano in 2014"

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Introduction

Mt. Ontake volcano erupted at 11:52 on September 27, 2014, claiming the lives of at least 58 hikers. This eruption was the worst volcanic disaster in Japan since the 1926 phreatic eruption of Mt. Tokachidake claimed 144 lives (Table 1). The timing of the eruption contributed greatly to the heavy death toll: near midday, when many hikers were near the summit, and during a weekend of clear weather conditions following several rainy weekends. The importance of this timing is reflected by the fact that a somewhat larger eruption of Mt. Ontake in 1979 resulted in injuries but no deaths. In 2014, immediate precursors were detected with seismometers and tiltmeters about 10 min before the eruption, but the eruption started before a warning was issued.

The Coordinating Committee for Prediction of Volcanic Eruption met the next day to investigate observations by institutions such as the Japan Meteorological Agency (JMA). They concluded that the eruption was phreatic, based on analysis of volcanic ash collected immediately after the eruption, and also concluded that the eruption could evolve to a magmatic one, based on experience at other volcanoes. Urgent research began under the Grants-in-Aid for Scientific Research program funded by the Japan Society for the Promotion of Science (JSPS). This special issue was planned to collect the research carried out in response to the 2014 eruption of Mt. Ontake.

Before reviewing the papers in this issue, we summarize the recent activity of Mt. Ontake and selected results from JMA monitoring. Magmatic activity is relatively low in comparison with other active volcanoes in Japan. Geological studies show that at least four magmatic eruptions occurred over the past 10,000 years, the most recent from Gonoike crater around 6000 years ago, and that phreatic eruptions occurred every several hundred years (Oikawa et al. 2015). No historical records of eruptions prior to 1979 have been found, although fumarolic activity in the Jigukudani valley to the southwest of the summit (Fig. 1) has been reported for the past several hundred years (Oikawa 2008).

On October 28, 1979, the first recorded eruption in human history occurred, a phreatic eruption with total discharged mass of about 200,000 tons corresponding to VEI 2. This eruption opened new craters near the top of Jigukudani valley (Fig. 1). In 1991, a very small phreatic eruption occurred from one of the vents created by the 1979 eruption. In 2007, another small eruption occurred from the same vent, and a very long period (VLP) earthquake and crustal deformation were detected (Nakamichi et al. 2009). No further eruptions occurred until September 2014.

Figure 2 shows results of long-term monitoring by the JMA. Fumarole height data (Fig. 2a) are lacking from 1981 to 1988 but show a relatively low level of activity during 3-year periods before both the 2007 and 2014 eruptions. Fumarole vent temperatures, measured intermittently, decayed through 2012, although there are few more recent measurements (Fig. 2b). Seismic activity near the summit has been monitored from 1988 to present and increased in association with the eruptions in 1991 and 2007 (Fig. 2c). The level of seismic activity was low during the 3-year period before September 2014.

JMA detected unusual seismic activity on September 10–11, 2014, two weeks before the eruption. Daily events counts were the largest since the 2007 eruption, but no volcanic tremor or crustal deformation was detected. Low-frequency earthquakes were detected, but were much fewer in number than those observed in association with the 2007 eruption. This is the main reason that the JMA chose not to raise the volcano warning level, and makes comparison between the 2007 and 2014 eruptions a primary issue in many of these studies.

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Table 1 List of recent Japanese eruptions that claimed >10 lives (supplemented to Japan Meteorological Agency 2013)

Date (Y/M/D)	Volcano	Victims	Description
1721/6/22	Asama	15	Ballistic ejecta
1741/8/18	Oshima-Oshima	1467	Tsunami
1779/11/8-9	Sakurajima	>150	Ballistic ejecta and lava flow
1781/4/11	Sakurajima	15	Tsunami caused by an off-shore eruption
1783/8/5	Asama	1151	Pyroclastic flow, mud flow and flood by a collapse of natural dam
1785/4/18	Aogashima	130–140	Phreatomagmatic eruption?
1792/5/21	Unzen	>15,000	Debris avalanche and tsunami caused by it
1822/3/12	Usu	50	Pyroclastic flow
1856/9/25	Hokkaido-Koma	21–29	Ballistic ejecta and pumice flow
1888/7/15	Bandai	461	Debris avalanche
1900/7/17	Adatara	73	Destruction of a sulfur mine
1902/8/7	Izu-Torishima	125	Phreatomagmatic eruption
1914/1/12	Sakurajima	58–59	Ballistic ejecta and lava flow
1926/5/24	Tokachidake	144	Mud flow
1940/7/12	Miyake	11	Ballistic ejecta
1952/9/24	Bayonnaise	31	Phreatomagmatic explosion with submarine eruption
1958/6/24	Aso	31	Ballistic ejecta
1991/6/3	Unzen	43	Pyroclastic flow
2014/9/27	Ontake	58 (+5 missing)	Ballistic ejecta

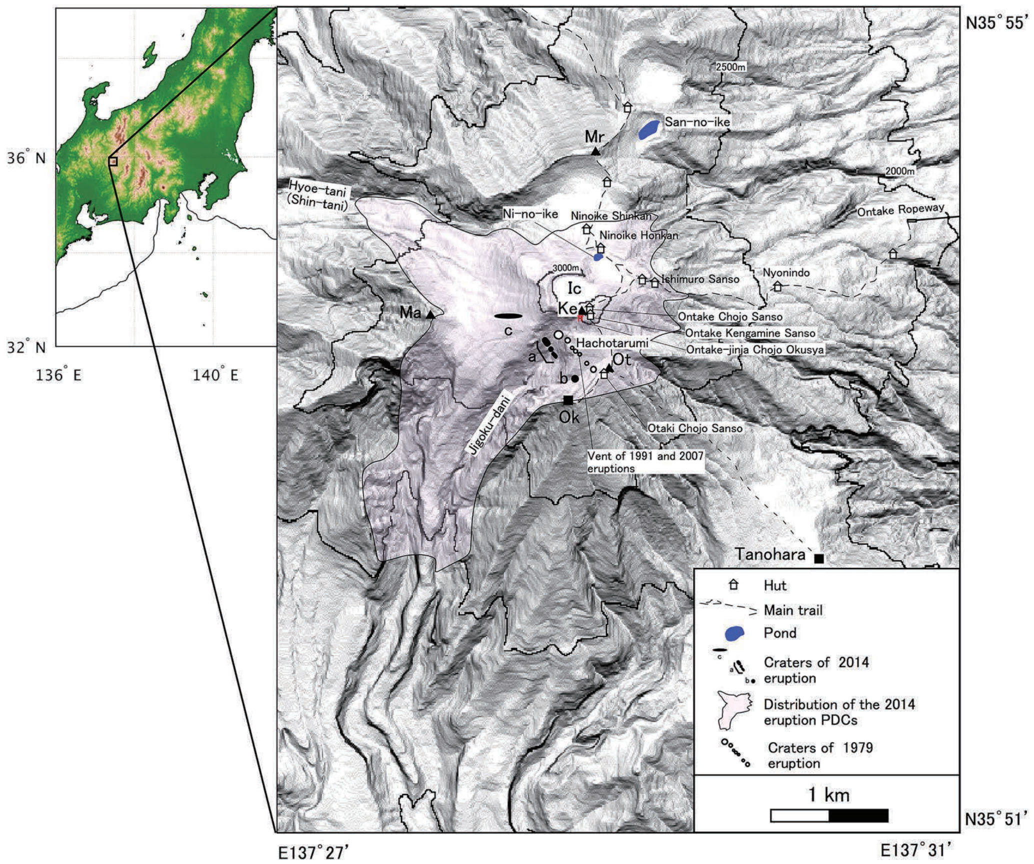

Fig. 1 Location map of Mt. Ontake volcano, modified from Fig. 1 of Oikawa et al. (2016)

