AIMS Geosciences

AIMS Geosciences, 10(2): 208–227.
DOI: 10.3934/geosci.2024012
Received: 06 October 2023
Revised: 13 March 2024
Accepted: 18 March 2024
Published: 28 March 2024

http://www.aimspress.com/journal/geosciences

Brief report

Effects of extreme rainfall on phreatic eruptions: A case study of Mt. Ontake in Japan

Nobuo Uchida*

The Volcanological Society of Japan, 406, 6-2-9 Hongo, Bunkyo, Tokyo 113-0033, Japan

* **Correspondence:** Email: nu8829nobby@leaf.ocn.ne.jp; Tel: +81-90-2257-8322.

Abstract: Sometimes, natural disasters caused by volcanic eruptions have tragic consequences. Phreatic eruptions are large explosions of steam rocks and hot water caused by the sudden evaporation of water to steam. The September 2014 eruption of Mt. Ontake in Japan was the deadliest in recorded history. Numerous studies have analyzed the occurrence of phreatic eruptions of Mt. Ontake. However, at present, although it is explained that the magma did not move, studies on the cause of the eruption and the elucidation of the process are limited. This study investigates the role of external water of meteoric origin and determines its role in the eruption process. According to a survey of rainfall records by the Japan Meteorological Agency, heavy rain that broke historical records occurred immediately before the phreatic eruption of Mt. Ontake. It was hypothesized that extreme rainfall was the source of the external water supply that caused the phreatic eruption without the magma moving. Various studies on eruptions have confirmed the consistency of this hypothesis. Regarding the eruptive process, extreme rainfall collided with the hot rocks outside the magma chamber, triggering frequent occurrences of vaporization associated with boiling, leading to large explosions in sealed rocks above the zone of water infiltration. This research can contribute to disaster prevention in the future. In order to achieve this, it is necessary to install rainfall measuring instruments on all volcanoes and perform a comparative, multidisciplinary approach to all the monitored parameters.

Keywords: Phreatic eruption; Mt. Ontake; eruption forecast; extreme rainfall

Abbreviations: AMeDAS: Automated Meteorological Data Acquisition System; GNSS: Global Navigation Satellite System

1. Introduction

Humans have a great concern regarding natural disasters. Volcanic eruptions, earthquakes, floods, and droughts are fears closely associated with our daily lives. In particular, phreatic eruptions require vigilance as a pattern of activity that occurs suddenly without prior notice. Scientists worldwide are working on this issue, but the process by which phreatic eruptions occur has not yet been determined. Moreover, it appears that there are currently no papers advocating the method of disaster prediction.

Mt. Ontake is located in central Japan and is the second-highest volcano in the country after Mt. Fuji. According to Oikawa et al. [1], no historical eruption was recorded prior to October 28, 1979. Mount Ontake, which was classified as extinct volcano, erupted abruptly at approximately 5:00 am. Fortunately, no casualties were reported because it occurred early.

The Coordinating Committee for Prediction of Volcanic Eruptions of Japan has designated 111 active volcanoes, and selected 50, including Mt. Ontake. In response to this proposal, the Japan Meteorological Agency has been observing and monitoring the area as a target of a 24-hour continuous observation system equipped with seismograph, inclinometer, infrasound instrument, global navigation satellite system (GNSS), and remote cameras (Figure 1) [2]. The Japan Meteorological Agency, universities, and related research institutes have installed observation equipment to monitor and research these volcanoes.

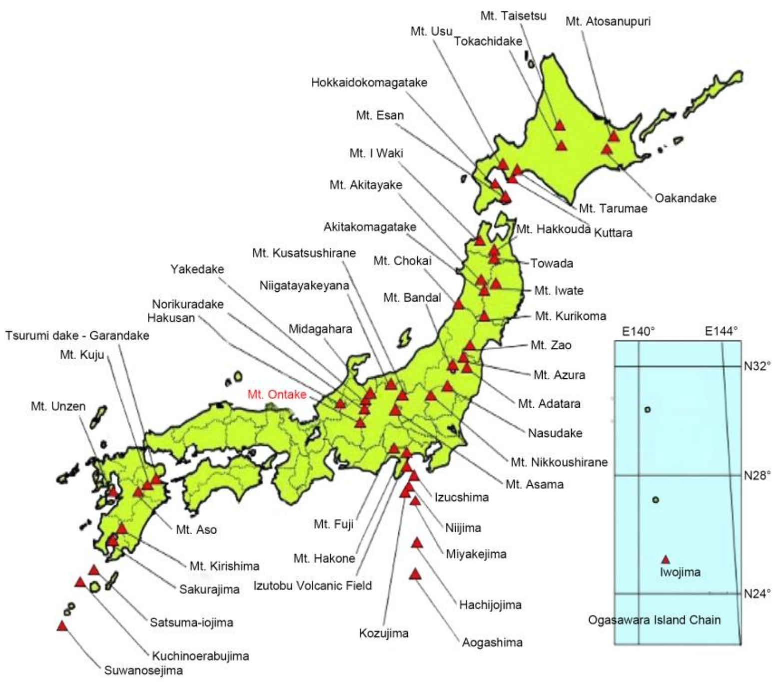

Figure 1. Names and locations of 50 volcanoes under constant observation.

Mt. Ontake erupted again without warning at 11:52 am on September 27, 2014. According to Yamaoka et al. [3], Kaneko et al. [4], and Maeno et al. [5], the impact of steam and ballistic rocks during the eruption caused the deaths of 58 people and the disappearance of 5 others. At lunchtime, many climbers enjoying the autumn foliage gathered near the summit when the volcano suddenly erupted, resulting in many casualties.

Many articles on volcanic eruptions triggered by extreme rainfall have been published in recent years. For instance, Farquharson and Amelung [6] used the Kilauea volcano on Hawaii's Big Island to illustrate how prolonged studies of climate and volcanic activities have revealed the processes by which climate affects the volcanic system, suggesting a potential trajectory for the field of volcanology.

Barclay et al. [7] provided examples, such as the Soufrière Hills volcano located on Montserrat Island. A prospective hypothesize is that an increase in extreme rainfall patterns worldwide could increase the probability of rainfall triggering volcanic phenomena. In addition, Aubry et al. [8] and Simmons et al. [9] have demonstrated the relationship between volcanic eruptions and precipitation. According to Farquharson and Ameling [10], excessive rainfall has been identified as the potential cause of volcanic activity.

Meanwhile, Yamaoka et al. [3], Maeno et al. [5], Stix and de Moor [11], Minami et al. [12], Takagi and Onizawa [13], Sasaki et al. [14], and Ikehata and Maruoka [15] stated that it is important to determine whether magmatic processes are the primary driving mechanism or whether hydrothermal processes play an important role. Moreover, Maeno et al. [5] suggested that in the case of phreatic eruptions of Mt. Ontake, a significant amount of external water (surface or hydrothermal) was involved. However, according to Oikawa et al. [1], Yamaoka et al. [3], Sasaki et al. [14], and Miyaoka and Takagi [16], it was under a 24-hour observation system but difficult to predict in advance.

