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

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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

Introduction

Non-juvenile eruptions, often referred to as phreatic or hydrothermal eruptions, represent one of the most common explosive eruption types on Earth. Phreatic eruptions, which are violent and dramatic events, result in the rapid ejection of boiling water, steam, mud, and rock fragments from source craters (Morgan et al. 2009). Phreatic eruptions pose a significant hazard to areas in proximity of the erupting crater and occasionally lead to larger-scale deadly density currents (e.g., Yamamoto et al. 1999; Fujinawa et al. 2006). Low-temperature pyroclastic flows (pyroclastic density currents) accompanying phreatic eruptions have been reported in Japan, Tongariro (New Zealand), and La Soufriere (Guadeloupe) (e.g., Fujinawa et al. 2008; Lube et al. 2014; Miura et al. 2012; Nakamura and Glicken 1988; Sheridan 1980; Yamamoto et al. 1999). Low-temperature pyroclastic density currents accompanying phreatic eruptions are steam driven and usually laterally directed by the phreatic explosion (Lube et al. 2014). It has also been hypothesized that those pyroclastic density currents are produced by collapse of the phreatic non-buoyant plume (Yamamoto et al. 1999). However, occurrence of these flows has itself not been well observed. On August 6, 2012, a volcano erupted at Te Maari, Tongariro in New Zealand (Breard et al. 2014; Fitzgerald et al. 2014; Lube et al. 2014); however, the eruption was only indirectly observed because

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it occurred at night. The actual timing and origin of the pyroclastic flows accompanying phreatic eruption occurrence in a series of eruptions thus remain unclear. On September 27, 2014, there was an eruption of Ontake Volcano (Ontake-san, Mount Ontake); 64 people were dead or missing. This was a phreatic eruption accompanied by pyroclastic density currents (PDCs) (Nakano et al. 2014; Oikawa et al. 2015; Yamamoto 2014). Over 150 climbers were near the craters at the summit area at the start of the eruption, which increased the damage caused by the event. This is unlike the Te Maari 2012 nocturnal eruption (e.g., Lube et al. 2014). There were numerous eyewitnesses to the eruption, as well as recorded images, videos, and photographs. In this study, we reconstructed the sequence of the September 27, 2014 eruption on the basis of the recorded videos and photographs and via interviews with survivors of the eruption. An eruption model was then built from the reconstructed eruption sequence.

Geology of Ontake Volcano

Ontake Volcano (the highest peak of which is Kengamine: 3067 m a.s.l.) is located on the boundary of Gifu and Nagano Prefectures in central Japan. Lavas and volcaniclastic deposits of the Ontake Volcano have built a huge stratovolcano of up to ~80 km^3 (Kobayashi and Matsumoto 1994). The volcano consists of older (0.78–0.39 Ma) and younger (after ca. 0.1 Ma) Ontake Volcanoes (Kioka et al. 1998; Matsumoto and Kobayashi 1995, 1999; Takeuchi et al. 1998; Yamada and Kobayashi 1988). The frequency of magmatic and phreatic eruptions in the Holocene is 0.3 times/ky and 2 times/ky, respectively (Oikawa et al. 2014, 2015). However, no historical records of eruptions of Ontake Volcano before the 1979 phreatic eruption have yet been discovered (Oikawa 2008). From historical records, we know that fumarolic activity in Jigoku-dani has been recognized within the summit area since the middle of the eighteenth century (Oikawa 2008).

The 1979 eruption, which was a phreatic eruption, started at around 05:00 JST (UTC + 9), on October 28 (Kobayashi 1979; Ossaka et al. 1983; Soya et al. 1980; Yamada and Kobayashi 1988). The eruption intensity gradually increased and reached a maximum at around 14:00. The eruption plume altitude reached approximately 2 km (above the crater), according to visual measurements. The eruption terminated after around 1 day. The eruption vents across Hatchotarumi on the valley head of Jigoku-dani opened up in a NW–SE direction with a length of approximately 500 m (Fig. 1). Clay-rich fine fall ash and minor volcanic block-sized ballistic rocks (Ossaka et al. 1983) amounting to 0.95–1.23 × 10^6 m^3 (Maeno et al. 2016) were produced during this eruption. The ejected volcanic block-sized ballistic rocks reached the huts around the Kengamine peak.

In 1991 and 2007, there were small emissions of volcanic ash (micro-eruptions) from a fumarole in Hatchotarumi (Fig. 1), which is also one of the 1979 eruption vents (e.g., JMA 1991; Nakamichi et al. 2009). The tephra volume of each eruption was less than 1 × 10^2 m^3.

Outline of the 2014 eruption

The 2014 phreatic eruption (e.g., Imura et al. 2014; Minami et al. 2015; Miyagi et al. 2014) started at around 11:52 JST (UTC + 9) on September 27 (JMA 2014). Erupted materials are mainly composed of alternation rocks and minerals (non-juvenile materials) (e.g., Minami et al. 2015; Miyagi et al. 2014). During the eruption, new vents opened from the west of Ichi-no-ike across the valley head of Jigoku-dani. The new vents of the 2014 eruption are located to the south of the 1979 eruption craters, distributed almost linearly along a span of approximately 800 m (Figs. 1, 2). Before the 2014 eruption, fumaroles were active at some of the 1979 craters and Jigoku-dani. However, they were not activated before/after the 2014 eruption.

The day of the eruption was sunny, with weak wind, and, as noted, the phreatic eruption was accompanied by PDCs (Nakano et al. 2014; Oikawa et al. 2014, 2015; Yamamoto 2014). This eruption formed small pyroclastic cones in Jigoku-dani (Fig. 2a, b; Nakano et al. 2014; Oikawa et al. 2015). However, these cones were eroded by rainfall during typhoons No. 18 and 19 on October 5–6 and 13–14, 2014 (Oikawa et al. 2015). The height of the eruption plume reached approximately 7.8 km above the crater at around 12:10–12:20, September 27, 2014, based on a radar echo analysis (Sato et al. 2016). However, after 17:40, the eruption plume height decreased to less than 2 km above the craters. The plume and resultant ash fall were directed east by a westerly wind and resulted in an ash fall mainly to the east (The Joint Research Team for Ash Fall in Ontake 2014 Eruption 2015). The ash fall was mostly terminated before the morning of September 28 (Fukuyama and Hiramatsu 2015; Tajima et al. 2014). However, the outflow of gray muddy water (likely hot spring water) from the craters in Jigoku-dani started after the eruption on September 27, 2014 (Kishimoto et al. 2014; Nakano et al. 2014; Oikawa et al. 2014, 2015) and continued till July 2015. The tephra volume from the 2014 eruption was 0.7–1.2 × 10^6 m^3 (Maeno et al. 2016).

Fifty-eight people were killed during this eruption, with still five missing (as of November 2015). The main cause of death of 56 individuals, according to the news (October 27, 2014, and August 2, 2015, Asahi Shimbun), was injury inflicted by ballistic rocks. One person was reportedly killed by inhalation burns, and another person was killed by unknown causes.