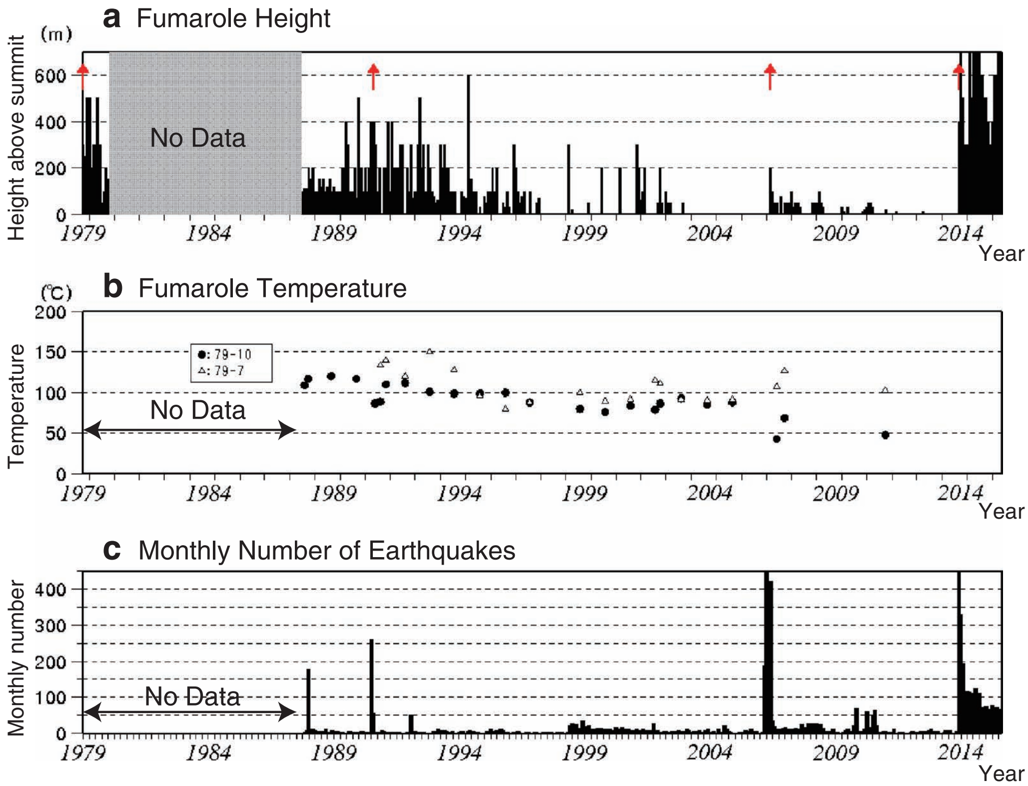

Fig. 2 Results of long-term monitoring of volcanic activity by the Japan Meteorological Agency: **a** fumarole height based on visual measurements; **b** fumarole temperature measured at an active vent of the 1979 eruption; **c** monthly number of earthquakes near the summit of Mt. Ontake. Earthquakes are counted for the same station under a constant criterion using S-P time and maximum amplitude in seismograms

Contents of the special issue

In this section, we briefly review the papers of the special issue together with related papers published in other journals. The papers are classified into five categories depending on the principal study methodology.

Visual observations

The 2014 eruption of Mt. Ontake provided an unusually rich set of visual records of phreatic eruption. Hikers near the crater took still photographs and videos from many locations immediately after the onset of the eruption. Researchers took photographs and videos from news-media helicopters in good weather conditions. These visual data are valuable for process studies of phreatic eruptions, which have rarely if ever been recorded in such detail. Two papers (Kaneko et al. 2016; Oikawa et al. 2016) are based mainly on the visual data; see also Maeno et al. (2016) for eruption chronology based on combined analysis of visual images and the tephra sequence.

Kaneko et al. (2016) describe the spatial characteristics of the eruption based in large part on aerial observations made the following day. Three major craters opened at the head of Jigukudani valley (Fig. 1); the central crater was the main vent. A pyroclastic density current (PDC) with relatively low destructive force travelled approximately 2.5 km downvalley from this central vent. Ballistics ejecta emerged tens of seconds after the beginning of the eruption, reached distances of up to 950 m from the vent, and attained maximum initial velocities estimated at 111 m/s.

Oikawa et al. (2016) describe the sequence of the eruption based on interviews and visual records such as still photographs and videos taken by hikers, which provide precise time records of the eruption. The interviewees included mountain guides and workers in mountain huts. Oikawa et al. (2016) divide the eruption into three phases: PDC flow, pyroclastic fall with muddy rain, and muddy water overflowing from the crater. The eruption began with dry pyroclastic density currents and without any precursory surface phenomena. The temperature of the PDCs in the summit area was generally 30–100 °C. During the period over which the PDCs covered the surface, many lapilli and volcanic block-sized ballistic ejecta fell within 1 km of the crater.

Geological observations

During the 2014 Mt. Ontake eruption tephra was ejected as PDC, ballistics, and air fall. Takarada et al. (2016)

and Maeno et al. (2016) document the total volume of tephra and the size of the eruption and Sasaki et al. (2016) describe the resulting lahar. Kaneko et al. (2016) and Tsunematsu et al. (2016) analyze the distribution of ballistic ejecta and Tsunematsu et al. (2016) simulate ballistic trajectory and calculate a landing energy of 10^4 J, essential data for future shelter designs.

Takarada et al. (2016) estimate discharged mass of the fallout deposit by a segment-integration method and find a total mass of around 1×10^6 tons, more than 90% of which occurs proximal to the craters. The discharged mass of the 2014 eruption is about half that of the 1979 eruption.

Sasaki et al. (2016) describe the syneruptive-spouted type lahar generated by water directly emitted from the craters. The lahar flowed downvalley south of the crater to a distance of 5 km. A rough estimate of the emplaced volume is 1.2×10^5 m^3, about 1/10 of the total discharge volume. The chemical characteristics of the lahar material are the same as those of the tephra, indicating a common origin.

Maeno et al. (2016) reconstruct the eruption sequence based on observations of PDC and fallout deposits in the proximal area near the crater. The deposits indicate that the eruption began dry but evolved to wet. The deposits show, from bottom to the top, gravity-driven dilute PDCs from the vent-opening phase; fallout from a vigorous moist plume during vent development; and wet ash fall. The particle concentration and initial flow velocity of the PDCs are estimated to be 2×10^{-4}–2×10^{-3} and 24–56 m/s, respectively.

Tsunematsu et al. (2016) estimate ejection velocities of ballistic projectiles by comparing simulation results with the observations by Kaneko et al. (2016). To account for the observed distribution in the summit area, ballistic projectiles are ejected at a vertical angle of 20° from vertical and at an azimuthal angle 20° clockwise from the north. The optimal ejection velocity is 145–185 m/s for a particle diameter of 20 cm with a drag coefficient of 0.62–1.01, and the mean landing energy is of the order of 10^4 J.

Seismological observations

Seismological observations are used to analyze source processes of earthquakes and tremors and locate their sources. Kato et al. (2015) and Zhang and Wen (2015) provide detailed descriptions of the hypocenters associated with the eruption. Maeda et al. (2015) infer crack opening immediately before the eruption. Ogiso et al. (2015) track the source location of tremor beneath the crater. Finally, Terakawa et al. (2016) reveal stress changes associated with the eruption, strongly implying fluid-pressure changes.

Kato et al. (2015) perform a high-resolution analysis of seismicity associated with the 2014 eruption using a matched-filter detection technique. They succeed in relocating the volcano-tectonic earthquakes (VT) and long-period earthquakes (LP) from August and September 2014. VT seismic activity increased from 6 September to 11 September, and a change in the frequency-magnitude distribution of the seismic activity (b-value) was also observed. During the 10-minute period before the eruption, VT earthquakes migrated upward and extended in a N–S direction, which roughly coincides with the orientation of the newly opened vents. The authors emphasize that hypocenter migration immediately before the eruption may reflect the movement of hydrothermal fluids to the surface.

Zhang and Wen (2015) (*Geophysical Research Letters*) apply the match-and-locate method to detect and precisely locate seismic activity associated with the 2007 and 2014 eruptions. The results for 2007 show less variation in the epicenter location than those associated with the 2014 eruption, consistent with the results of Kato et al. (2015).

Maeda et al. (2015) analyze a very long period earthquake (VLP event) that occurred 25 s before the start of the eruption and infer opening of an ENE-WSW-oriented tensile crack at a depth of 0.3–1 km from the surface. They infer that hydrothermal fluid flowed through the crack toward the surface.

Ogiso et al. (2015) use the spatial amplitude distribution of tremor data associated with the eruption to track the source location of the tremor. They find that it was located beneath the crater and descended 2 km over the course of several minutes following the onset of the eruption; this appears to be a robust solution.