The present study investigates the potential effects of scientific advancement on the preservation of the current status quo. This research aims to examine the hydrodynamic correlation between anomalous rainfall and volcanic activity, with specific emphasis on Mt. Ontake.

Currently, despite the frequent occurrence of phreatic eruptions in many volcanoes, accurately predicting their timing and location remains a challenging task. The urgent nature of the situation led to the rapid publication of this report, even in its early phase, motivated by its ultimate goal of preventing significant risk to humanity. Unfortunately, the progress of current research on the relationship between extreme rainfall and phreatic eruptions appears to be slow. Volcano monitoring technology in Japan has not yet integrated rainfall observation equipment, and the relationship between rainfall and eruptions has not been investigated. This research mainly aims to investigate the source that is involved in phreatic eruptions. The study seeks to elucidate the complex correlation between external water (surface or hydrothermal) and magma, with the objective of revealing the underlying factors responsible for such volcanic explosions.

2. Materials and methods

For a phreatic eruption to trigger an eruption, a greater quantity of water must have been continuously supplied from the exterior (surface or hydrothermal). In addition, it was speculated that a strong water flow would be required for water to penetrate deeply into the volcanic structure. In addition to analyzing rainfall at the time of the eruption, this paper attempted to discover new clues by combining previously published papers.

As a result of investigating what the conditions for the eruption were, it was highly likely that the weather conditions of never-before-seen record-breaking rainfall had a significant impact on the eruption.

2.1. Analysis of mountain structure

Each volcano has a unique history and volcanic structure. In the case of Mt. Ontake, according to newspaper reports and the Nagoya University Mt. Ontake Volcano Research Facility website [17] at the time of report, due to the strong shaking of the western Nagano earthquake (magnitude 6.8) that occurred on September 14, 1984, the collapse of the volcanic edifice "Ontake collapse" occurred. The volcanic body collapsed on a large scale, exposing the interior of the volcanic edifice (Figure 2a and 2b). Caudron et al. [18] conducted an analysis by showing seismic stations placed on a map of Mt. Ontake. This study sheds light on previously undetected pressurized fluids and shows great potential for their monitoring (Figure 2c).

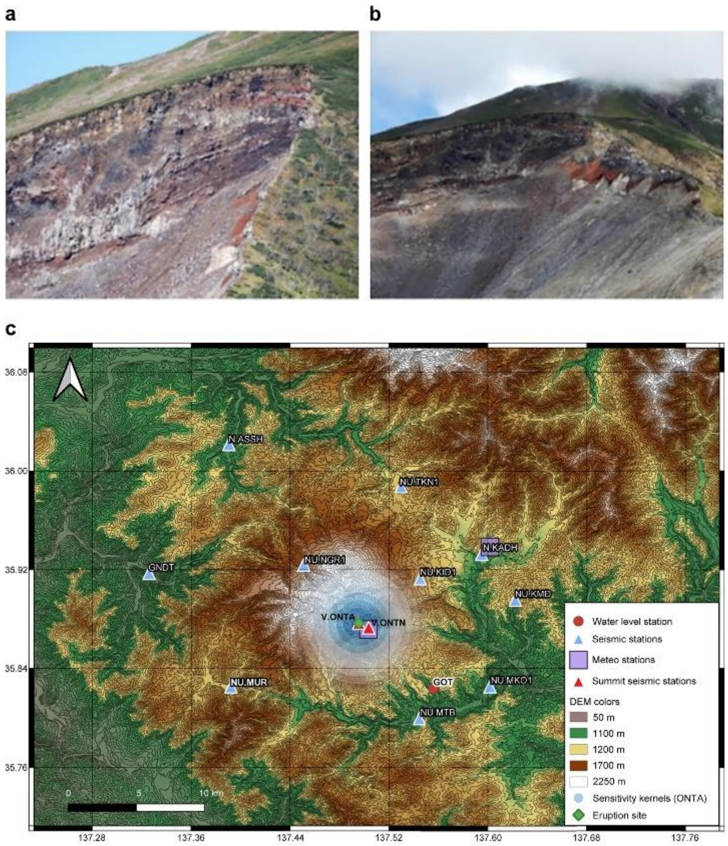

Figure 2. (a) The volcanic body collapsed on a large scale, (b) the exposed internal structure and volcanic edifice of Mt. Ontake due to the "Ontake collapse" in 1984 and (c) satellite view of the 2014 eruption at Mt Ontake with permission from ref. [18].

According to the photograph and caption of this scene, the volcanic edifice with a wide opening reveals the interior, where lava and volcanic ejecta are piled up intricately, revealing the tephra layer, pumice layer, and lava layer volcanic body. In addition, enormous caves and andesitic lavas show fissured plate-like joints that resemble stacked flat plates. These extensive network of fissures, faults, and gaps may have played an important role in phreatic eruptions by serving as storage for rainwater. Another image depicts the abundance of both large and small waterfalls, showcasing the significant quantity of water stored within the mountain body, which is continuously draining water. This is called Waterfall Mountain. Hot spring sites such as Kiso Ontake and Kaida Kogen, located near the base of Mt. Ontake, utilize the geothermal water to enhance the tourism industry. In addition, the cold water discharged by waterfalls facilitates the production of hydroelectric power by creating rivers.

2.2. Analysis of eruption products

The pyroclastic materials from the 2014 eruption of Mt. Ontake consisted of altered volcanic fragments, alunite, anhydrite, pyrite, and quartz, according to Ikehata and Maruoka [15]. The result shows that it may have originated from the mountain's acidic alteration zone. In addition, Minami et al. [12] and Ikehata and Maruoka [15] reported that the difference in sulfur isotope values between anhydrite and pyrite from the 2014 eruption ranges between 270 and 281 °C for isotope equilibration temperatures. Moreover, note that the phreatic eruptions of 1979 and 2014 reveal geoscientific similarities in hydrothermal systems.

2.3. Rainfall survey

For meteorological observation, the Japan Meteorological Agency uses an automated meteorological data acquisition system (AMeDAS; [19]). AMeDAS continuously collects precipitation and other data at approximately 1,300 locations throughout Japan, and historical rainfall records from 1976 to the present have been published for daily totals and maximum hourly rainfall for each day. This investigation established a causal relationship between the eruption of Mt. Ontake and the prior occurrence of extreme rainfall. In addition, an investigation of the weather patterns during the volcanic eruptions in October 1979 and September 2014 revealed an extraordinary occurrence of heavy rainfall at Mt. Ontake. According to the AMeDAS data, the average annual precipitation at Mt. Ontake is 3,694 mm, with the majority falling between May and September (Table 1) [20].