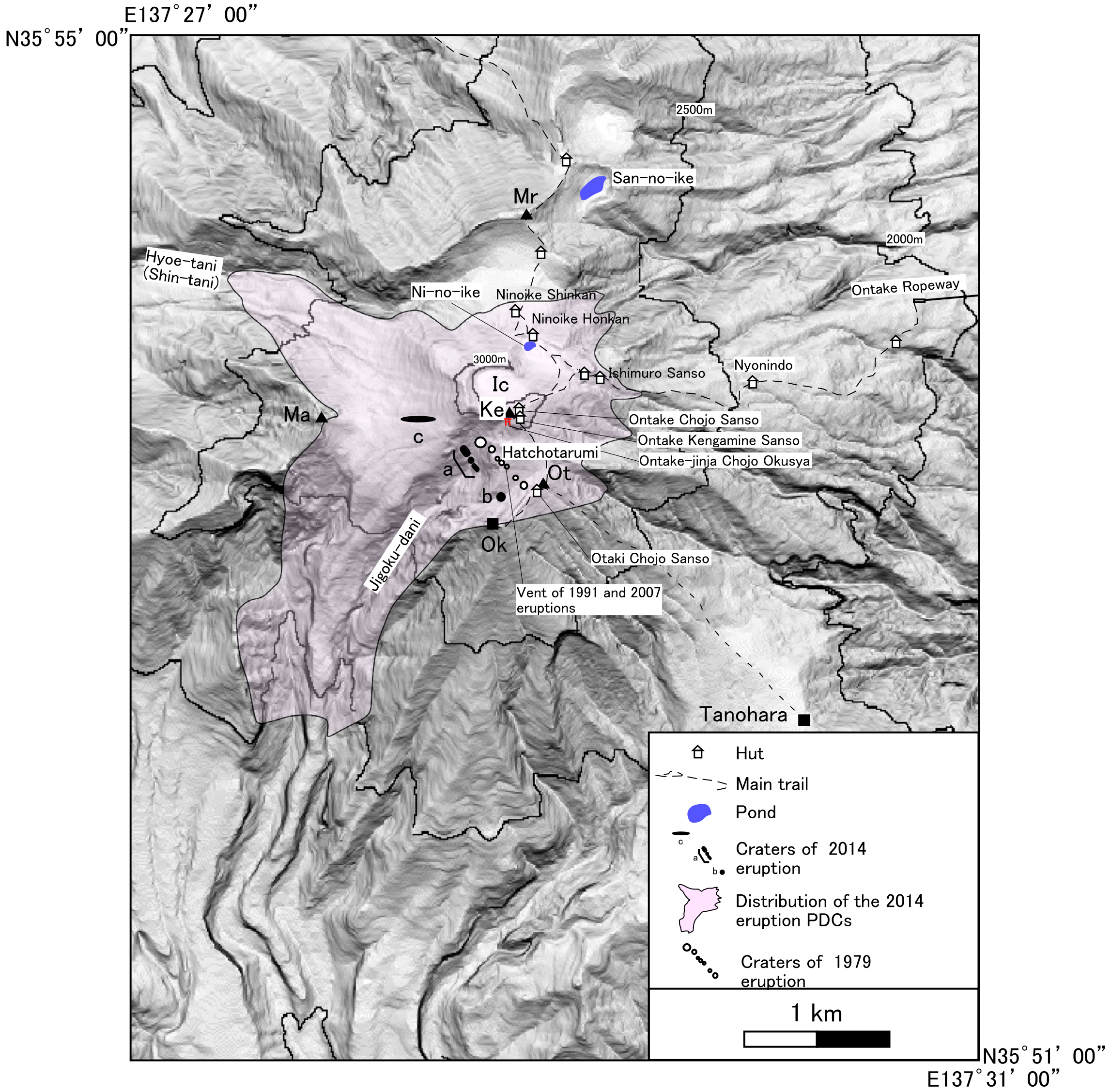

Fig. 1 Shaded relief map of inclination around Ontake Volcano, constructed using the topographic data of the digital map 10-m grid (elevation) published by the geospatial information authority of Japan. *Ic* Ichi-no-ike, *Ke* Kengamine, *Ma* Mamahaha-dake, *Mr* Marishiten-san, *Ot* Otaki-chojyo, *Ok* Okunoin

Methods

We analyzed the eruption sequence of the 2014 eruption on the basis of recorded images in photographs and videos obtained by climbers and via interviews with mountain guides and workers in mountain huts. For analysis, we used six videos and >50 photographs taken by six people. The locations from where these evidence sources were recorded are shown in Fig. 3. The numbers in Fig. 3 represent the position of the witness and observation points. Place names are also provided in Fig. 3.

Images were arranged in a time series, according to the time information of exchangeable image file format (exif) for digital photographs and to the time stamp of videos. However, time recording by a digital camera for exif information is not always accurate. The clock of digital cameras is often not adjusted to the correct time by the user. We therefore arranged the images using the following procedure. First, a group of photographs that had been calibrated with accurate clocks (such as GPS clocks) were arranged along a time axis. Next, on the basis of the similarity of shape and height of the plume, photographs with inaccurate time data were located at the correct time. Finally, photographs taken with the same camera were arranged along the time axis according to the photographing interval obtained from exif information.