Terakawa et al. (2016) (*Nature Communications*) analyze temporal change in the focal mechanism of earthquakes beneath the craters to document the stress variation associated with the phreatic eruption. Substantial deviation from the average stress field is observed in the focal mechanism in the period before the phreatic eruption.

Geodetic observations

Geodetic observation reveals deformation processes and can permit direct estimation of the location and geometry of the source of deformation. The four papers dealing with geodetic observations all consider both the 2007 and 2014 eruptions.

Takagi and Onizawa (2016) use Global Navigation Satellite System (GNSS) observations and model the inflation that occurred before the 2007 eruption as a volume increase of 6×10^6 m^3, mainly as crack opening (diking) at an estimated depth of 5 km below sea level. A smaller volume change of 0.38×10^6 m^3 at a depth of about 1 km beneath the surface is estimated for the period before the 2014 eruption. The apparent lack of deeper volume change prior to the 2014 eruption is viewed as consistent with the water-level observations of Koizumi et al. (2016).

Koizumi et al. (2016) analyze a groundwater-pressure monitoring record maintained from 1998 on at a borehole 10 km southeast of the summit. That record shows a clear drop in pressure prior to the 2007 eruption but no pressure change before or after the 2014 eruption, consistent with the inference of little or no additional magmatic intrusion.

Miyaoka and Takagi (2016) apply a stacking method to increase the signal-to-noise ratio of GNSS data and compare the period before the 2014 eruption to that before the 2007 eruption. The 2014 data reveal minor crustal deformation caused by volume change in a shallow source beginning one month before the eruption. The volume change is unresolvable but appears similar to that associated with the 2007 eruption.

Murase et al. (2016) use leveling-survey and GNSS data from 2002-present to estimate a source model of crustal deformation. Data from 2006 to 2007 are used to construct a model of crack opening for the 2007 eruption. From 2007 to 2013, no GNSS change was observed, but leveling surveys showed uplift on the eastern flank, suggesting continued crack opening there. During the 2014 eruption, baseline shortening and subsidence was observed, indicating deflation of the source beneath the summit.

Observations and analysis of the hydrothermal system

Geochemical study of volcanic fluids and tephra provides detailed information regarding the hydrothermal system that appears to have fed the eruption. Five papers show the possible range of depth and temperature of the source region as well as process that may connect the hydrothermal system with underlying magma. Based on the lack of juvenile materials, sulfur isotope equilibrium temperatures of 270–280 °C, and some indications of magmatic influence, these eruptions may be classified as "hydrothermal eruptions," in which most of eruption energy is derived from the hydrothermal system itself, indirectly influenced by deeper magmatic intrusion.

Ikehata and Maruoka (2016) analyze pyroclastic material from the 2014 eruption and show that it derives from acidic alteration zones. Sulfur isotope systematics show that the pyroclastic material equilibrated at a temperature of 270–280 °C. Pyroclastic material from the somewhat larger 1979 eruption is very similar in terms of mineral assemblage and sulfur isotope composition, with the exception of the sulfur isotope composition of anhydrite.

Minami et al. (2016) compare the mineral assemblage of the volcanic ash from the 2014 eruption with the well-known mineralogy of porphyry copper systems. The ash contains partly altered volcanic rock fragments and volcanic glass accompanied by alteration minerals, as is typical of non-juvenile hydrothermal-eruption deposits. The mineral composition indicates that the ash was derived from depths of less than 2 km.

Mori et al. (2016) describe a series of measurements of volcanic gas near the 2014 eruption vents which reveal that the volcanic gas was not directly emitted from magma but was influenced by hydrothermal system. The SO_2 flux was more than 2000 t/day one day after the onset of the eruption but decreased to 130 t/day over the course of the following two months. Taking the significant decline in the SO_2/H_2S ratio into account, it is likely that the H_2S flux remained about 700–800 t/day for two months after the onset of the eruption. Such a sustained high flux of H_2S is a peculiar feature of Mt. Ontake relative to other major volcanoes. A similar pattern of variation was observed following the 1979 eruption.

Sano et al. (2015) (*Nature Communications*) describe the results of intermittent monitoring (13 samples/33 years) of helium-isotope data from 1981 to present in the vicinity of Mt. Ontake. These data show an increasing $^3He/^4He$ ratio from 2000 to 2014 at the site nearest to the crater. This suggests increasing contribution of mantle helium and may reflect magmatic activity beneath Mt. Ontake volcano.

Sabry and Mogi (2016) mapped the electrical resistivity structure beneath Mt. Ontake using a GREATEM (GRounded Electrical source Airborne Transient ElectroMagnetic) system. A low-resistivity layer beneath the eastern flank of the volcano suggests the presence of a hydrothermal zone at around 500 m depth, potentially connected to the phreatic eruption.

Discussion

Shallow source structure

Several lines of evidence indicate that the source of the phreatic eruption was very shallow, originating beneath the crater at depths of less than 2 km and possibly less than 1 km. Geochemical study of volcanic fluids and tephra implies that the erupted materials came from a shallow hydrothermal system below the summit. This inference is consistent with analysis of the single VLP event (suggesting opening at 0.3–1 km depth) and models for geodetic deformation. The earthquake hypocenter locations (Kato et al. 2015) are 1–2 km deeper than the depth of the source of the phreatic eruption estimated from other methods. This inconsistency may result from uncertainty regarding the shallow seismic-velocity structure. Improved seismic-velocity mapping of Mt. Ontake would allow better hypocenter location beneath the summit area.

Since the 2014 eruption, the crater area has deflated at a nearly constant rate (Fig. 3). InSAR analysis (Narita and Murakami 2016) shows that ongoing deflation at a rate of 2–3 × 10^5 m^3 per year is also shallow-rooted (0.5 km depth) and localized, consistent with continued depressurization of the hydrothermal system. Post-eruption heat-discharge rates and the corresponding water mass fluxes are larger (order 10^4–10^5 tons per day, Terada 2014) than the deflation volume estimated with geodetic observations, suggesting continued contribution of additional hydrothermal fluids from larger, deeper source areas. A low-resistivity structure mapped by Sabry and Mogi (2016) extends beneath both the crater and eastern flank and suggests a possible connection to a larger hydrothermal system. The leveling survey by Murase et al. (2016) documents uplift and subsidence on the eastern flank between 2007 and 2014, possibly related to a hydrothermal system beneath the eastern flank.

Suggestions for future disaster mitigation

Most of the precursors that we rely on to forecast volcanic eruptions depend upon detection of fluid movement or its consequences. Because of the shallow source region and the low viscosity of the moving fluids, phreatic eruptions such as the 2014 eruption of Mt. Ontake can occur with little warning; fluid movement may begin only minutes in advance of eruption. However, obvious and potentially useful seismic and geodetic precursors may be detected tens of seconds to tens of minutes before eruption. In the case of the 2014 eruption of Mt. Ontake, rapid growth of tremor activity (Fig. 3 of Ogiso et al. 2015) and tilting (Fig. 7 of Takagi and Onizawa 2016) were observed about 7 min before the eruption. From the standpoint of public safety, it is therefore useful to consider options for communicating very short-term warning of phreatic eruptions. Given the short time frame, warnings may need to be generated automatically by means of an objective algorithm and communicated directly to the public by devices such as sirens or cellular devices.

Longer-term "precursors" such as changes in ground level (Murase et al. 2016) and helium-isotope ratios (Sano et al. 2015) have also been documented at Mt. Ontake. However, given the long-term (annual to decadal) evolution of these phenomena, and the inherent intermittency of the data, these observations are not useful for near-real-time forecasting. They can be very useful for retrospective process understanding.

There were also midterm (days) changes in seismic activity prior to the 2014 eruption of Mt. Ontake. The implications of the midterm seismic changes were regarded as ambiguous in real time. No complementary geodetic deformation was observed, but retrospective analysis of geodetic data (Miyaoka and Takagi 2016) confirmed that minor near-summit deformation did occur. An improved local geodetic network or analysis of InSAR data might have facilitated near-real-time interpretation of midterm seismic and geodetic changes.