According to newspaper articles and the Japan Meteorological Agency website (in Japanese) from the time, the precipitation in the months preceding the eruptions in October 1979 and September 2014 set a record. The former was Typhoon No. 20 [21], a low-pressure system with a new world record of 870 hPa at the time of its formation making landfall on October 20, when the typhoon hit Japan, its strength declined, but the extreme rainfall brought by the typhoon caused the worst damage nationwide, with 110 deaths. The latter is an announcement by the Japan Meteorological Agency that a meteorological front and typhoons No. 11 and No. 12 overlapped and hit Japan around August 10, 2014 [22]. In various parts of Japan, 13 locations with maximum 1-hour, 15 locations with 24-hour, and 23 locations with 48-hour precipitation in August 2014 have broken records since the beginning of statistics. It lingered around Mt. Ontake for approximately 2 weeks and brought extreme rainfall, totaling 893 mm in August (Table 2).

Table 1. Monthly rainfall at Mt. Ontake between 2006 and 2021.

	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	Total	Av.
Jan	///	36	82	71	62	11	28	60	51	102	91	54	129	28	125	57	983	61
Feb	4	137	52	220	203	75	182	124	101	70	231	153	14	109	173	53	1,897	119
Mar	198	260	108	296	354	104	346	196	338	150	96	35	305	135	213	269	3,399	212
Apr	151	84	198	269	375	285	207	221	140	546	439	402	486	165	131	292	4,388	274
May	507	330	346	365	528	640	166	222	179	247	491	187	469	252	206	736	5,868	367
Jun	322	452	420	445	615	501	439	383	175	365	406	234	519	620	732	338	6,962	435
Jul	1,218	574	197	1,182	893	419	754	654	451	685	334	501	895	559	2,208	531	12,052	753
Aug	79	301	341	279	220	464	304	389	893	549	298	441	641	765	73	1,189	7,224	452
Sep	324	361	175	200	430	644	179	367	312	590	774	422	1,178	123	399	398	6,872	429
Oct	289	268	183	320	327	344	251	304	380	291	419	497	144	481	291	71	4,857	304
Nov	165	54	81	245	32	279	185	164	275	415	210	95	59	89	186	114	2,645	165
Dec	89	85	117	65	190	65	160	52	182	166	271	37	188	142	34	119	1,958	122
Total	3,346	2,942	2,299	3,954	4,227	3,828	3,198	3,133	3,473	4,174	4,057	3,054	5,023	3,464	4,768	4,163	59,101	3,694
Av.	279	245	192	330	352	319	267	261	289	348	338	255	419	289	397	347	4,925	

Note: These data can be obtained from [20].

1,000 mm or more   500 mm or more

Table 2. Maximum monthly, daily, and hourly rainfall leading up to October 1979 and September 2014 eruptions of Mt. Ontake.

07/2014			08/2014			09/2014				08/1979			09/1979			10/1979		
Date	mm	Max mm/h	Date	mm	Max mm/h	Date	Earthquake	mm	Max mm/h	Date	mm	Max mm/h	Date	mm	Max mm/h	Date	mm	Max mm/h
1	1	1	1	0	0	1	4	21	6	1	0	0	1	14	6	1	91	27
2	0.5	0.5	2	0	0	2		0	0	2	0	0	2	12	3	2	0	0
3	23	5	3	23.5	7	3		1	1	3	1	1	3	3	1	3	28	5
4	27	7.5	4	29	9.5	4		42.5	10.5	4	10	6	4	65	13	4	28	11
5	46.5	11	5	21.5	8.5	5		59.5	14.5	5	0	0	5	2	1	5	0	0
6	4	1.5	6	22.5	10.5	6	1	9	3.5	6	35	8	6	0	0	6	6	1
7	91.5	10.5	7	0	0	7	2	6	3	7	66	21	7	14	4	7	33	4
8	9	2.5	8	20.5	7	8	5	0	0	8	1	1	8	0	0	8	5	2
9	36.5	24.5	9	9.5	3	9	10	0	0	9	0	0	9	0	0	9	0	0
10	51.5	6.5	10	185	32	10	52	0	0	10	0	0	10	0	0	10	0	0
11	1	1	11	29.5	8	11	85	8.5	6	11	0	0	11	0	0	11	0	0
12	0	0	12	39	10	12	10	0	0	12	25	13	12	0	0	12	0	0
13	82	15.5	13	0	0	13	7	0	0	13	0	0	13	1	1	13	0	0
14	20	7.5	14	34	14	14	8	0	0	14	0	0	14	6	1	14	0	0
15	0	0	15	85	15	15	27	0	0	15	0	0	15	69	9	15	0	0
16	31	12	16	146	29.5	16	18	0	0	16	0	0	16	0	0	16	0	0
17	8	8	17	102	16	17	10	0	0	17	6	3	17	2	1	17	0	0
18	1	0.5	18	11.5	4.5	18	24	0	0	18	31	12	18	3	2	18	21	3
19	5.5	1.5	19	6	3.5	19	3	0	0	19	0	0	19	8	4	19	187	32
20	1	1	20	0	0	20	10	0	0	20	30	8	20	0	0	20	3	2
21	1.5	1.5	21	0	0	21	17	0	0	21	152	23	21	1	1	21	0	0
22	0	0	22	2.5	1	22	3	0	0	22	67	17	22	33	11	22	0	0

Continued on next page

07/2014			08/2014			09/2014			
Date	mm	Max	Date	mm	Max	Date	Earthquake	mm	Max
23	0	0	23	18.5	7.5	23	10	0	0
24	0	0	24	7	3	24	9	74.5	14.5
25	0	0	25	12.5	3	25	8	89.5	16
26	0	0	26	76	26.5	26	6	0	0
27	1	1	27	0	0	27	483	Eruption	
28	0	0	28	1.5	1.5	28	131	0	0
29	0	0	29	1.5	1	29	53	0	0
30	0	0	30	9	3	30	58	0	0
31	8	8	31	0	0				
Total	450.5		Total	893		Total		311.5	
Total: 89 days; 1,655 mm									

08/1979			09/1979			10/1979		
Date	mm	Max	Date	mm	Max	Date	mm	Max
23	16	8	23	7	3	23	0	0
24	16	7	24	27	9	24	///	///
25	26	10	25	78	14	25	///	///
26	0	0	26	71	15	26	///	///
27	79	12	27	34	13	27	///	///
28	2	1	28	49	8	28	Eruption	
29	0	0	29	22	6	29	///	///
30	0	0	30	19	11	30	///	///
31	0	0				31	///	///
Total	563		Total	540		Total	402	
Total: 89 days; 1,505 mm								

Note: Rainfall that exceeds 100 mm in a row is shown in yellow. Heavy rain immediately preceding the assumed trigger for an eruption is shown in blue.

Data for each month is available from: Aug.1979: [23], Sep. 1979: [24], Oct. 1979: [25], Jul. 2014: [26], Aug. 2014: [27], Sep. 2014: [28].

In addition to the large amount of continuous rainfall that began several months before the eruption, extreme rainfall exceeding 20 mm per hour was observed inside the volcano briefly. The infiltration can be subjected to a pressurization effect and the hypothesis asserts that the eruption of Mt. Ontake was initiated by historically unprecedented record-breaking extreme precipitation conditions.