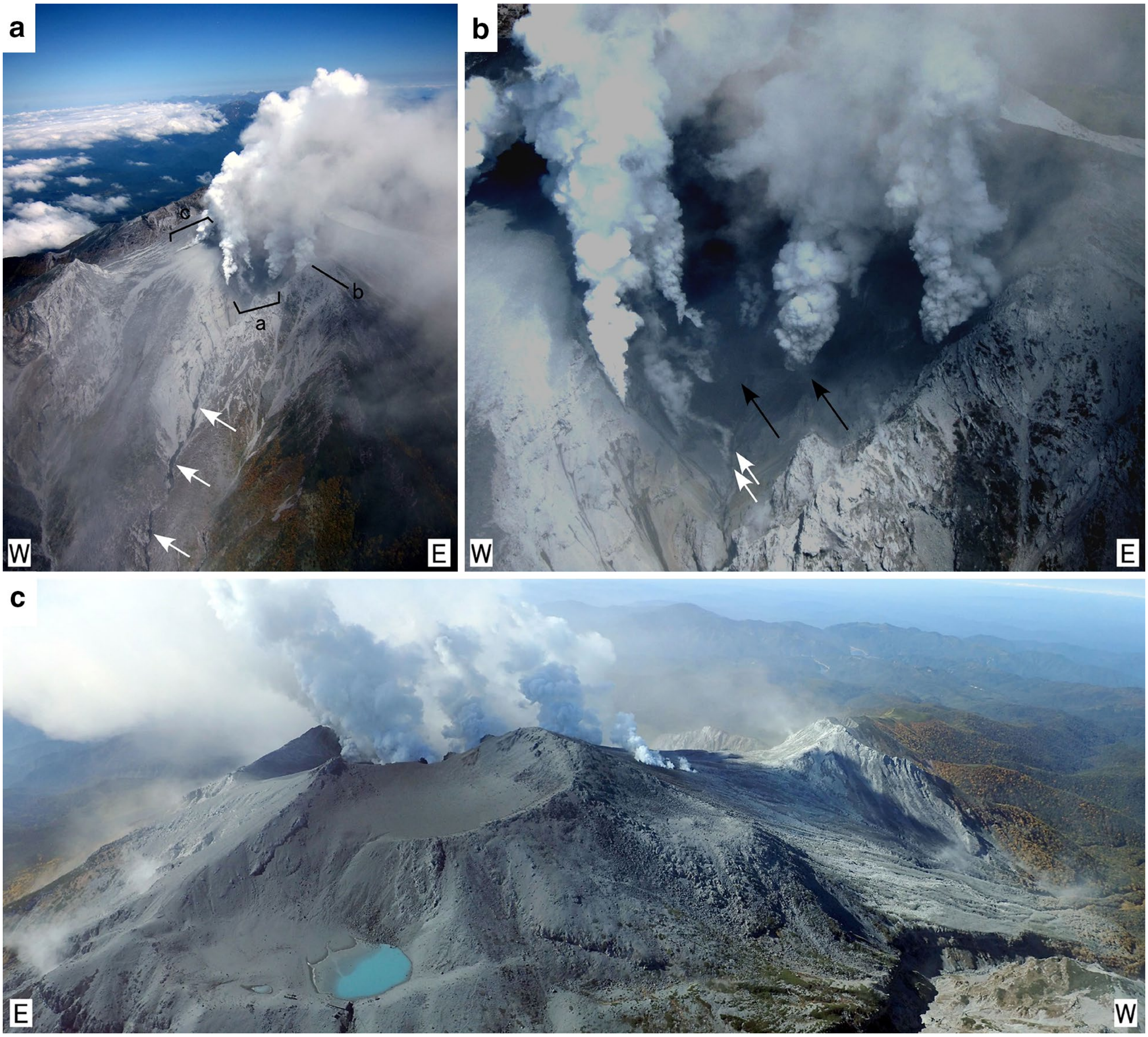

Fig. 2 Aerial photographs of Ontake Volcano on the day following start of the 2014 eruption. Photographs were taken on September 28, 2014, by T Oikawa from a helicopter of Chunichi Shimbun. The area covered by the PDCs is colored in *gray* or *griseous white* in the photographs. **a** View from the SSE. The valley that extends in front of the photograph is Jigoku-dani (also see Fig. 1). **a**–**c** Crater names (also see Fig. 1). *White arrows* show the direction of muddy water flow from the 2014 craters in the Jigoku-dani. **b** The craters in Jigoku-dani and under the Okunoin, viewed from the south. The rightmost crater in the photograph is the crater under Okunoin. *White arrows* show the direction of muddy water flow from the 2014 craters. *Black arrows* represent small pyroclastic cones in the Jigoku-dani. **c** Summit of Ontake Volcano, viewed from the north. The *center left* of the crater topography is Ichi-no-ike, and the pond is Ni-no-ike. The *right side* of the photograph is the Hyoe-tani (Shin-tani) side

Videos (recorded from the east side of the crater) published by the mass media (specifically the broadcaster NHK), videos recorded by the Chubu Regional Bureau, Ministry of Land, Infrastructure, Transport and Tourism from the south side of the crater, and videos recoded by climbers from the north and southeast side of the crater were used. Each of the recording positions, except for that of the Chubu Regional Bureau, is shown in Fig. 3. The Chubu Regional Bureau's recording position was at Takigoshi, approximately 6 km SSW from the summit.

We interviewed four mountain hut workers at the summit area of Mt. Ontake, three mountain guides, and a photographer. In addition, published interview articles in various sources (such as newspapers and books) (e.g., Yama-to-keikoku 2014) were also used. Interviews were carried face-to-face. Care was taken to ensure that

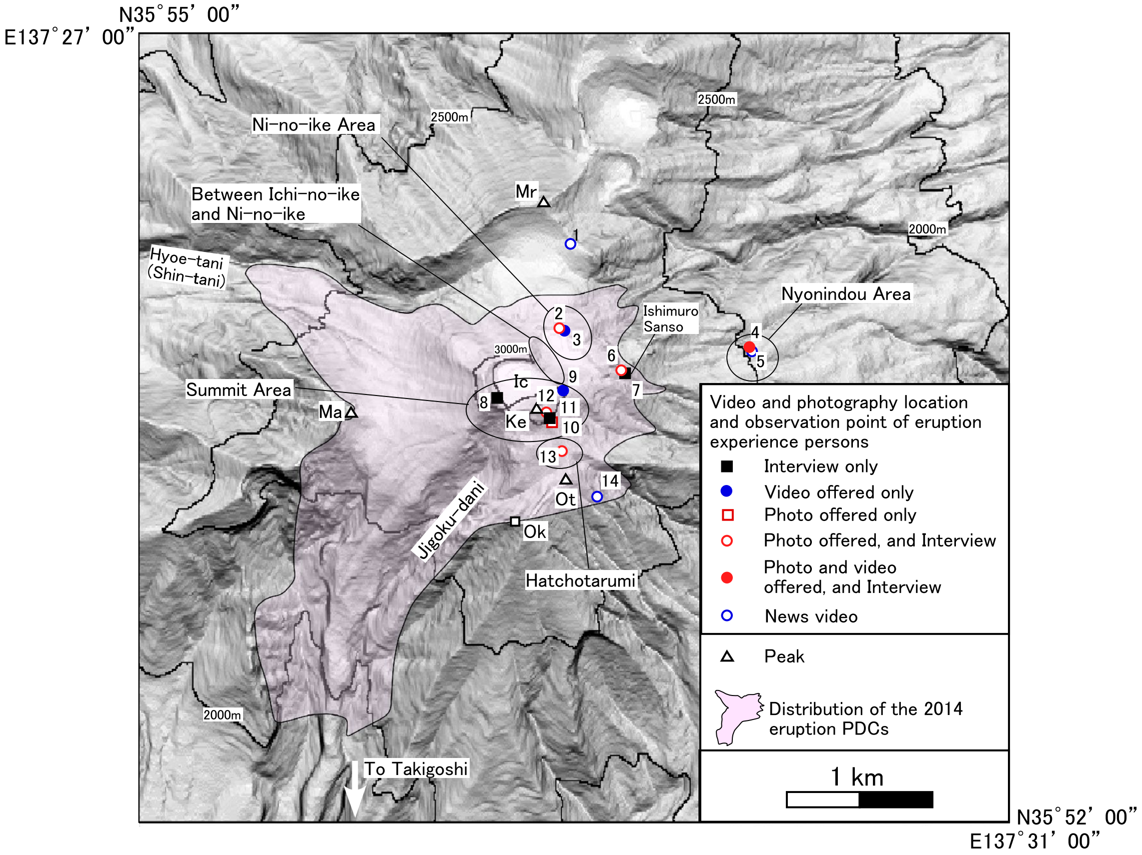

Fig. 3 Observation point of hut workers and climbers (mountain guides and photographers). It also shows place and area names. *Ic* Ichi-no-ike, *Ke* Kengamine, *Ma* Mamahaha-dake, *Mr* Marishiten-san, *Ot* Otaki-chojyo, *Ok* Okunoin

any bias would be minimized. Witnesses recounted their experience of the eruption chronologically. Our questions were simple and intended only to confirm facts. The matching of multiple testimonies did not produce any conflicting accounts.