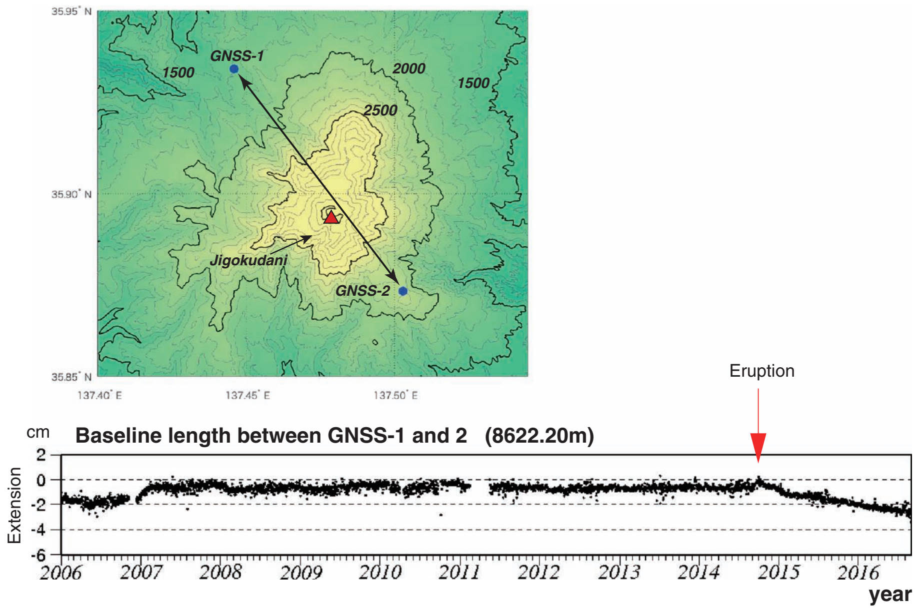

Fig. 3 Temporal change in baseline length between GNSS-1 (Ochiai-Karatani station) and GNSS-2 (Tanohara station); GNSS plot courtesy of the Japan Meteorological Agency

It is possible that magmatic intrusion prior to 1979 initiated the recent sequence of phreatic eruptions (1979, 1991, 2007, 2014) by adding heat and magmatic volatiles to the hydrothermal system. This speculation is consistent with increasing $^3He/^4He$ ratios observed since 1981 in proximal samples (Sano et al. 2015). The nature of geodetic deformation in 2007 suggests additional intrusion of new magma at mid-crustal depths of approximately 5 km. Although none of the recent eruptions have ejected juvenile material, the possibility of magma eruption remains, and the officials concerned with forecasting and public safety must consider the possibility that purely phreatic eruptions will evolve into phreatomagmatic eruptions.

It also seems possible, perhaps likely, that the recent cycle of phreatic eruptions at Mt. Ontake (1979, 1991, 2007, 2014) reflects repeated pressurization and breaching of the shallow hydrothermal system. In the absence of seismicity and associated fracturing, there is a fairly universal tendency for permeability to decrease due to mineral precipitation and other hydrothermal-alteration processes (Gleeson and Ingebritsen 2016). Thus, diminished fumarolic activity may reflect a period of sealing and pressurization of the shallow hydrothermal system; fractures begin to open or shear when fluid pressure is sufficiently elevated.

Monitoring and forecasting capability might be improved by deploying additional geophysical- and geochemical-monitoring capabilities in the near vicinity of the summit crater. Magnetometers will be deployed to monitor the magnetic total field, which may help to map ongoing hydrothermal alteration and temperature changes at relatively shallow depths. Gas monitoring will also help to understand the ongoing hydrothermal processes. Generating continuous long-term time series will require sustained effort in a remote near-summit environment that is characterized by extreme weather and discharge of high-temperature, low-pH hydrothermal fluids.

The 2014 eruption provides some lessons regarding public safety in the context of phreatic eruption. Most fatalities were related to impact ejecta. At Mt. Ontake, there was a window of several tens of seconds before the first ballistic impacts (Kaneko et al. 2016), which achieved energy on the order of 10^4 J (Tsunematsu et al. 2016). Thus, the public should be aware of nearby structures or natural features that can provide shelter from ejecta. The temperature of the PDC in this specific case was 30–100 °C (Oikawa et al. 2016), but could potentially have been higher because the temperature at the hydrothermal source is estimated to have been 270–280 °C (Ikehata and Maruoka 2016). Whereas the fatalities caused by ballistic impact occurred within 1 km of the vent, the vent-sourced lahar traveled about 5 km, sufficient distance to threaten nearby communities and affect the pH and turbidity of water supplies (Sasaki et al. 2016); thus, there is also potential for more distal damage.

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FRONTIER LETTER — Open Access

Preparatory and precursory processes leading up to the 2014 phreatic eruption of Mount Ontake, Japan

Aitaro Kato*, Toshiko Terakawa, Yoshiko Yamanaka, Yuta Maeda, Shinichiro Horikawa, Kenjiro Matsuhiro and Takashi Okuda

Earth, Planets and Space 2015, **67**:111 DOI: 10.1186/s40623-015-0288-x
Received: 15 April 2015, Accepted: 2 July 2015, Published: 16 July 2015

Abstract

We analyzed seismicity linked to the 2014 phreatic eruption of Mount Ontake, Japan, on 27 September 2014. We first relocated shallow volcano tectonic (VT) earthquakes and long-period (LP) events from August to September 2014. By applying a matched-filter technique to continuous waveforms using these relocated earthquakes, we detected numerous additional micro-earthquakes beneath the craters. The relocated VT earthquakes aligned on a near-vertical plane oriented NNW–SSE, suggesting they occurred around a conduit related to the intrusion of magmatic–hydrothermal fluids into the craters. The frequency of VT earthquakes gradually increased from 6 September 2014 and reached a peak on 11 September 2014. After the peak, seismicity levels remained elevated until the eruption. b-values gradually increased from 1.2 to 1.7 from 11 to 16 September 2014 then declined gradually and dropped to 0.8 just before the eruption. During the 10-min period immediately preceding the phreatic eruption, VT earthquakes migrated in the up-dip direction as well as laterally along the NNW–SSE feature. The migrating seismicity coincided with an accelerated increase of pre-eruptive tremor amplitude and with an anomalous tiltmeter signal that indicated summit upheaval. Therefore, the migrating seismicity suggests that the vertical conduit was filled with pressurized fluids, which rapidly propagated to the surface during the final 10 min before the eruption.

Keywords: Mount Ontake; 2014 phreatic eruption; Precursor; Earthquake; Relocation; Matched-filter technique; b-value

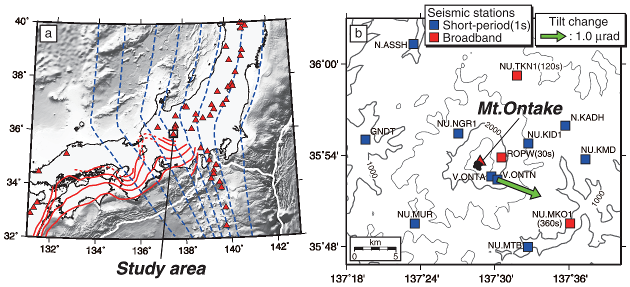

Figure 1

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FULL PAPER — Open Access

Descent of tremor source locations before the 2014 phreatic eruption of Ontake volcano, Japan

Masashi Ogiso*, Hirotoshi Matsubayashi and Tetsuya Yamamoto

Earth, Planets and Space 2015, **67**:206 DOI: 10.1186/s40623-015-0376-y
Received: 12 August 2015, Accepted: 16 December 2015, Published: 29 December 2015

Abstract

On 27 September 2014, Ontake volcano, in central Japan, suddenly erupted without precursory activity. We estimated and tracked the source locations of volcanic tremor associated with the eruption at high temporal resolution, using a method based on the spatial distribution of tremor amplitudes. Although the tremor source locations were not well constrained in depth, their epicenters were well located beneath the erupted crater and the summit. Tremor sources were seen to descend approximately 2 km over a period of several minutes prior to the beginning of the eruption. Detailed analysis of the time series of tremor amplitudes suggests that this descent is a robust feature. Our finding may be an important constraint for modeling the 2014 eruption of Ontake volcano as well as for monitoring activities on this and other volcanoes.