2.4. Surveys using seismic and inclinometer equipment

According to findings of Oikawa at al. [1], Takagi and Onizawa [13], Sasaki et al. [14], Ikehata and Maruoka [15], Miyaoka and Takagi [16], Ogiso et al. [29], Maeda et al. [30], and Kato et al. [31], the tiltmeter detected an initial upward northwesterly tilt of the ground at 11:45 am on September 27, 2014. A phreatic eruption occurred seven minutes later, at 11:52 a.m., as observed by the seismometer positioned ten minutes earlier at 11:41 am as shown in Figure 3 [32].

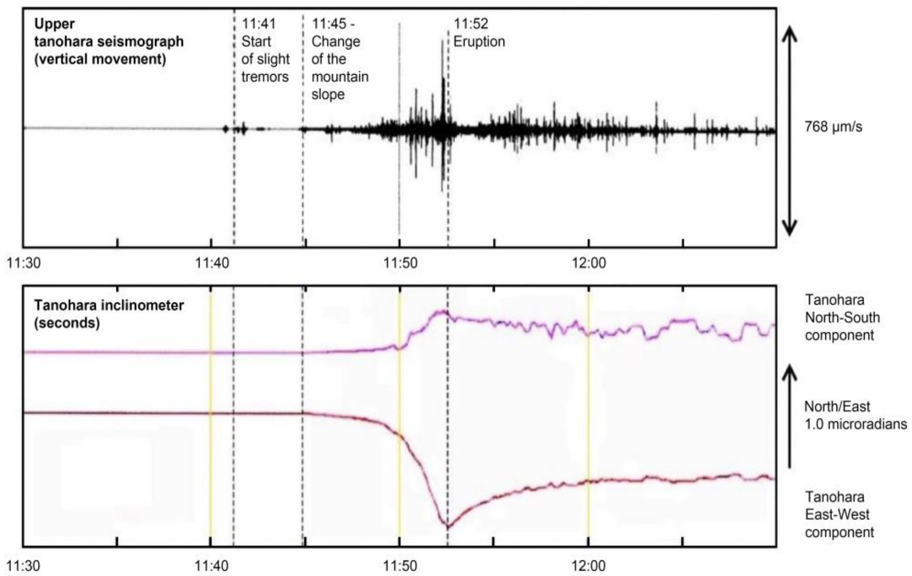

Figure 3. Seismograph and tiltmeter observations just before and after the eruption of Mt. Ontake. Observations on the seismograph and indications on the inclinometer began at, and the eruption occurred at, 11:41 min, 11:45 min, and 11:52 min, respectively.

It was emphasized by Miyaoka and Takagi [16], Ogiso et al. [29], and Kato et al. [31] that no precursory phenomena such as crustal movements were observed before the eruption. According to surveys conducted by Oikawa et al. [1], Yamaoka et al. [3], Maeno et al. [5], Takagi and Onizawa [13], Sasaki et al. [14], and Maeda et al. [30] using pre-existing observation instruments, the phreatic eruptions were of short duration, which prevented timely eruption predictions. The rapid commencement of eruption phenomenon is a remarkable feature of phreatic eruptions, and therefore the failure to promptly predict the eruption may have played a role in the tragedy.

2.5. *Mt. Ontake's occurrence process of phreatic eruptions*

Kaneko et al. [4], Maeno et al. [5], Minami et al. [12], and Sasaki et al. [14] reported that the phreatic eruption of Mt. Ontake was caused by water discharged directly from the void. Meanwhile, Yamaoka et al. [3], Kaneko et al. [4], Maeno et al. [5], Stix and de Moor [11], Minami et al. [12], and Ikehata and Maruoka [15] concluded that it is a hydrothermal eruption because it originates from the water system.

Ikehata and Maruoka [15] analyzed the pyroclastic materials from the eruption and found that the ejecta did not contain many different substances. Most of these minerals are probably derived from the acidic alteration bodies of Mt. Ontake and exhibit a spectrum of isotopic equilibrium temperatures. They make important discoveries indicating geochemical similarities in the hydrothermal systems beneath the 2014 and 1979 eruptions.

This indicates that the phreatic eruption was not initiated by a direct interaction between magma and water but rather by the direct interaction between hot water and minerals.

Takagi and Onizawa [13] modeled the pressure source of Mt. Ontake and utilized GNSS to observe ground deformation. They noted that the event occurred just beneath the crater in terms of depth. Maeda et al. [30] investigated the origin of long-period earthquake (VLP) and suggested that the source is located at 2,040 m above sea level and 600 m below the surface.

Observation of the epicenter graphs of Mt. Ontake earthquake and volcanic activity data from December 1, 2006 to October 7, 2014 are provided by the Japan Meteorological Agency as shown in Figure 4 [32].

Oikawa et al. [1] and Kaneko et al. [4] described the trajectory of the fumarole in 2014 as a new fumarole that formed several hundred meters away from the location of the old fumarole formation in 1979. Meanwhile, Ogiso et al. [29] reported that at approximately 11:45 am, a sudden depressurization event initiated at a shallow depth and the hydrothermal system disturbance propagated downward. According to them, this is an important factor in interpreting the phreatic eruption process of Mt. Ontake. As soon as decompression began, volcanic tremors were induced and volcanic gas and steam eventually escaped through a fissure just below the crater and through a steam eruption.

Kaneko et al. [4] and Maeda et al. [30] analyzed and identified a very long-period ground motion (VLP event) that occurred 25 s before the eruption, and he detected a fault slip in the ENE-WSW direction at a depth of 0.3–1 km. They noted that a tensile crack opened in the rock, through which hydrothermal fluid flowed to the surface, possibly serving as a conduit for gas rising to the surface prior to the eruption.