With these data, we reconstructed the eruption sequence from 11:52 until 18:00 on September 27, during which period the main eruption phenomenon of the 2014 eruption occurred.

Results and discussion

Eruption sequence

The eruption of September 27 can be divided into three phases: Phase 1, from 11:52 (JST) to around 12:15; Phase 2, from around 12:15–16:00; and Phase 3 after around 16:00.

Phase 1: 11:52:30–ca. 12:15, September 27, 2014

According to the testimonies of workers in the mountain huts (2, 11, 12, and 13 in Fig. 3), the onset of eruption was sudden, without any clear precursory surface phenomena, such as ground rumbling, strong seismic motion, and strong smell of sulfide. The images with time information suggest that the eruption began suddenly at ca. 11:52:30. The interviewees reported no perceptive sound at the start of the eruption, and only a small infrasound, from a small tremor of windows and doors of mountain huts, was observed (3 in Fig. 3).

Phase 1 is characterized by the occurrence of low-temperature PDCs. Figure 4 shows the area covered by PDCs. The PDCs flowed down 2.5 km SW and 2 km NW from the craters (Fig. 2a, c). In addition, PDCs moved horizontally by approximately 1.5 km toward N and E beyond summit ridges.

According to the interviews (8, 11, 12, 13 in Fig. 3), when the climbers at the summit were covered by the PDCs, visibility deteriorated significantly to <1 m. The temperature in the PDCs was higher than of surrounding air. The PDCs were dry, with humidity lower than the dew point, and did not contain liquid water. One person in Hatchotarumi (13 in Fig. 3), which is approximately 500 m east of the craters in Jigoku-dani, did not suffer skin burns, but chocolate kept in his backpack melted and his hair was partly damaged and discolored. Although

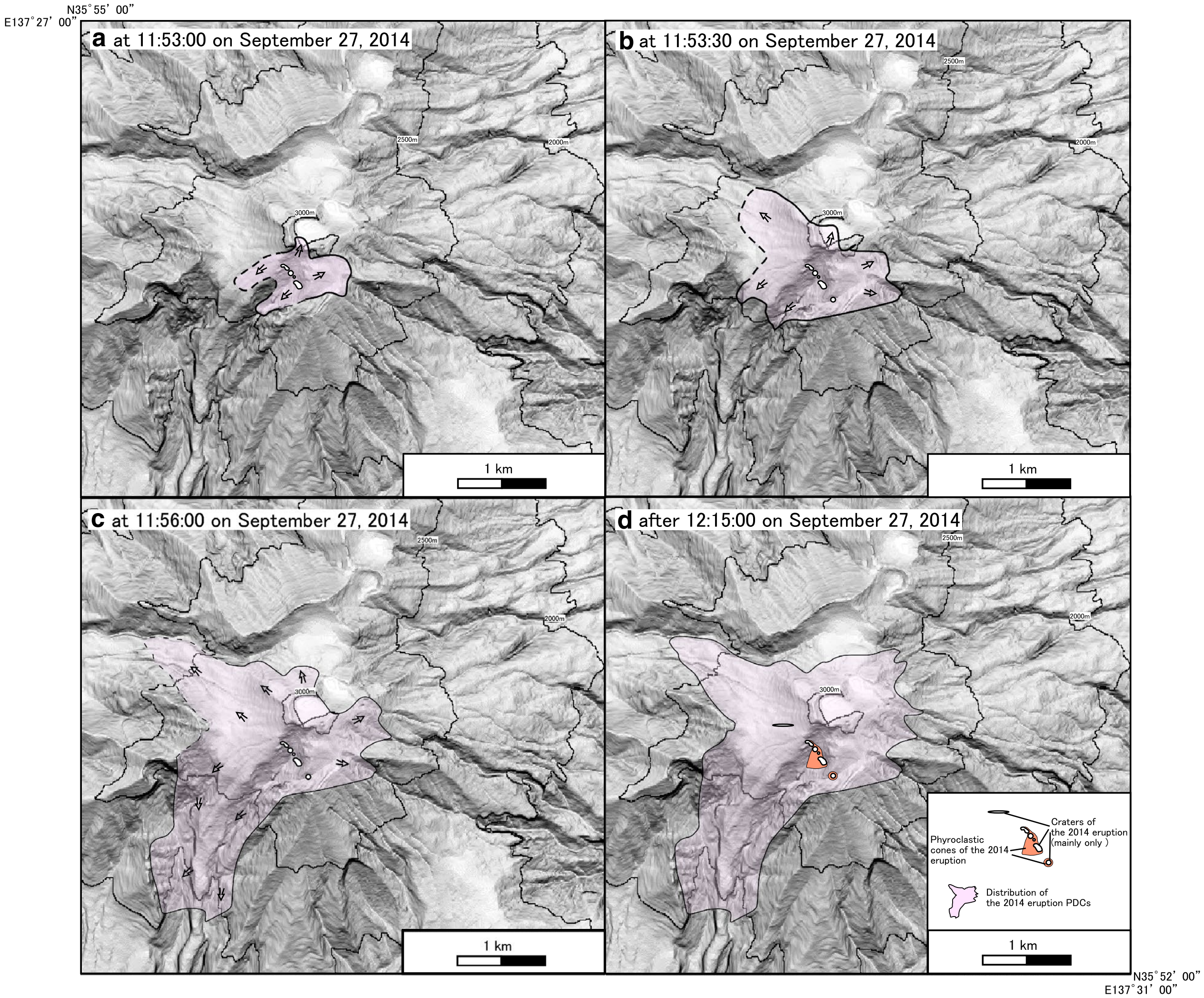

Fig. 4 Distribution of PDCs on September 27, 2014

vegetation was spread across the area that the PDCs covered, the leaves of *Pinus pumila* between Marishiten-san and Kangamine were only discolored to brown. During this phase, the volcanic block-sized rock fragments (with a maximum diameter of 74 cm) showered densely on the summit area and Hatchotarumi. Rock fragments of 20–30 cm diameter fell approximately 1.3 km away from the craters (Oikawa et al. 2015). However, based on our preliminary field survey, the density of volcanic block-sized rocks is high (one/m^2 or more) within a distance of about 700 m from the 2014 craters.

Phase 1 is divided into three sub-phases: Phase 1a from 11:52:30 to around 11:53, Phase 1b from around 11:53 to around 12:00, and Phase 1c from around 12:00 to 12:15. The division into phases 1a and 1b is based on differences in crater activity and on the expanding area of PDCs. The division into phases 1b and 1c is based on the presence of a short eruption pause.