Keywords: Tremor location; Migration; Mechanism of phreatic eruption; Volcano monitoring; Ontake volcano

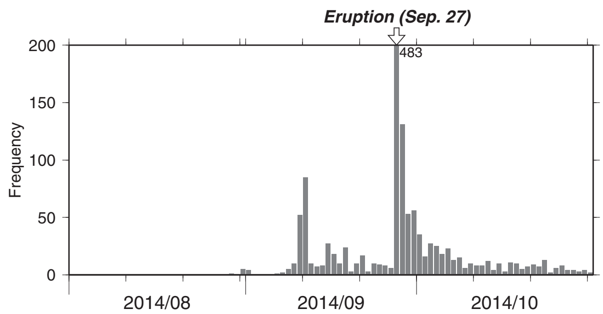

Figure 1

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FULL PAPER Open Access

Preparatory process preceding the 2014 eruption of Mount Ontake volcano, Japan: insights from precise leveling measurements

Masayuki Murase*, Fumiaki Kimata, Yoshiko Yamanaka, Shinichiro Horikawa, Kenjiro Matsuhiro, Takeshi Matsushima, Hitoshi Mori, Takahiro Ohkura, Shin Yoshikawa, Rikio Miyajima, Hiroyuki Inoue, Taketoshi Mishima, Tadaomi Sonoda, Kazunari Uchida, Keigo Yamamoto and Harushisa Nakamichi

Earth, Planets and Space 2016, **68**:9 DOI: 10.1186/s40623-016-0386-4

Received: 6 October 2015, Accepted: 13 January 2016, Published: 22 January 2016

Abstract

Preparatory activity preceding the 2014 eruption of Mount Ontake volcano was estimated from vertical deformation detected using a precise leveling survey. Notable uplift (2006–2009) and subsidence (2009–2014) were detected on the eastern flank of the volcano. We estimated pressure source models based on the vertical deformation and used these to infer preparatory process preceding the 2014 eruption. Our results suggest that the subsidence experienced between 2009 and 2014 (including the period of the 2014 eruption) occurred as a result of a sill-like tensile crack with a depth of 2.5 km. This tensile crack might inflate prior to the eruption and deflate during the 2014 activity. A two-tensile-crack model was used to explain uplift from 2006 to 2009. The geometry of the shallow crack was assumed to be the same as the sill-like tensile crack. The deep crack was estimated to be 2 km in length, 4.5 km in width, and 3 km in depth. Distinct uplifts began on the volcano flanks in 2006 and were followed by seismic activities and a small phreatic eruption in 2007. From the partially surveyed leveling data in August 2013, uplift might continue until August 2013 without seismic activity in the summit area. Based on the uplift from 2006 to 2013, magma ascended rapidly beneath the summit area in December 2006, and deep and shallow tensile cracks were expanded between 2006 and 2013. The presence of expanded cracks between 2007 and 2013 has not been inferred by previous studies. A phreatic eruption occurred on 27 September 2014, and, following this activity, the shallow crack may have deflated.

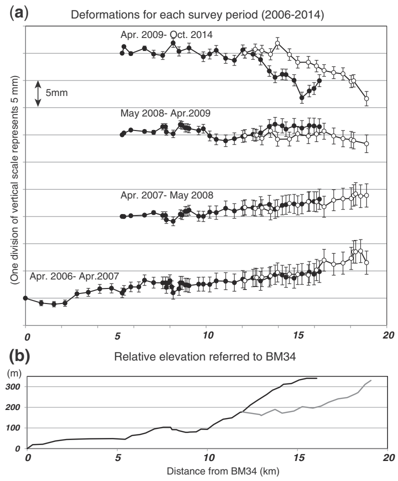

Figure 2

Keywords: Mount Ontake volcano; Preparatory process; Precise leveling survey; Vertical deformation; Pressure source

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FULL PAPER Open Access

Volcanic plume measurements using a UAV for the 2014 Mt. Ontake eruption

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Earth, Planets and Space 2016, **68**:49 DOI: 10.1186/s40623-016-0418-0

Received: 30 November 2015, Accepted: 24 February 2016, Published: 22 March 2016

Abstract

A phreatic eruption of Mt. Ontake, Japan, started abruptly on September 27, 2014, and caused the worst volcanic calamity in recent 70 years in Japan. We conducted volcanic plume surveys using an electric multirotor unmanned aerial vehicle to elucidate the conditions of Mt. Ontake's plume, which is flowing over 3000 m altitude. A plume gas composition, sulfur dioxide flux and thermal image measurements and a particle sampling were carried out using the unmanned aerial vehicle for three field campaigns on November 20 and 21, 2014, and June 2, 2015. Together with the results of manned helicopter and aircraft observations, we revealed that the plume of Mt. Ontake was not directly emitted from the magma but was influenced by hydrothermal system, and observed SO_2/H_2S molar ratios were decreasing after the eruption. High SO_2 flux of >2000 t/d observed at least until 20 h after the onset of the eruption implies significant input of magmatic gas and the flux quickly decreased to about 130 t/d in 2 months. In contrast, H_2S fluxes retrieved using SO_2/H_2S ratio and SO_2 flux showed significantly high level of 700–800 t/d, which continued at least between 2 weeks and 2 months after the eruption. This is a peculiar feature of the 2014 Mt. Ontake eruption. Considering the trends of the flux changes of SO_2 and H_2S, we presume that majority of SO_2 and H_2S are supplied, respectively, from high-temperature magmatic fluid of a deep origin and from hydrothermal system. From the point of view of SO_2/H_2S ratios and fumarolic temperatures, the plume degassing trend after the 2014 eruption is following the similar course as that after the 1979 eruptions, and we speculate the 2014 eruptive activity will cease slowly similar to the 1979 eruption.

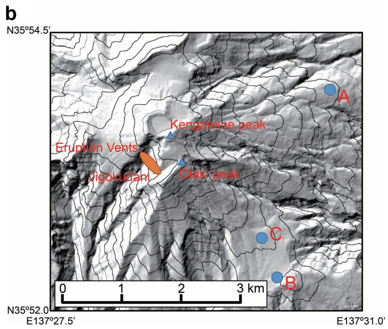

Figure 1

Keywords: Mt. Ontake; The 2014 eruption; Phreatic eruption; Volcanic plume; Sulfur dioxide; Hydrogen sulfide; Volcanic gas flux; UAV; MultiGAS

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FULL PAPER **Open Access**

2014 Mount Ontake eruption: characteristics of the phreatic eruption as inferred from aerial observations

Takayuki Kaneko*, Fukashi Maeno and Setsuya Nakada

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Abstract

The sudden eruption of Mount Ontake on September 27, 2014, led to a tragedy that caused more than 60 fatalities including missing persons. In order to mitigate the potential risks posed by similar volcano-related disasters, it is vital to have a clear understanding of the activity status and progression of eruptions. Because the erupted material was largely disturbed while access was strictly prohibited for a month, we analyzed the aerial photographs taken on September 28. The results showed that there were three large vents in the bottom of the Jigokudani valley on September 28. The vent in the center was considered to have been the main vent involved in the eruption, and the vents on either side were considered to have been formed by non-explosive processes. The pyroclastic flows extended approximately 2.5 km along the valley at an average speed of 32 km/h. The absence of burned or fallen trees in this area indicated that the temperatures and destructive forces associated with the pyroclastic flow were both low. The distribution of ballistics was categorized into four zones based on the number of impact craters per unit area, and the furthest impact crater was located 950 m from the vents. Based on ballistic models, the maximum initial velocity of the ejecta was estimated to be 111 m/s. Just after the beginning of the eruption, very few ballistic ejecta had arrived at the summit, even though the eruption plume had risen above the summit, which suggested that a large amount of ballistic ejecta was expelled from the volcano several tens-of-seconds after the beginning of the eruption. This initial period was characterized by the escape of a vapor phase from the vents, which then caused the explosive eruption phase that generated large amounts of ballistic ejecta via sudden decompression of a hydrothermal reservoir.