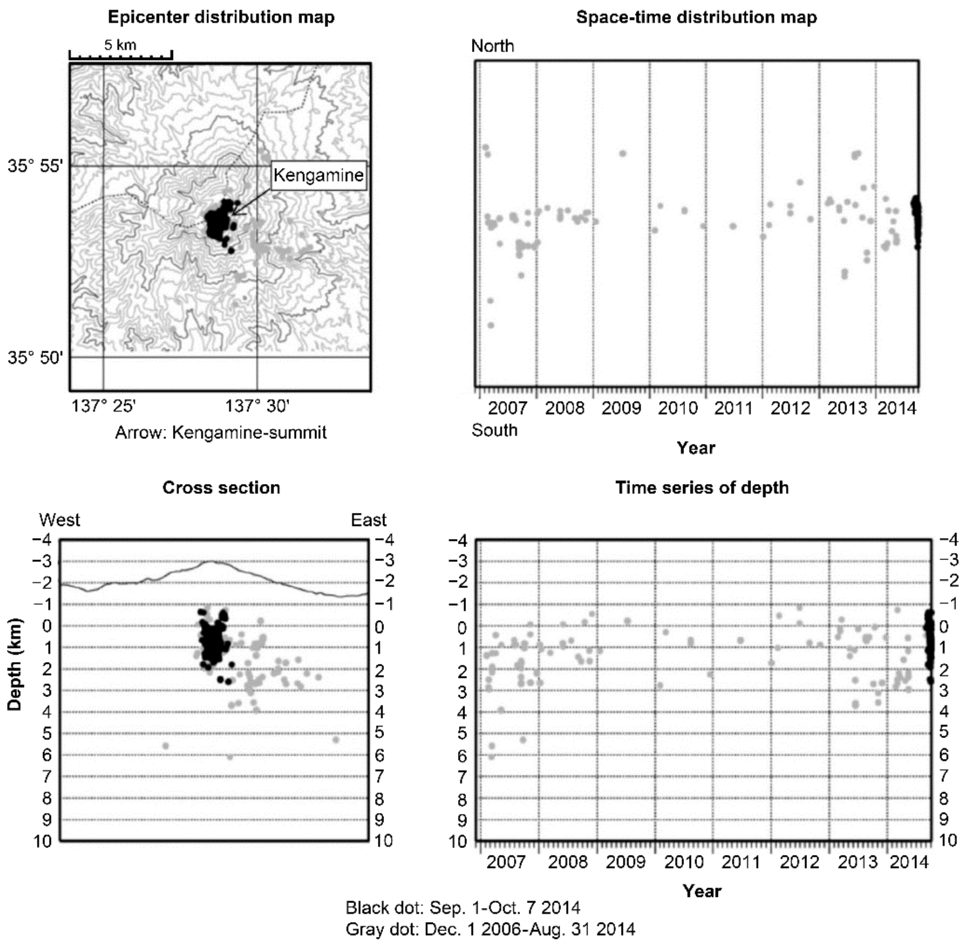

Figure 4. Distribution of epicenter map of Mt. Ontake, showing spatial and temporal distribution and depth from December 1, 2006, to October 7, 2014.

Important findings from the research conducted by Kato et al. [31] shows that looking at the seismic activity since mid-September 2014 (Table 2), 4 occurrences were observed, September 1, a brief cessation, 1 on September 6, 52 on September 10, and 85 on September 11. After that, however, the frequency of earthquakes gradually decreased and appeared to subside. On the day of the 27th eruption, it reached 483 measurements suddenly. Seismic activity continued as high-temperature fluid spread over existing faults and fissures.

In essence, they concluded that the explosion was initiated by a fluid at high temperatures, where vertical conduits facilitated the rapid propagation of pressurized fluid. In other words, the pressurized energy continued to descend within the vertically sealed conduit in search of a discharge point. However, it eventually lost the ability to sustain itself, resulting in an immediate explosion. It is interesting to note that water vapor did not originate as a volcanic plume until the explosion occurred, which indicates that the new craters appeared in 2014.

The results presented by Stix and de Moor [11] are very important because they approach the origin of the theme of this paper. The magmatic gases are released by intrusion, crystallization, or a combination. The top of the hydrothermal system is susceptible to water intrusion from the outside. Unusual torrential rain can infiltrate deep layers and act as a trigger for gas to be released from the magma body. Gas rises through the crack and joins the hydrothermal system above, and the addition of hot magma gas then pressurizes the system and facilitates the explosion. Figure 5 presents a schematic diagram of the phreatic eruption process of Mt. Ontake to illustrate this idea.

Mt. Ontake was observed by an inclinometer at 11:45 a.m. on September 27, 2014, and 7 minutes later, a major eruption occurred at 11:52 a.m. Given the short period between the initial observation and the eruption, as well as the size of the eruption, it is important to not ignore the possible effects of heavy rains on the magma body as one of the probable justifications.

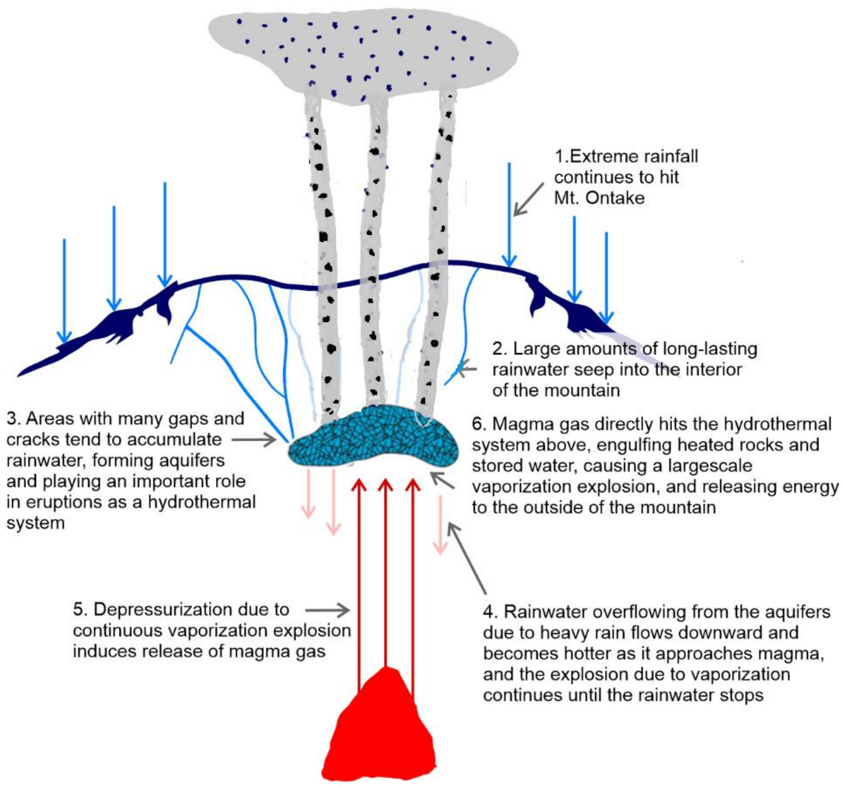

Figure 5. Schematic diagram depicting processes leading to a large explosion due to extreme heavy rain, shown in the case of a phreatic eruption in which magma does not move.

3. Results

The September 2014 eruption process can be summarized as follows: heavy rainfall infiltrated the volcanic body, reaching the hot rocks of the magma chamber, and then creating energy from the decrease in pressure associated with boiling.

The depressurization phenomenon, which is associated with evaporation, temporarily decreased while gradually increasing the energy. However, due to a continuous inflow of water, the amplified pressure energy is redirected upward within the constraints of the confined space. After the gas and water vapor passed through the first open fissure, amplified pressure energy was subsequently released from the surface. Both the 1979 and 2014 eruptions were similar, particularly the fact that they were preceded by a period of inactivity and were triggered by heavy rainfall.

Based on the results of the earlier investigations which strongly suggest that the phreatic eruption of Mt. Ontake was triggered by excessive rainfall. Farquharson and Amelung [6] explored the relationship between climate and volcanic systems, whereas Barclay, et al. [7] argued that an increase in the pattern could increase the probability of rainfall causing volcanic events.

Aubry et al. [8] and Simmons et al. [9] established a relationship between volcanic eruptions and rainfall, while Farquharson and Ameling [10] identified that excessive rainfall can act as a catalyst for volcanic activity. Although the number of researchers listed here is small, their combined findings indicate a significant correlation between heavy rains and volcanic eruptions.