Phase 1a (11:52:30 to around 11:53)

The eruption started from the newly opened craters in Jigoku-dani, at an altitude of 2700–2800 m a.s.l. (a in Fig. 1, Fig. 4a). Before the eruption, neither prominent fumaroles nor crater topography existed at this location. According to the interviews (10, 11, 12, 13 in Fig. 3) and analysis of images, the PDCs started immediately after the eruption, flowing southwest (Jigoku-dani side) and east (Hatchotarumi side) of the craters (Figs. 4, 5). According to the photographers who were in Hatchotarumi (13 in Fig. 3), they were engulfed by PDCs less than ten seconds after becoming aware of the eruption. Volcanic block- and lapilli-sized ejected rocks also

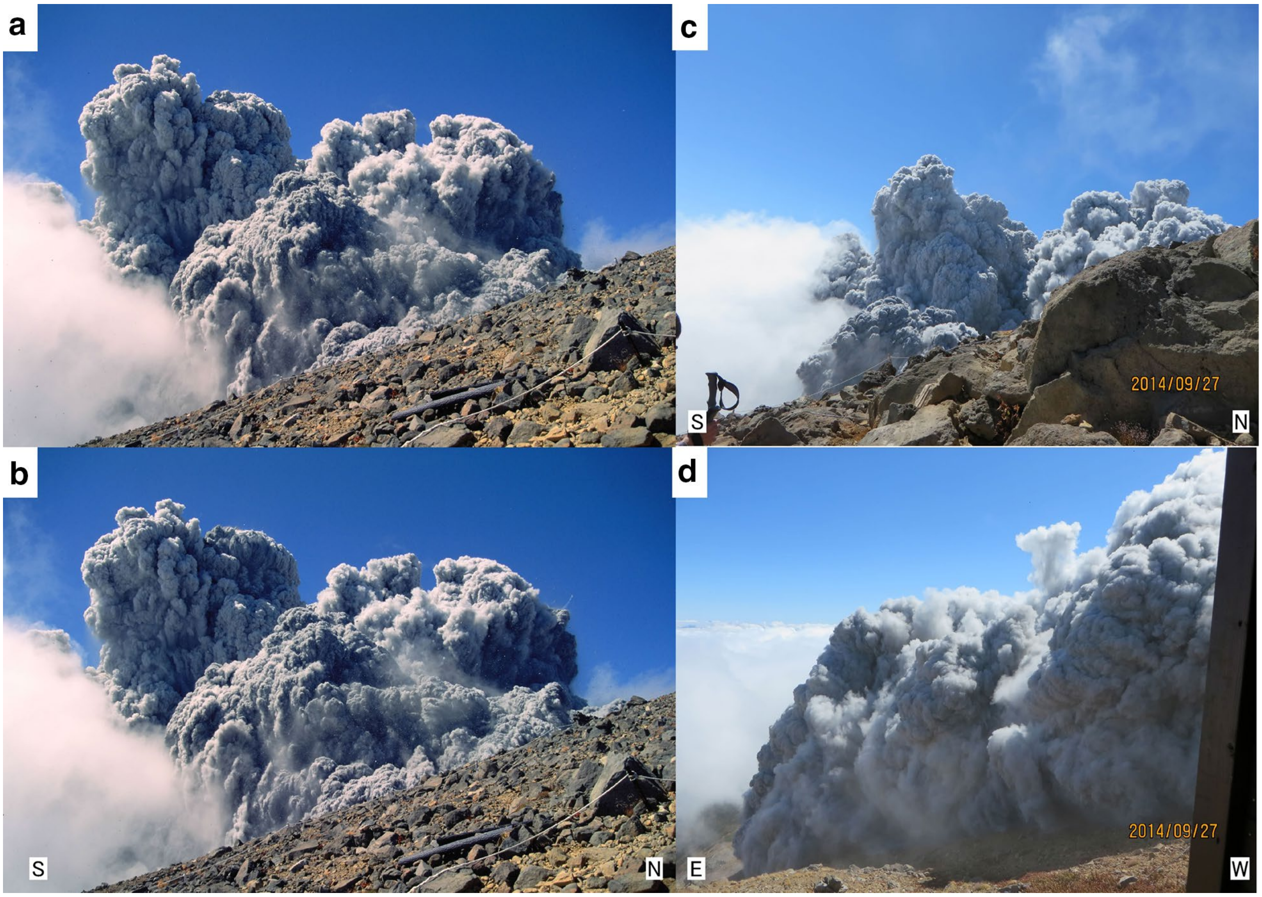

Fig. 5 Photographs of Hatchotarumi covered by PDCs. **a** Photograph taken by F Kaito in Hatchotarumi at around 11:52:30, September 27. **b** Photograph taken by F Kaito in Hatchotarumi immediately after taking photograph **a**. **c** Photograph taken by M Yamamoto near Kengamine at around 11:52:30, September 27. **d** Photograph taken by M Yamamoto near Kengamine on 27 s after taking photograph **c** (around 11:52:57, September 27)

reached Hatchotarumi at around the same time as the arrival of the PDCs. The PDCs and ejection of rocks continued until 12:15 in Hatchotarumi.

Based on the angle of elevation noted from a photograph (Fig. 6e), during this sub-phase, the eruption column reached an altitude of approximately 3200 m a.s.l.

Phase 1b (around 11:53 to around 12:00)

At around 11:53, subsequent to the opening of craters in Jigoku-dani, the crater under Okunoin, at approximately 2800 m a.s.l. (b in Fig. 1, Fig. 4a), began to erupt. Before the eruption, neither prominent fumaroles nor crater topography existed at this new crater location. The activity of this sub-phase continued in the other craters in Jigoku-dani. The area covered by PDCs increased during this sub-phase eruption (Figs. 4, 6). A video recorded (e.g., Shinano Mainichi Shimbun 2014) near Marishiten-san (about 1.5 km north of the craters: 1 in Fig. 3) by a climber suggested occurrence of column-collapse-type PDC in this sub-phase; the eruption column that rose to an altitude of approximately 3500 m a.s.l. collapsed, and PDCs occurred. The PDCs flowed down the slopes on the southwest (to Jigoku-dani), northwest (to Shin-tani), north (to Ichi-no-ike and Ni-no-ike), and northeast side (Figs. 4b, c, 6). The front of the southwest PDC stopped at 11:59:40 at a point 2.5 km away from the crater (Yamamoto 2014). According to the interviews (8, 11, 10, and 13 in Fig. 3), numerous ballistics of lapilli and volcanic block-sized rocks started to fall during this sub-phase in an area within approximately 1 km to the north (Kengamine and Ichinoike peaks) and to the west (Hatchotarumi) of the craters of Jigoku-dani.