Keywords: Volcano; Aerial observation; Ballistics; Impact crater; Ontake; Phreatic eruption

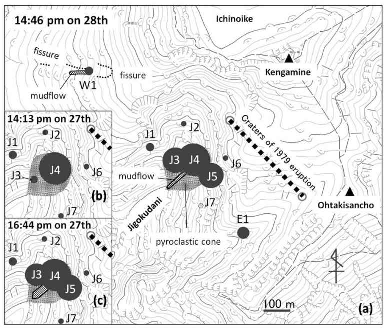

Figure 2

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FULL PAPER **Open Access**

Three-dimensional resistivity modeling of GREATEM survey data from Ontake Volcano, northwest Japan

Sabry Abd Allah* and Toru Mogi

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Received: 25 December 2015, Accepted: 13 April 2016, Published: 6 May 2016

Abstract

Ontake Volcano is located in central Japan, 200 km northwest of Tokyo and erupted on September 27, 2014. To study the structure of Ontake Volcano and discuss the process of its phreatic eruption, which can help in future eruptions mitigation, airborne electromagnetic (AEM) surveys using the grounded electrical-source airborne transient electromagnetic (GREATEM) system were conducted over Ontake Volcano. Field measurements and data analysis were done by OYO Company under the Sabo project managed by the Ministry of Land, Infrastructure, Transport and Tourism. Processed data and 1D resistivity models were provided by this project. We performed numerical forward modeling to generate a three-dimensional (3D) resistivity structure model that fits the GREATEM data where a composite of 1D resistivity models was used as the starting model. A 3D electromagnetic forward-modeling scheme based on a staggered-grid finite-difference method was modified and used to calculate the response of the 3D resistivity model along each survey line. We verified the model by examining the fit of magnetic-transient responses between the field data and 3D forward-model computed data. The preferred 3D resistivity models show that a moderately resistive structure (30–200 Ωm) is characteristic of most of the volcano, and were able to delineate a hydrothermal zone within the volcanic edifice. This hydrothermal zone may be caused by a previous large sector collapse.

Keywords: Airborne EM; 3D resistivity modeling; GREATEM survey; Volcanic surveys

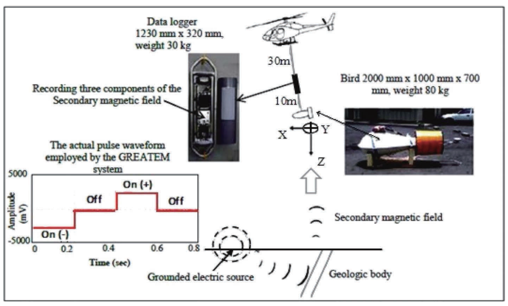

Figure 2

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Reconstruction of the 2014 eruption sequence of Ontake Volcano from recorded images and interviews

Teruki Oikawa*, Mitsuhiro Yoshimoto, Setsuya Nakada, Fukashi Maeno, Jiro Komori, Taketo Shimano, Yoshihiro Takeshita, Yoshihiro Ishizuka and Yasuhiro Ishimine

Earth, Planets and Space 2016, **68**:79 DOI: 10.1186/s40623-016-0458-5
Received: 9 December 2015, Accepted: 29 April 2016, Published: 14 May 2016

Abstract
A phreatic eruption at Mount Ontake (3067 m) on September 27, 2014, led to 64 casualties, including missing people. In this paper, we clarify the eruption sequence of the 2014 eruption from recorded images (photographs and videos obtained by climbers) and interviews with mountain guides and workers in mountain huts. The onset of eruption was sudden, without any clear precursory surface phenomena (such as ground rumbling or strong smell of sulfide). Our data indicate that the eruption sequence can be divided into three phases. Phase 1: The eruption started with dry pyroclastic density currents (PDCs) caused by ash column collapse. The PDCs flowed down 2.5 km SW and 2 km NW from the craters. In addition, PDCs moved horizontally by approximately 1.5 km toward N and E beyond summit ridges. The temperature of PDCs at the summit area partially exceeded 100 °C, and an analysis of interview results suggested that the temperature of PDCs was mostly in the range of 30–100 °C. At the summit area, there were violent falling ballistic rocks. Phase 2: When the outflow of PDCs stopped, the altitude of the eruption column increased; tephra with muddy rain started to fall; and ambient air temperature decreased. Falling ballistic rocks were almost absent during this phase. Phase 3: Finally, muddy hot water flowed out from the craters. These models reconstructed from observations are consistent with the phreatic eruption models and typical eruption sequences recorded at similar volcanoes.

Keywords: Ontake Volcano; Phreatic eruption; Eruption sequence; Photo; Video; Interview; Pyroclastic density current; Ash column collapse; Muddy rain; Lahar

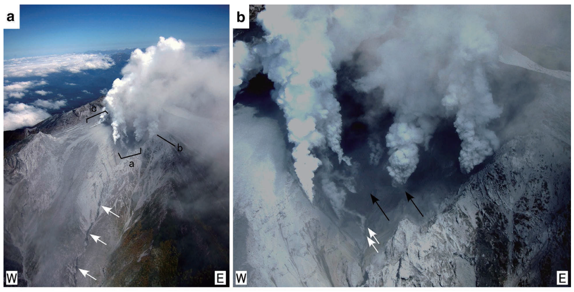

Figure 2

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Reconstruction of a phreatic eruption on 27 September 2014 at Ontake volcano, central Japan, based on proximal pyroclastic density current and fallout deposits

Fukashi Maeno*, Setsuya Nakada, Teruki Oikawa, Mitsuhiro Yoshimoto, Jiro Komori, Yoshihiro Ishizuka, Yoshihiro Takeshita, Taketo Shimano, Takayuki Kaneko and Masashi Nagai

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Received: 1 December 2015, Accepted: 18 April 2016, Published: 17 May 2016

Abstract
The phreatic eruption at Ontake volcano on 27 September 2014, which caused the worst volcanic disaster in the past half-century in Japan, was reconstructed based on observations of the proximal pyroclastic density current (PDC) and fallout deposits. Witness observations were also used to clarify the eruption process. The deposits are divided into three major depositional units (Units A, B, and C) which are characterized by massive, extremely poorly sorted, and multimodal grain-size distribution with 30–50 wt% of fine ash (silt–clay component). The depositional condition was initially dry but eventually changed to wet. Unit A originated from gravity-driven turbulent PDCs in the relatively dry, vent-opening phase. Unit B was then produced mainly by fallout from a vigorous moist plume during vent development. Unit C was derived from wet ash fall in the declining stage. Ballistic ejecta continuously occurred during vent opening and development. As observed in the finest population of the grain-size distribution, aggregate particles were formed throughout the eruption, and the effect of water in the plume on the aggregation increased with time and distance. Based on the deposit thickness, duration, and grain-size data, and by applying a scaling analysis using a depth-averaged model of turbulent gravity currents, the particle concentration and initial flow speed of the PDC at the summit area were estimated as 2×10^{-4}–2×10^{-3} and 24–28 m/s, respectively. The tephra thinning trend in the proximal area shows a steeper slope than in similar-sized magmatic eruptions, indicating a large tephra volume deposited over a short distance owing to the wet dispersal conditions. The Ontake eruption provided an opportunity to examine the deposits from a phreatic eruption with a complex eruption sequence that reflects the effect of external water on the eruption dynamics.

Keywords: Phreatic eruption; Pyroclastic density current; Ontake volcano; Aggregate; Grain-size distribution; Particle concentration; Flow speed

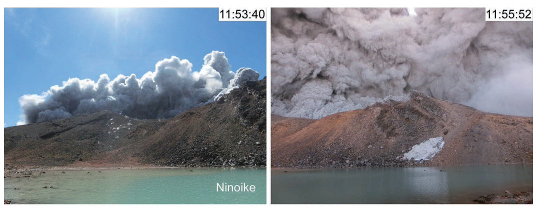

Figure 2

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FULL PAPER Open Access

Estimation of ballistic block landing energy during 2014 Mount Ontake eruption

Kae Tsunematsu*, Yasuhiro Ishimine, Takayuki Kaneko, Mitsuhiro Yoshimoto, Toshitsugu Fujii and Koshun Yamaoka

Earth, Planets and Space 2016, **68**:88 DOI: 10.1186/s40623-016-0463-8
Received: 30 November 2015, Accepted: 6 May 2016, Published: 25 May 2016

Abstract

The 2014 Mount Ontake eruption started just before noon on September 27, 2014. It killed 58 people, and five are still missing (as of January 1, 2016). The casualties were mainly caused by the impact of ballistic blocks around the summit area. It is necessary to know the magnitude of the block velocity and energy to construct a hazard map of ballistic projectiles and design effective shelters and mountain huts. The ejection velocities of the ballistic projectiles were estimated by comparing the observed distribution of the ballistic impact craters on the ground with simulated distributions of landing positions under various sets of conditions. A three-dimensional numerical multiparticle ballistic model adapted to account for topographic effect was used to estimate the ejection angles. From these simulations, we have obtained an ejection angle of $\gamma = 20°$ from vertical to horizontal and $\alpha = 20°$ from north to east. With these ejection angle conditions, the ejection speed was estimated to be between 145 and 185 m/s for a previously obtained range of drag coefficients of 0.62–1.01. The order of magnitude of the mean landing energy obtained using our numerical simulation was 10^4 J.