This study is in agreement with Gaete et al. [33] and Strelow et al. [34] highlights those phreatic eruptions, which are frequently modest and undocumented, present dangers to residents living near volcanoes, including both inhabitants and visitors. In addition, Gaete et al. [34] investigated Lascar Volcano (Chile) and observed that an abnormally strong precipitation event triggered the eruption.

Strehlow et al. [35] use the eruption of Mt. Ontake as an example in their study to emphasize that the effects of phreatic eruptions should not be underestimated, as they investigate Mt. Ruapehu in New Zealand. However, they stated that the risks associated to inactive volcanoes might surpass prior estimations.

A recent study by Maeda and Watanabe [35] argues that the analysis of the epicenter of the eruption of Mt. Ontake revealed that it could have occurred on the topmost part of the magma rather than at the center of the magma chamber. All the references cited in this paper share the same common point; external water and phreatic eruptions are directly involved instead of molten magma.

Nevertheless, it is crucial to acknowledge the limitations of reaching conclusive inferences based on the two examples given provided. However, this study is presented to invoke and, possibly support new and useful eruption warning to be set up in the future. This is significant because phreatic eruptions present a substantial difficulty in accurately predicting their timing and location. From the aforementioned studies, it is necessary to be most cautious about the possibility of recurrence when the following conditions are met:

1. There is the absence or reduction in volcanic plume activity for over two years (Figure 6; [33]).

2. Multiple occurrences of precipitation exceeding 500 mm/month, 100 mm/day, and over 20 mm/hour within a brief time frame.

3. Increased intensity of earthquake swarms were registered during low degassing periods, despite the absence of a volcanic fumarole.

It was useful to highlight the time relationship between the extreme rainfall and the phreatic eruptions analyzed in this paper. On the premise of potential recurrences, a most accurate comparison of all the available long-term monitoring data-series, included the meteorological ones, is essential to afford forecasting strategies aiming to reduce the volcanic risks.

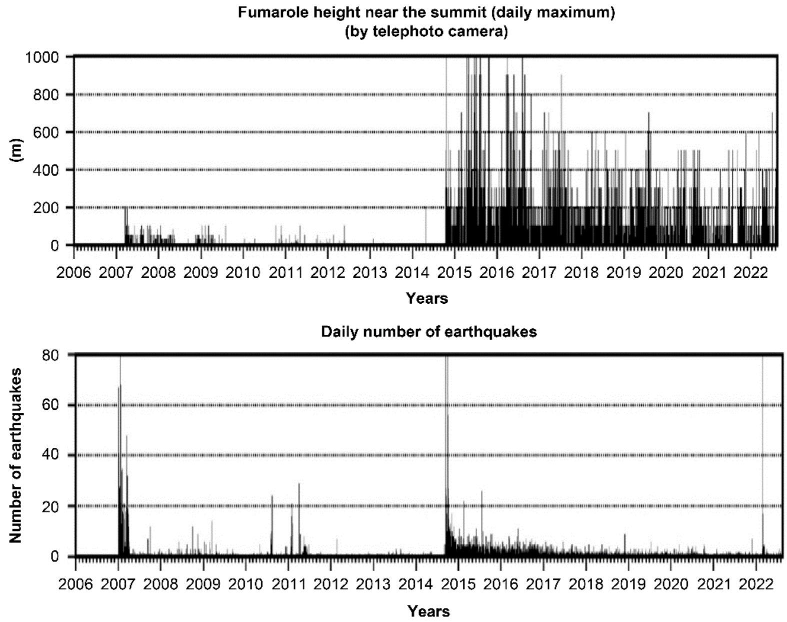

Figure 6. Fumarole volcanic activity (top) and volcanic seismic activity (bottom).

4. Discussion

4.1. Will phreatic eruptions always occur if there is an abundance of precipitation?

According to the Japan Meteorological Agency website, the yearly rainfall of Mt. Ontake was higher than that of 2014 in 2015, 2016, 2018, 2020, and 2021. In addition, the monthly precipitation was also higher as shown in Table 1. However, from 2014 to 2021, while earthquakes and volcanic plume were observed, no eruption has occurred, even after the heavy precipitation periods.

This is a phenomenon in which the release of fumarole energy from the pre-existing crater, prompted by seismic observations due to an explosion resulting from vaporization. In other words, it is not considered as an explosive eruption due to its lack of occurrence in a sealed state. This issue remains for further research in the future.

4.2. Why do the dates of rainfall and volcanic eruptions not coincide?

Mt. Ontake reaches the maximum altitude of 3,067 m, exhibits complex channels and narrow crevices, and takes many days to infiltrate through the complex system of channels and reach the buried heat source. The daily precipitation for the eruption that occurred on October 28, 1979, was recorded 187 mm on October 19, 1979, with an hourly maximum of 32 mm. The combination of previously stored rainwater and the pressurization of these rainwaters may have been a contributing factor. The Japan Meteorological Agency report that a seismic swarm occurred in the Ontake town on September 10–11, 2014, prior to the eruption on September 27. This event prompted the issuance of a volcano information notice, which advised surrounding towns of the possibility of a minor phreatic eruption. The occurrence of this event can be attributed to a complex time lapse that was impacted by the intensity of short-term precipitation, which accumulated to 102.0 mm on September 4 and 5 as shown in Table 2. Subsequently, there was no rainfall until September 23, and the seismic activity declined. However, the total rainfall on September 24 and 25 was 164 mm, with 14.5 mm per hour on September 24 and 16.0 mm per hour on September 25. It is probable that the heavy rainfall caused a build-up of pressure, which directly led to the eruption a few days later. Further research will be required in the future to investigate the correlation between the time interval of rainfall dates, earthquake occurrence dates, and eruption occurrence dates.

4.3. Why are no phreatic eruptions of mountains besides Mt. Ontake investigated in this paper?

AMeDAS was installed in the same area as the 24-hour observation equipment on Mt. Ontake, but nowhere else in Japan. Volcanoes have experienced phreatic eruptions similar to Mt. Ontake. The following examples illustrate the time relationship between extreme rainfall and phreatic eruptions based on a rainfall survey conducted by AMeDAS several kilometers away from the erupting volcano. The notation in parentheses indicates the following (Location of AMeDAS place name, prefecture name):