The peak of Kengamine was covered by PDCs during this sub-phase. At the peak of Kengamine, where the largest number of people (33 persons) died, it is estimated that the ejected rocks started to fall at around 11:53:35 (Fig. 6). Analysis of images suggests that on the slopes between Ichi-no-ike and Ni-no-ike, impact craters were formed by ejected rocks that started to fall at around 11:53:30–11:53:40 (Fig. 6). According to

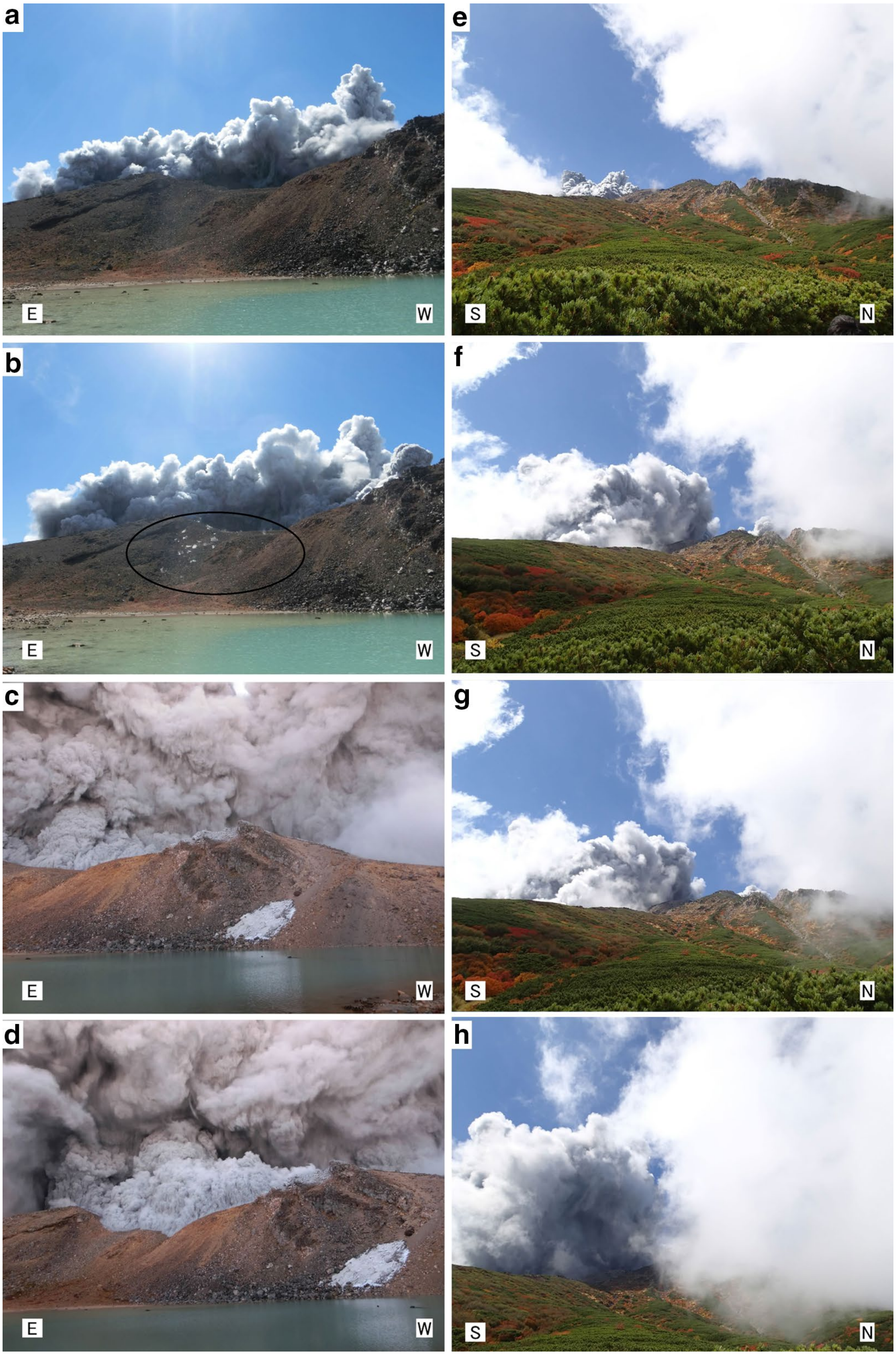

Fig. 6 Photographs **a**–**d** from Ninoike Honkan and **e**–**h** from around Nyonindo. Photographs **a**–**d** were taken by Y Kodera and E–H by S Tamura. Photographing times are as follows: **a** around 11:53:30, **b** around 11:53: 40, **c** around 11:55:52, **d** around 11:56:14, **e** 11:52:54, **f** 11: 53:20, **g** 11:54:35, and **h** 11: 55:38 (all photographs were taken on September 27, 2014). In photograph **b**, there is *white smoke* (in the *circle*) between Ichi-no-ike and Ni-no-ike. This smoke is a cloud of dust from the fall of ballistic rocks

the interviews (8, 11, and 12 in Fig. 3), Kengamine was engulfed by PDCs within 1–2 min of the commencement of the eruption, and the ejected rocks started to fall at the same time. According to image analysis, the peak of Kengamine was covered by an ash cloud from around 11:53:35, approximately 1 min after the start of eruption.

Phase 1c (around 12:00–12:15)

At around 12:00, there was a very short pause in the eruption. An interview (8 in Fig. 3) suggested that at the summit area (in and around Kengamine and Ichi-no-ike), visibility improved during a period of a few to several tens of seconds just before 12:00. Then, an explosion or sound of falling rocks was heard again, and the PDC occurred at around 12:00. At the same time, according to another interview (2 in Fig. 3), ballistic rocks started falling on the Ni-no-ike area. At about 11:57, the climber in Marishiten-san heard loud noise of falling rocks and observed the plume rising higher (Yama-to-keikoku 2014). At 12:01, the PDCs flowed again down the eastern slope; images of these PDCs were recorded in photographs taken from Nyonindo, located on the eastern side of the mountain (Fig. 7). According to the interview (13 in Fig. 3), inundation with PDCs ended before 12:15. Within approximately 1 km from the craters in Jigoku-dani, a number of lapilli to volcanic block-sized ejected rocks also fell in this sub-phase. It should be noted that volcanic lightning associated with the eruption began at around 12:00, according to some interviewees (2 and 4 in Fig. 3).

The active craters in this phase formed in Jigoku-dani (a in Fig. 1), near Okunoin (b in Fig. 1). The starting time of eruption at the craters on the west side of Ichi-no-ike (c in Fig. 1) is unknown. According to the images, the craters on the west side of Ichi-no-ike were not active during the previous sub-phase, but became active before 13:00 on September 27. However, these craters started erupting during this third sub-phase.

PDCs did not cover Nyonindo and Marishiten-san, but volcanic ash fall began at around 12:05, according to interviews (4 in Fig. 3, Yama-to-keikoku 2014). Ash fall occurred in the form of dry aggregated ash with no moisture.

