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Paper:

Eruption Pattern and a Long-Term Magma Discharge Rate over the Past 100 Years at Kelud Volcano, Indonesia

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Kelud Volcano is among the most active volcanoes in Indonesia, with repeated explosive eruptions throughout its history. Here, we reconstructed the relationship between the repose period and the cumulative volume of erupted material over the past 100 years and estimated the long-term magma discharge rate and future eruptive potential and hazards. Tephra data and eruption sequences described in historical documents were used to estimate the volume and mass discharge rate. The volumes of the 1901, 1919, 1951, 1966, 1990, and 2014 eruptions were estimated as 51–296 × 10^6 m^3. The mass discharge rates were estimated to be on the order of 10^7 kg/s for the 1919, 1951, and 2014 eruptions and the order of 10^6 kg/s for the 1966 and 1990 eruptions. Based on a linear relationship between the repose period and cumulative erupted mass, the long-term mass discharge rate was estimated as $\sim 1.5 \times 10^{10}$ kg/year, explaining the features of the larger eruptions (1919, 1951, and 2014) but not those of the smaller eruptions (1966 and 1990). This estimate is relatively high compared to other typical basaltic-andesitic subduction-zone volcanoes. This result provides important insights into the evolution of magmatic systems and prediction of future eruptions at Kelud Volcano.

Keywords: plinian eruption, discharge rate, tephra, volume, Kelud

1. Introduction

The eruption histories of volcanoes often show a correlation between the eruption recurrence interval and the volume of erupted material (e.g., [1–4]). In the simple case of a linear relationship, the volume of erupted material is proportional to the interval preceding the eruption; thus, a large-scale eruption occurs after a long repose period, or that on a small scale after a short repose period. This type of relationship between eruption interval and volume, which differs for each volcano, may reflect the dynamic behavior of the magma reservoir–conduit system responding to the flow of magma from deep to shallower reservoirs, or to the stress field around the magmatic system (e.g., [2, 3]). Therefore, understanding the relationship between the eruption interval (or repose period) and the (cumulative) volume of the erupted material will lead to a better understanding of the conditions and evolution of magma reservoir–conduit systems, as well as the cause of the differences in activities between volcanoes. The correlation can also be used to estimate the long-term magma discharge rate over 10^2 to 10^4 years, which has been determined for many active volcanoes [1–9] and applied to predict the repose period or volume of future eruptions.

Kelud Volcano, Indonesia, is a typical volcano that has had repeated explosive eruptions throughout its history. Thus, it offers an opportunity to study recurrence on a scale of from 10 to 10^2 years. In this study we reconstructed the relationship between the repose period and the cumulative volume of the erupted material during the last 100 years at Kelud Volcano, estimated the magma discharge rate, and evaluated future eruptive potential and hazards.

Kelud Volcano, on the island of Java, is among the most active volcanoes in Indonesia. More than 30 eruptions have been recorded in historical times [10]. The 1000 AD eruption is the oldest in the historical record of eruptions for the entire Indonesian archipelago. Since AD 1300, periods of unrest between eruptions range from 9 to 75 years [11, 12]. The last eruption occurred on 13 February 2014 and was an explosive plinian eruption. The eruptions during the last century have been characterized by volcanic explosivity index (VEI, [13]) 4-scale plinian eruptions (1901, 1919, 1951, 1966, 1990,