1. The eruption of Mt. Aso (located in Miniaso, Kumamoto Prefecture) started on October 9, 2016. The highest recorded precipitation rates were 77 mm/h on July 18, 2016, and 106 mm/d and [36].
2. Mt. Aso (located in Minamiaso, Kumamoto Prefecture) experienced an eruption on July 27, 2020. The daily total of 365 mm and an hourly maximum of 68.5 mm were recorded on July 8, 2020 [37].
3. Mt. Aso (located in Minamiaso, Kumamoto Prefecture) erupted on October 20, 2021. However, as of August 14, 2021, a daily precipitation was 111 mm with an hourly maximum of 42.5 mm was recorded [38].
4. The eruption of Suwanosejima, (located in Suwanosejima, Kagoshima Prefecture) occurred on July 27, 2020.On July 8, 2020, a daily dose of 365 mm and a maximum of 68.5 mm per hour were recorded [39].
5. A minor eruption occurred at Mt. Asama (located in Tomi, Nagano Prefecture) on August 7, 2019. However, on August 2, 2019, meteorological data indicated a daily precipitation of 40.5 mm, with an hourly maximum of 40.5 mm [40].
6. Mt. Motoshirane (located in Kusatsu, Gunma Prefecture) suddenly erupted on January 23, 2018. As of July 6, 2017, the volcano documented a daily average of 150.5 mm and an hourly maximum of 50.0 mm [41].
7. The Sakurajima volcano (located in Kagoshima, Kagoshima Prefecture) erupted on July 28, 2019. The total rainfall from June 27 to July 27 was 1,053 mm, with seven consecutive days of maximum hourly rainfall in June 2019 [42] and July 2019 [43] exceeded 20 mm.
8. Mt. Hakone, (located in Hakone, Kanagawa Prefecture) displayed seismic and volcanic plume activity on May 6, 2015, prompting the Japan Meteorological Agency to issue an eruption warning. The daily precipitation on April 20, 2015 was 142.5 mm, with an hourly maximum of 23.5 mm [44].

The direct correlation between heavy rains and phreatic eruptions can be argued by the many examples listed above. However, a robust statistical approach should include a greater sample to result in robust and useful analytical results.

5. Conclusions

This paper presents the example of the eruption of Mt. Ontake, focusing on the relationship between phreatic eruptions and extreme rainfall, and advocates "a fusion between volcanological and meteorological approaches during the monitoring and forecasting of eruption activity". It discusses the time relationship between heavy rainfall and phreatic eruptions and outlines the processes leading to explosive activity without magma movement. For future research on phreatic eruptions, it is recommended to install rain gauges similar to AMeDAS not only in Japan but also in other volcanoes worldwide. In the future, it is expected that many scientists will share their research and it is anticipated that volcanology research will advance scientifically, resulting in its contribution as a natural disaster countermeasure. In this study a clear and concise language rather than relying on specialized terminology, in order to meet the interest of researcher as well as everyone who are within the vicinity of a volcanic area for different reasons (e.g., job, tourism, education, and residence).

Data and material availability

The data used in Tables 1 and 2 are publicly available from the website of the Japan Meteorological Agency, the organization in charge of meteorology of the Japanese government.

Figures 1, 3, 4, and 6 can be obtained from the website of the Japan Meteorological Agency.

Figure 2a,b were published with permission from the website of the Ontake Volcano Research Institute, Nagoya University. And Figure 2c was taken from an open access article published in *Nature Communications* https://www.nature.com/articles/s41467-022-32252-w. The Ontake Volcano Research Institute of Nagoya University permitted the publication of Figure 2.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

The data published by the Japan Meteorological Agency on its website in the explanation of Mt. Ontake's volcanic activity (September 2014) was important for the preparation of this paper. This paper was greatly aided by the high-level data provided by universities, local governments, and private companies that created this material. With the permission of the Nagoya University Ontakesan Research Institute, the website's photographs and data were of great assistance to this paper.

Conflict of interest

The author declares no conflict of interest.

References

1. Oikawa T, Yoshimoto M, Nakada S, et al. (2016) Reconstruction of the 2014 eruption sequence of Ontake volcano from recorded images and interviews. *Earth Planet Sp* 68: 79. https://doi.org/10.1186/s40623-016-0458-5
2. The Japan Meteorological Agency, 50 Volcanoes That Require Enhanced Monitoring and Observation Systems for Volcanic Disaster Prevention Available from the following. Available from: https://www.data.jma.go.jp/vois/data/tokyo/STOCK/kaisetsu/katsukazan_toha/katsukazan_toha.html#kanshikazan.
3. Yamaoka K, Geshi N, Hashimoto T, et al. (2016) The phreatic eruption of Mt. Ontake volcano in 2014. *Earth Planet Sp* 68: 175. https://doi.org/10.1186/s40623-016-0548-4
4. Kaneko T, Maeno F, Nakada S (2014) Mt. Ontake eruption: characteristics of the phreatic eruption as inferred from aerial observations. *Earth Planet Sp* 68: 1–11.
5. Maeno F, Nakada S, Oikawa T, et al. (2016) Reconstruction of a phreatic eruption on 27 September 2014 at Ontake volcano, central Japan, based on proximal pyroclastic density current and fallout deposits. *Earth Planet Sp* 68: 82. https://doi.org/10.1186/s40623-016-0449-6
6. Farquharson JI, Amelung F (2020) Extreme rainfall triggered the 2018 rift eruption at Kīlauea volcano. *Nature* 580: 491–495. https://doi.org/10.1038/s41586-020-2172-5
7. Barclay J, Johnstone JE, Matthews AJ (2006) Meteorological monitoring of an active volcano: implications for eruption prediction. *J Volcanol Geotherm Res* 150: 339–358. https://doi.org/10.1016/j.jvolgeores.2005.07.020
8. Aubry TJ, Farquharson JI, Rowell CR, et al. (2022) Impact of climate change on volcanic processes: current understanding and future challenges. *Bull Volcanol* 84: 58. https://doi.org/10.1007/s00445-022-01562-8
9. Simmons J, Elsworth D, Voight B (2004) Instability of exogenous lava lobes during intense rainfall. *Bull Volcanol* 66: 725–734. https://doi.org/10.1007/s00445-004-0353-y
10. Farquharson JI, Amelung F (2022) Volcanic hazard exacerbated by future global warming-driven increase in heavy rainfall. *R Soc Open Sci* 9: 220275. https://doi.org/10.1098/rsos.220275
11. Stix J, de Moor JM (2018) Understanding and forecasting phreatic eruptions driven by magmatic degassing. *Earth Planet Sp* 70: 83. https://doi.org/10.1186/s40623-018-0855-z
12. Minami Y, Imura T, Hayashi S, et al. (2016) Mineralogical study on volcanic ash of the eruption on September 27, 2014 at Ontake volcano, central Japan: correlation with porphyry copper systems. *Earth Planet Sp* 68: 67. https://doi.org/10.1186/s40623-016-0440-2
13. Takagi A, Onizawa S (2016) Shallow pressure sources associated with the 2007 and 2014 phreatic eruptions of MT. Ontake, Japan. *Earth Planet Sp* 68: 135. https://doi.org/10.1186/s40623-016-0515-0