Keywords: Ballistics; Mount Ontake; 3D multiparticle numerical model; Drag; Topographic effect

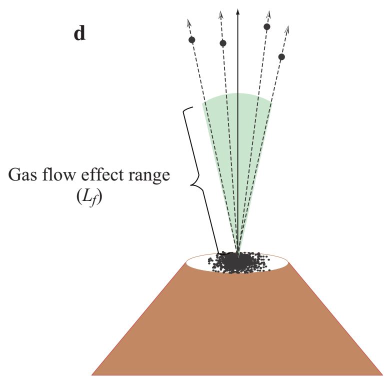

Figure 2

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FULL PAPER Open Access

Estimation of total discharged mass from the phreatic eruption of Ontake Volcano, central Japan, on September 27, 2014

Shinji Takarada*, Teruki Oikawa, Ryuta Furukawa, Hideo Hoshizumi, Jun'ichi Itoh, Nobuo Geshi and Isoji Miyagi

Earth, Planets and Space 2016, **68**:138 DOI: 10.1186/s40623-016-0511-4
Received: 4 January 2016, Accepted: 11 July 2016, Published: 2 August 2016

Abstract

The total mass discharged by the phreatic eruption of Ontake Volcano, central Japan, on September 27, 2014, was estimated using several methods. The estimated discharged mass was 1.2×10^6 t (segment integration method), 8.9×10^5 t (Pyle's exponential method), and varied from 8.6×10^3 to 2.5×10^6 t (Hayakawa's single isopach method). The segment integration and Pyle's exponential methods gave similar values. The single isopach method, however, gave a wide range of results depending on which contour was used. Therefore, the total discharged mass of the 2014 eruption is estimated at between 8.9×10^5 and 1.2×10^6 t. More than 90 % of the total mass accumulated within the proximal area. This shows how important it is to include a proximal area field survey for the total mass estimation of phreatic eruptions. A detailed isopleth mass distribution map was prepared covering as far as 85 km from the source. The main ash-fall dispersal was ENE in the proximal and medial areas and E in the distal area. The secondary distribution lobes also extended to the S and NW proximally, reflecting the effects of elutriation ash and surge deposits from pyroclastic density currents during the phreatic eruption. The total discharged mass of the 1979 phreatic eruption was also calculated for comparison. The resulting volume of 1.9×10^6 t (using the segment integration method) indicates that it was about 1.6–2.1 times larger than the 2014 eruption. The estimated average discharged mass flux rate of the 2014 eruption was 1.7×10^8 kg/h and for the 1979 eruption was 1.0×10^8 kg/h. One of the possible reasons for the higher flux rate of the 2014 eruption is the occurrence of pyroclastic density currents at the summit area.

Keywords: Ontake; 2014 Eruption; Phreatic; Discharged mass; Ash fall; Distribution; 1979 Eruption; Flux rate

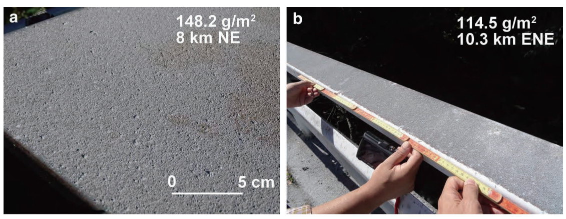

Figure 1

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LETTER Open Access

Source mechanism of a VLP event immediately before the 2014 eruption of Mt. Ontake, Japan

Yuta Maeda*, Aitaro Kato, Toshiko Terakawa, Yoshiko Yamanaka, Shinichiro Horikawa, Kenjiro Matsuhiro and Takashi Okuda

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Abstract

The phreatic eruption of Mt. Ontake in 2014 was preceded for 25 s by a very long period (VLP) seismic event recorded at one broadband and three short-period seismic stations located within 5000 m of the summit. We performed waveform inversion of the event within a frequency band of 0.1–0.5 Hz that pointed to an ENE-WSW opening (NNW-SSE striking) subvertical tensile crack at a depth of 300–1000 m beneath the region of the eruptive vents. This crack orientation is consistent with alignments of volcano-tectonic (VT) earthquake hypocenters and eruptive vents as well as normal faulting (E-W tension) focal mechanisms of the VT earthquakes. We interpreted these results as follows: the VLP source crack was one of a group of preexisting faults that was opened immediately before the eruption because of the passage of ascending gas from depth to the surface.

Keywords: Phreatic eruption; Mt. Ontake; VLP event; Waveform inversion

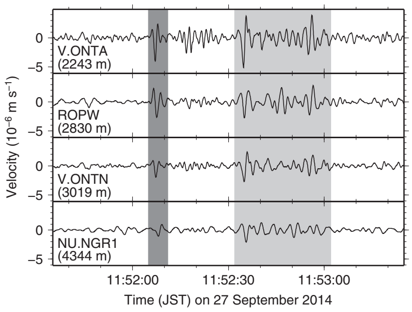

Figure 2

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LETTER Open Access

Groundwater pressure changes and crustal deformation before and after the 2007 and 2014 eruptions of Mt. Ontake

Naoji Koizumi*, Tsutomu Sato, Yuichi Kitagawa and Tadafumi Ochi

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Abstract

Volcanic activity generally causes crustal deformation, which sometimes induces groundwater changes, and both of these phenomena are sometimes detected before volcanic eruptions. Therefore, investigations of crustal deformation and groundwater changes can be useful for predicting volcanic eruptions. The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, has been observing groundwater pressure at Ohtaki observatory (GOT) since 1998. GOT is about 10 km southeast of the summit of Mt. Ontake. During this observation period, Mt. Ontake has erupted twice, in 2007 and in 2014. Before the 2007 eruption, the groundwater pressure at GOT clearly dropped, but it did not change before or after the 2014 eruption. These observations are consistent with the crustal deformation observed by Global Navigation Satellite System stations of the Geospatial Information Authority of Japan. The difference between the 2007 and 2014 eruptions can be explained if a relatively large magma intrusion occurred before the 2007 eruption but no or a small magma intrusion before the 2014 eruption.

Keywords: Mt. Ontake; Groundwater; Crustal deformation; Volcanic eruption; Magma; Precursor

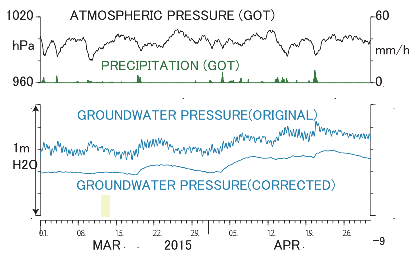

Figure 2

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LETTER Open Access

Detection of crustal deformation prior to the 2014 Mt. Ontake eruption by the stacking method

Kazuki Miyaoka* and Akimichi Takagi

Earth, Planets and Space 2016, **68**:60 DOI: 10.1186/s40623-016-0439-8
Received: 16 September 2015, Accepted: 6 April 2016, Published: 14 April 2016

Abstract

The phreatic eruption of Mt. Ontake in central Japan occurred in September 27, 2014. No obvious crustal deformation was observed prior to the eruption, and the magnitudes of other precursor phenomena were very small. In this study, we used the stacking method to detect crustal deformation prior to the eruption. The stacking method is a technique to improve the signal-to-noise ratio by stacking multiple records of crustal deformation. We succeeded in detecting a slight crustal deformation caused by a volume change in the shallow region beneath the volcano's summit from 1 month prior to the eruption. We also detected a slight crustal deformation that may have been caused by a volume increase in the deep region from one and a half months before the eruption. The magnitude of the volume change in the shallow region did not differ significantly in the 2014 eruption compared to the volume change during the small Mt. Ontake eruption in 2007, and the volume change in the deep region was rather smaller in 2014 than in 2007.