Fig. 7 PDC downflow (shown by *arrow*). The photograph was taken by S Tamura around Nyonindo at around 12:01:21, September 27

Phase 2: ca. 12:15–ca. 16:00 (JST), September 27, 2014

Phase 2 was characterized by pyroclastic fall with muddy rain (Fig. 8), although muddy rainfall had also been observed in some places from the latter stages of Phase 1b. According to the interviews (2, 4, 8, and 13 in Fig. 3), muddy rainfall started around 12:16–12:20 in Nyonindo, from 12:00 to 12:35 in Ni-no-ike, at 12:50 in the south of Ichi-no-ike, and before 12:15 in Hatchotarumi. Accordingly, Phase 2 is considered to have started at around 12:15 when the stream of PDCs stopped. When muddy rain started, the eruption plume reached approximately 7.8 km above the summit (Sato et al. 2016). According to some of the interviews (8, 11, 12, and 13 in Fig. 3), the air above the summit area and Hatchotarumi was hot at the time of PDC flow, but it cooled once muddy rain started.

Pyroclastic fall in this phase mainly consisted of muddy aggregated ash or lapilli. Muddy rain with pyroclastic fall was also observed in an ash fall area approximately 11 km to the east of the craters (Fig. 8b). Some interviewees (2 and 8 in Fig. 3) suggested that the ejection of rocks ended at around 12:40 at the summit area. On the other hand, according to the news video (NHK news on September 27, 15:00), ejection of volcanic block-sized rocks from the Jigoku-dani craters continued until at least 14:00 in Jigoku-dani. However, eyewitness accounts and image analysis suggest that the number of ballistic rocks falling in the summit area and Hatchotarumi reduced significantly during this phase. Ash fall weakened gradually and had mostly ended by the morning of September 28 (Fukuyama and Hiramatsu 2015; Tajima et al. 2014).

Phase 3: after ca. 16:00 (JST), September 27, 2014

Phase 3 was characterized by an overflow of gray muddy water (likely hot spring water) from the craters. According to the photographs of the craters in Jigoku-dani taken by news media (Asahi Shimbun Digital 2014), muddy water (lahar) was overflowing directly from the crater at 16:44. The outflow of muddy water from the craters in Jigoku-dani cannot be confirmed in photographs taken at 15:11 (Mainichi Newspapers 2014). Photographs therefore constrain the overflow time to between 15:11 and 16:44, and this is estimated to have occurred around 16:00. For convenience, we assume this time to be the start of Phase 3. On September 28, the lahar deposits

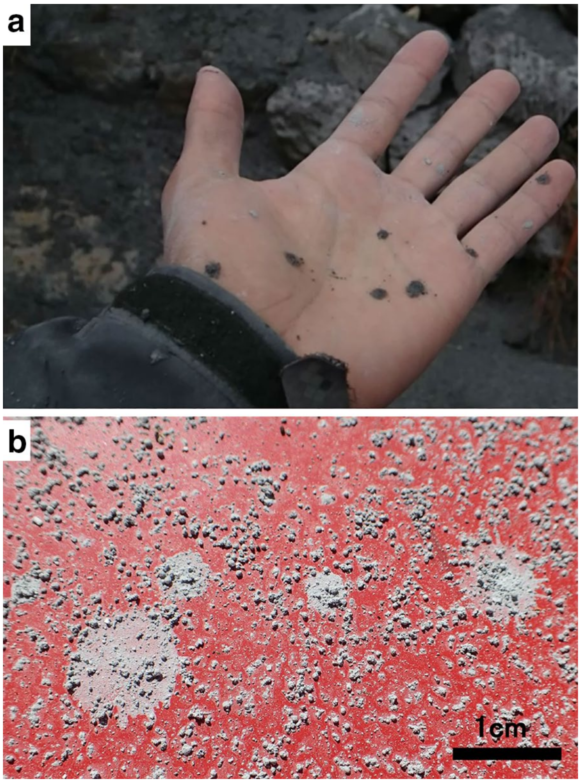

Fig. 8 Photographs of muddy rain fall. **a** Muddy rain falling in Nyonindo. The photograph was taken by S Tamura at around 12:20, September 27, 2014. **b** Trace of muddy rain at Kooku, Kiso-town, Nagano Prefecture (approximately 11 km east of the 2014 craters). The photograph was taken by T Oikawa on September 29, 2014

Fig. 9 Muddy water outflow in Nigori-kawa (the lower section of the Jigoku-dani). The photograph was taken on November 7, 2014 at 1300 m a.s.l. in Nigori-kawa (approximately 6 km from the craters in Jigoku-dani). The plumes (*arrow*) in the photograph rise up from the craters in Jigoku-dani

originating from muddy water were confirmed in the riverbed of Nigori-kawa (Nigori River), downstream from Jigoku-dani (Kishimoto et al. 2014). Muddy water that flowed downstream to Otaki-gawa (Otaki River) was confirmed from September 28 onward. The muddy water outflow from the craters in Jigoku-dani continued from November 2014 to July 2015 (Fig. 9).

After the muddy water outflow, the plume lost its momentum. According to radar echo observations (Sato et al. 2016), the plume column height decreased approximately 2 h after the muddy water outflow started.

Temperature of PDCs

The overall PDC temperature at the summit area was estimated to have been mostly in the range of 30–100 °C, locally exceeding 100 °C. We obtained the following information about the temperature of the PDCs at the summit area and Hatchotarumi. Based on eyewitness accounts (6, 8, 11, 12, and 13 in Fig. 3) from climbers and hut workers, people who were caught in the PDC felt hot air, but the temperature was not high enough to damage the plants in the area. The ignition temperature of leaves and bark of conifers is 430–460 °C (e.g., Iwakawa 1985). According to a report by news media, one person died because of inhalation burns and some people suffered light burns. However, people caught in the PDCs and those who suffered burns were a minority. Humans do not experience burns at atmospheric temperatures <100 °C at a relative humidity of 5–10 %, or at temperatures <50 °C at a relative humidity of 100 % (e.g., Ito 2015). In addition, materials such as raincoats and backpacks made of nylon did not melt in the PDCs. However, chocolate kept in the backpack of a person in Hatchotarumi melted, and a part of his hair was discolored. The melting temperature of typical chocolate is approximately 30 °C and that of the discolored part of hair is >100 °C in hot air (e.g., Yamashita et al. 2012). The estimated temperature of the PDCs accompanying the eruption was higher than or equal to that of the 2012 eruption of Te Maari Volcano (100–64 °C in proximal, 51–58 °C in distal: Efford et al. 2014), and lower than that of the 1900 eruption of Adatara Volcano (over 100 °C, under 400 °C: Fujinawa et al. 2006).

Eruption model from eruption sequence

The eruption sequence of the 2014 eruption is summarized in Fig. 10: (1) the opening of new craters (Phase 1); (2) the PDCs, with a temperature range of 30–100 °C, occurring immediately after the eruption (during Phase 1). The temperature of these PDCs was above the dew point temperature; they were dry. (3) When the outflow of PDCs stopped, the height of the eruption column increased; tephra with muddy rain started to fall; and ambient air temperature decreased (Phase 2). (4) Finally, muddy hot water flowed out from the craters (Phase 3).