14. Sasaki H, Chiba T, Kishimoto H, et al. (2016) Characteristics of the syneruptive-spouted type lahar generated by the September 2014 eruption of Mount Ontake, Japan. *Earth Planet Sp* 68: 141. https://doi.org/10.1186/s40623-016-0516-z
15. Ikehata K, Maruoka T (2016) Sulfur isotopic characteristics of volcanic products from the September 2014 mount ontake eruption, Japan. *Earth Planet Sp* 68: 116. https://doi.org/10.1186/s40623-016-0496-z
16. Miyaoka K, Takagi A (2016) Detection of crustal deformation prior to the 2014 Mt. Ontake eruption by the stacking method. *Earth Planet Sp* 68: 60. https://doi.org/10.1186/s40623-016-0439-8
17. Mount Ontake Volcano Research Facility. Available from: https://www.seis.nagoya-u.ac.jp/center/kovo/midokoro/midokoro_detail06.html.
18. Caudron C, Aoki Y, Lecocq L, et al. (2022) Hidden pressurized fluids prior to the 2014 phreatic eruption at Mt Ontake. *Nat Commun* 13: 6145. https://doi.org/10.1038/s41467-022-32252-w
19. Japan Meteorological Agency, AMeDAS (Automated Meteorological Data Acquisition System), a Weather Observation Instrument. Available from: https://www.jma.go.jp/jma/kishou/know/amedas/kaisetsu.html.
20. Japan Meteorological Agency, AMeDAS, The Monthly and Annual Rainfall of Mt. Ontake in 2006 or 2021. Available from: https://www.data.jma.go.jp/obd/stats/etrn/index.php?prec_no=48&block_no=0416&year=&month=&day=&view=.
21. Japan Meteorological Agency, A Meteorological Example of Typhoon No. 20 Hitting Japan in 1979. Available from: https://www.data.jma.go.jp/obd/stats/data/bosai/report/1979/19791010/19791010.html.
22. Japan Meteorological Agency, Weather Examples of Typhoons No. 11 and No. 12 that Hit Japan in 2014. Available from: https://www.data.jma.go.jp/obd/stats/data/bosai/report/2014/20140730/jyun_sokuji20140730-0811.pdf.
23. Japan Meteorological Agency, The Rainfall Amount for August 1979 According to AMeDAS. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=48&block_no=0416&year=1979&month=08&day=&view=p1.
24. Japan Meteorological Agency, The Rainfall Amount for September 1979 According to AMeDAS. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=48&block_no=0416&year=1979&month=09&day=&view=p1.
25. Japan Meteorological Agency, The Rainfall Amount for October 1979 According to AMeDAS. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=48&block_no=0416&year=1979&month=10&day=&view=.
26. Japan Meteorological Agency, The Rainfall in July 2014 by AMeDAS. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=48&block_no=0416&year=2014&month=07&day=&view=p1.

27. Japan Meteorological Agency, The Rainfall in August 2014 by AMeDAS. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=48&block_no=0416&year=2014&month=8&day=&view=.
28. Japan Meteorological Agency, The Rainfall amount for September 2014 according to AMeDAS. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=48&block_no=0416&year=2014&month=09&day=&view=p1.
29. Ogiso M, Matsubayashi H, Yamamoto T (2015) Descent of tremor source locations before the 2014 phreatic eruption of Ontake volcano, Japan. *Earth Planet Sp* 67: 206. https://doi.org/10.1186/s40623-015-0376-y
30. Maeda Y, Kato A, Terakawa T, et al. (2015) Source mechanism of a VLP event immediately before the 2014 eruption of Mt. Ontake, Japan. *Earth Planet Sp* 67: 187. https://doi.org/10.1186/s40623-015-0358-0
31. Kato A, Terakawa T, Yamanaka Y, et al. (2015) Preparatory and precursory processes leading up to the 2014 phreatic eruption of Mount Ontake, Japan. *Earth Planet Sp* 67: 111. https://doi.org/10.1186/s40623-015-0288-x
32. Volcano Division, Earthquake and Volcanology Department, Japan Meteorological Agency (May 2014) Volcanic Eruption Prediction Coordination Committee Bulletin No. 119, Volcanic Activities of Mt. *Ontake* (May 2014 to October 13, 2014), Available from: https://www.data.jma.go.jp/vois/data/tokyo/STOCK/kaisetsu/CCPVE/Report/119/kaiho_119_08.pdf
33. Gaete A, Walter TR, Bredemeyer S, et al. (2020) Processes culminating in the 2015 phreatic explosion at Lascar volcano, Chile, monitored by multiparametric data. *Nat Hazards Earth Syst* 20: 377–397. https://doi.org/10.5194/nhess-20-377-2020
34. Strehlow K, Sandri L, Gottsmann JH, et al. (2017) Phreatic eruptions at crater lakes: occurrence statistics and probabilistic hazard forecast. *J Appl Volcanol* 6: 4. https://doi.org/10.1186/s13617-016-0053-2.45
35. Maeda Y, Watanabe T (2023) Seismic structure and its implication on the hydrothermal system beneath Mt. Ontake, central Japan. *Earth Planet Sp* 75: 1–115. https://doi.org/10.1186/s40623-023-01870-z
36. Japan Meteorological Agency, The Rainfall Amount of Mt. Aso on July 18, 2016, According to AMeDAS in Minamiaso, Kumamoto Prefecture. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=86&block_no=1660&year=2016&month=07&day=&view=p1.
37. Japan Meteorological Agency, The Rainfall Amount for Mt. Aso on July 8, 2020, According to AMeDAS in Minamiaso, Kumamoto Prefecture Japan Meteorological Agency. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=86&block_no=1660&year=2020&month=07&day=&view=p1.
38. Japan Meteorological Agency, The Rainfall Amount for Mt. Aso on August 14, 2021, According to AMeDAS in Minamiaso, Kumamoto Prefecture Japan Meteorological Agency, Aug 2021. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=86&block_no=1660&year=2021&month=08&day=&view=p1.

39. Japan Meteorological Agency, The Rainfall Amount for Suwanosejima on July 8, 2020, According to AMeDAS for Su Wanosejima, Kagoshima Prefecture. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=88&block_no=1654&year=2020&month=7&day=&view=.
40. Japan Meteorological Agency, The Rainfall Amount for mt. Asama on August 2: 2019 According to AMeDAS in Tomi, Na Gano Prefecture. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=48&block_no=0993&year=2019&month=8&day=&view=.
41. Japan Meteorological Agency, The Rainfall Amount for Motoshirane on July 6, 2017 of the Previous Year According to Ame DAS in Kusatsu, Gunma Prefecture. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=42&block_no=0343&year=2017&month=07&day=&view=p1.
42. Japan Meteorological Agency, The Rainfall Amount for Sakurajima in June 2019 According to AMeDAS in Kagoshima, Ka Goshima Prefecture. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_s1.php?prec_no=88&block_no=47827&year=2019&month=06&day=&view=p1.
43. Japan Meteorological Agency, The Rainfall Amount for Sakurajima in July 2019 According to AMeDAS in Kagoshima, Ka Goshima Prefecture. Available from: https://www.data.jma.go.jp/obd/stats/etrn/view/daily_s1.php?prec_no=88&block_no=47827&year=2019&month=07&day=&view=p1.
44. Japan Meteorological Agency, Hakone, Kanagawa Prefecture The Rainfall Amount for Mt. Hakone April 20: 2015 According to AMeDAS in Hakone. Available from: https://www.data.jma.go.jp/stats/etrn/view/daily_a1.php?prec_no=46&block_no=0390&year=2015&month=4&day=&view=.