Keywords: Mt. Ontake; Precursor phenomena; Crustal deformation; Stacking method; GNSS

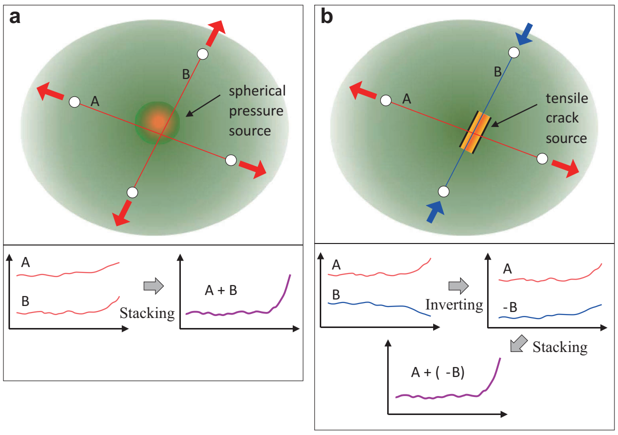

Figure 2

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Mineralogical study on volcanic ash of the eruption on September 27, 2014 at Ontake volcano, central Japan: correlation with porphyry copper systems

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Abstract

The volcanic ash of the eruption on September 27, 2014 at Ontake volcano consists mostly of altered rock fragments. The ash contains partly altered volcanic rock fragments consisting of primary igneous minerals (plagioclase, orthopyroxene, titanomagnetite, and feldspars) and volcanic glass accompanied by alteration minerals to some extents, and contains no juvenile fragments. These features indicate that the eruption was a non-juvenile hydrothermal eruption that was derived from the hydrothermal system developed under the crater. The major minerals derived from hydrothermal alteration zones are silica mineral, kaolin-group mineral, smectite, pyrophyllite, muscovite, alunite, anhydrite, gypsum, pyrite, K-feldspar, albite, and rutile. Minor chlorite, biotite, and garnet are accompanied. Five types of alteration mineral associations are identified from observations on individual ash particles: silica–pyrite, silica–pyrite ± alunite ± kaolin, silica–pyrophyllite–pyrite, silica–muscovite ± chlorite, and silica–K-feldspar ± albite ± garnet ± biotite. The associations indicate development of advanced argillic, sericite, and potassic alteration zones under the crater. Occurrence of anhydrite veinlet and the set of alteration zones indicate hydrothermal alteration zones similar to late-stage porphyry copper systems. Comparing the mineral associations with the geologic model of the late-stage porphyry copper systems, the source depths of mineral associations are estimated to range from near surface to >2 km. The depths of advanced argillic alteration, sericite, and potassic zones are 0 to ~2, ~1.5 to ~2, and >2 km, respectively.

Keywords: Hydrothermal eruption; Volcano-hydrothermal system; Acid-sulfate hydrothermal system; Ontake volcano

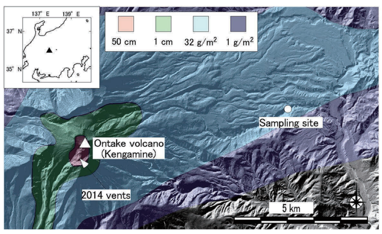

Figure 1

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LETTER Open Access

Sulfur isotopic characteristics of volcanic products from the September 2014 Mount Ontake eruption, Japan

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Abstract

Components and sulfur isotopic compositions of pyroclastic materials from the 2014 Mt. Ontake eruption were investigated. The volcanic ash samples were found to be composed of altered volcanic fragments, alunite, anhydrite, biotite, cristobalite, gypsum, ilmenite, kaolin minerals, native sulfur, orthopyroxene, plagioclase, potassium feldspar, pyrite, pyrophyllite, quartz, rutile, and smectite, and most of these minerals were likely derived from the acidic alteration zones of Mt. Ontake. The absence of juvenile material in the eruptive products indicates that the eruption was phreatic. The sulfur isotopic compositions of the water-leached sulfate, hydrochloric acid-leached sulfate, acetone-leached native sulfur, and pyrite of the samples indicate that these sulfur species were produced by disproportionation of magmatic SO_2 in the hydrothermal system at temperatures of 270–281 °C. This temperature range is consistent with that inferred from the hydrothermal mineral assemblage (e.g., pyrophyllite and rutile) in the 2014 pyroclastic materials (200–300 °C). Except for the sulfur isotopic compositions of anhydrite, which may have been altered by incorporation of sulfate minerals in a fumarolic area with lower sulfur isotopic values into the underground materials during the 1979 eruption, no significant differences in the mineral assemblages and sulfur isotopic compositions of the pyroclastic materials were identified between the products of the 2014 and 1979 Ontake phreatic eruptions, which suggests geochemical similarities in the underlying hydrothermal systems before the 2014 and 1979 eruptions.

Keywords: Mount Ontake; Phreatic eruption; Sulfur isotopic composition; Hydrothermal minerals

Figure 2

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LETTER Open Access

Shallow pressure sources associated with the 2007 and 2014 phreatic eruptions of Mt. Ontake, Japan

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Abstract

We modeled pressure sources under Mount Ontake volcano, Japan, on the basis of global navigation satellite system (GNSS) observations of ground deformation during the time period including the 2007 and 2014 phreatic eruptions. The total change in volume in two sources below sea level in the period including the 2007 eruption was estimated from GNSS network observations to be 6×10^6 m^3. Additionally, data from a GNSS campaign survey yielded an estimated volume change of 0.28×10^6 m^3 in a shallower source just beneath the volcanic vents. The 2007 eruption may have been activated by magmatic activity at depth. During the 2014 eruption, the volume change at depth was very small. However, tiltmeter data indicated inflation from a shallow source that began 7 min before the eruption, representing a volume change estimated to be 0.38×10^6 m^3. We infer that the potential for subsurface hydrothermal activity may have remained high after the 2007 eruption.

Keywords: Mt. Ontake; Phreatic eruption; Pressure source; GNSS; Tiltmeter

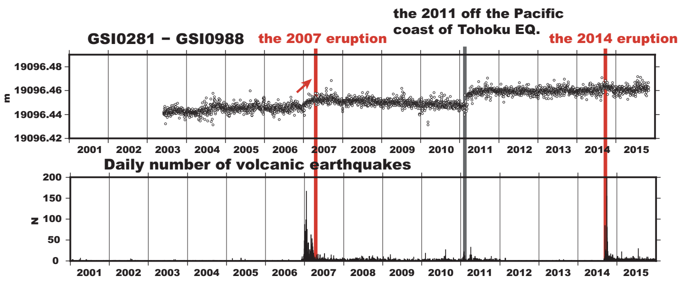

Figure 2

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LETTER Open Access

Characteristics of the syneruptive-spouted type lahar generated by the September 2014 eruption of Mount Ontake, Japan

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Abstract

Mount Ontake erupted at 11:52 am on September 27, 2014, which generated pyroclastic density currents, ballistic projectiles, ash falls, and a small-scale lahar that spouted directly from craters formed by the eruption. Because this lahar may have been generated by water released from within these craters, we refer to this lahar as a "syneruptive-spouted type lahar" in this study. The lahar of the 2014 eruption was small relative to the other syneruptive type lahars reported in the past that were snowmelt type or crater lake breakout type lahars. Nevertheless, in the 2014 event, the syneruptive-spouted type lahar extended approximately 5 km downstream from the Jigokudani crater via the Akagawa River, with an estimated total volume of ~1.2×10^5 m^3.
We have reviewed other representative syneruptive-spouted type lahars that have been reported in Japan. The syneruptive-spouted type lahar attributed to the September 2014 eruption had the longest runout distance and largest volume of all cases studied. The mineral assemblage identified from samples of the lahar deposits is similar to that of ash-fall deposits from the same eruption. Previous workers deduced that the ash was derived mainly from shallow depths (within 2 km of the surface). The syneruptive-spouted type lahar deposits are therefore also considered to have originated from shallow depths. A syneruptive-spouted type lahar is a small-scale phenomenon that causes little direct damage to infrastructure, but has long-term influence on water quality. Increases in turbidity and decreases in pH are expected to occur in the Mount Ontake area downstream of Nigorisawa after heavy rainfall events in the future. Therefore, the potential indirect (but long term) damage of syneruptive-spouted type lahars should be considered for hazard mapping and planning volcanic disaster prevention measures.

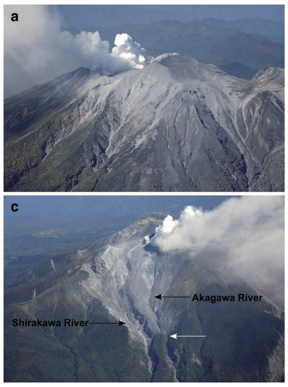

Figure 2

Keywords: Phreatic eruption; Syneruptive-spouted type lahar; Muddy water; Water quality; Ontake volcano

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