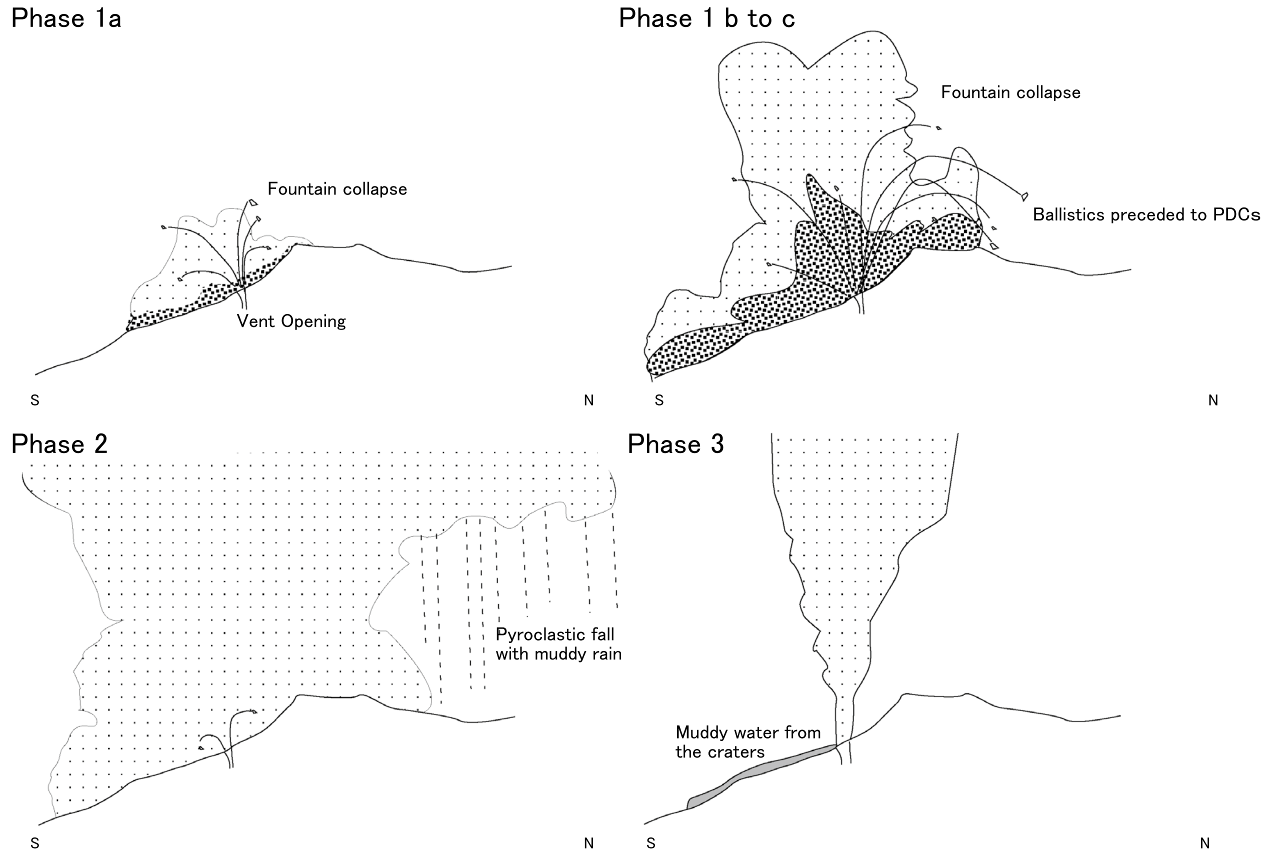

Fig. 10 Reconstructed eruption sequence of the Ontake eruption on September 27, 2014

The 2014 eruption was a phreatic one in origin as it did not contain evidence of juvenile magmatism (e.g., Minami et al. 2015). One of the dominant mechanisms of a phreatic eruption involves sudden decompression of superheated water, followed by an explosion because of the generation of a large amount of steam (flash steam) (e.g., Browne and Lawless 2001; Hedenquist and Henley 1985; Mayer et al. 2015; Thiery and Mercury 2009; Yamamoto et al. 1999). In engineering, similar explosive phenomena are referred to as BLEVE (boiling liquid expanding vapor explosion) (Abbasi and Abbasi 2007). An eruption model can be inferred from the reconstructed eruption sequence as follows: (1) Considering that new craters formed, the early eruption column contained a large amount of tephra (rock fragments and altered clay). The density of the eruption column was therefore high and PDCs occurred by a collapse of the eruption column under its own weight (Phase 1). According to Yamamoto et al. (1999) and Yamamoto (2014), PDCs occur during phreatic eruptions when the rock/hot water ratio is large. Yamamoto (2014) suggested that this occurs during the early phases of new crater formation. PDCs during the phreatic eruptions in 1888 at Bandai, in 1900 at Adatara, and in 2012 at Te Maari occurred at the time of formation or expansion of a crater (Fujinawa et al. 2006; Breard et al. 2014; Yamamoto et al. 1999). The sequence of the 2014 eruption is consistent with this theory. (2) During Phase 1, the temperature of PDCs with an ash cloud was 30–100 °C; the water contained in the PDCs was in the vapor state (flash steam). (3) Thereafter, the temperature of the plume decreased by the effect of adiabatic expansion as the eruption column rose. As a result, the internal temperature of the plume decreased to the dew point temperature to precipitate muddy rain. (4) Finally, muddy hot water, which did not transform to flash steam, overflowed from the craters. Considering the process of liquid water flashing to steam (e.g., Hedenquist and Henley 1985; Mayer et al. 2015) and the conditions of PDCs that result from a phreatic eruption (e.g., Yamamoto et al. 1999), our observations suggest that this model is consistent with the proposed sequence of events at Ontake.

Conclusions

We clarified the eruption sequence of the 2014 eruption of Ontake Volcano eruption from recorded images (such as photographs and videos obtained by climbers) and interviews with mountain guides and workers in mountain huts. The eruption sequence on September 27, 2014, is divided into three phases: Phase 1 (PDC flow phase), Phase 2 (pyroclastic fall with muddy rain), and Phase 3 (muddy water overflowing from the craters). It should be noted that no ground rumbling, strong seismic motion, or strong smell of sulfide was perceived before the eruption. The PDC temperature at the summit area is estimated to have been 30–100 °C, locally exceeding 100 °C. We constructed an eruption model from the reconstructed eruption sequence to describe the physics of the eruption. Our model reconstructed by these observations is consistent with the phreatic eruption models and typical eruption sequences of similar volcanoes. As in the case of the 2014 Ontake eruption, similar sequences can therefore be commonly expected to occur in other phreatic eruptions.

Authors' contributions

TO carried out image collection, interviews, and analyses of the collected data and drafted the manuscript. MY, SN, FM, JK, TS, YT, and YS conducted interviews and helped in the drafting of the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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