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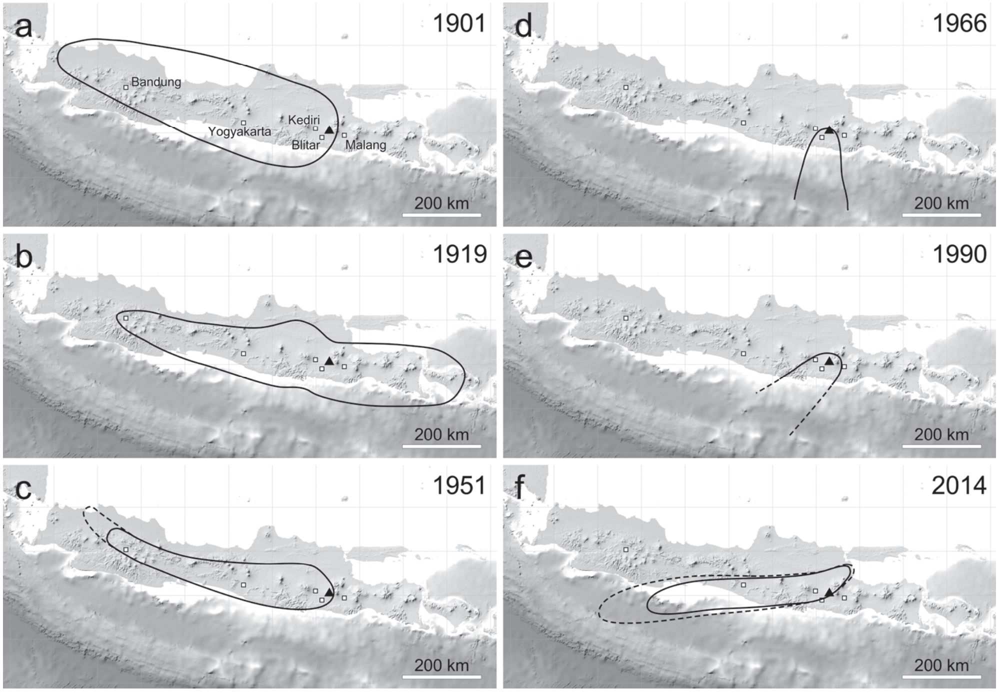

Fig. 1. Tephra distributions of explosive eruptions at Kelud Volcano, Java, Indonesia, since 1901. The location of Kelud Volcano is shown as a triangle. Broken lines indicate possible limit of tephra distribution. The data for the 1901, 1919, 1951, and 1966 eruptions are based on [21]. The data for the 1990 and 2014 eruptions are from [23, 24, 36].

and 2014), or smaller-scale lava dome-building eruptions (1920 and 2007–2008). The explosive activities at Kelud Volcano typically initiate with a phreatomagmatic phase followed by a short plinian eruption with convective columns reaching an altitude of more than 10 km. These eruptions produced devastating lahars, pyroclastic surges and flows as well as ashfall deposits. The 2014 eruption was observed by various geophysical monitoring instruments and provided an important opportunity to examine in detail the sequence of a plinian eruption and the associated hazards.

The recurrence history of plinian eruptions and dome formation at Kelud Volcano indicate that an eruption of a similar type and similar scale to the 2014 event can readily occur in the future. Ishihara et al. [14] reviewed the volumes of the eruptions at Kelud Volcano during the last century, based on published data [15] and estimated the long-term magma discharge rate. The volumes of the eruptions were estimated based on deposits calculated in previous studies, where different estimation methods were used and in some cases the methods included oversimplified or unclear assumptions. Therefore, when the estimated volumes of the various eruptions are compared, a large error must be considered. In this study, we investigated historical documents that describe the eruptions at Kelud Volcano since 1900 [15–26] and provide an overview of each eruption. Then, we re-evaluated the tephra data and estimate the volume and mass discharge rate for each eruption, as well as the long-term magma discharge rate over the past 100 years, using the same estimation method to compare all the data. The reanalysis of the tephra data provides important insights into the evolution of magmatic systems and will help in the prediction of future eruptions at Kelud Volcano.

2. Eruption Sequence and Deposit

2.1. 1901 Eruption

The 1901 eruption occurred after a calm interval of ∼37 years, the previous eruption occurring in 1864. The eruption occurred at midnight between 22 and 23 May 1901. The first eruption occurred at around 0:00 to 1:00. The eruption activity increased for the first 2 h, then the main eruption began at 3:00. The eruption plume rose from the summit crater followed by lapilli fall around the volcano. Immediately after the lapilli fall, wet dust and mud were deposited, followed by ash fall. In Kediri, 30 km NW of the volcano, ash fall began at approximately 3:30. The eruption sound was heard as far away as Pekalongan, 300 km WNW of the volcano. The ash fall was widespread, extending to Sukabumi and Bogor, 600 km west of the volcano (**Fig. 1(a)**, [21]). The estimated water volume of the crater lake at the summit was $\sim 38 \times 10^6$ m^3 before the eruption. The eruption occurred in the summit crater, but did not cause destruction of the crater wall. One report states that $\sim 200 \times 10^6$ m^3 of solid material was ejected during the eruption [16, 26]. This volume is based on the distribution of the fallout deposit, but the estimation method is unknown. Therefore, a large uncertainty was assumed for this eruption.

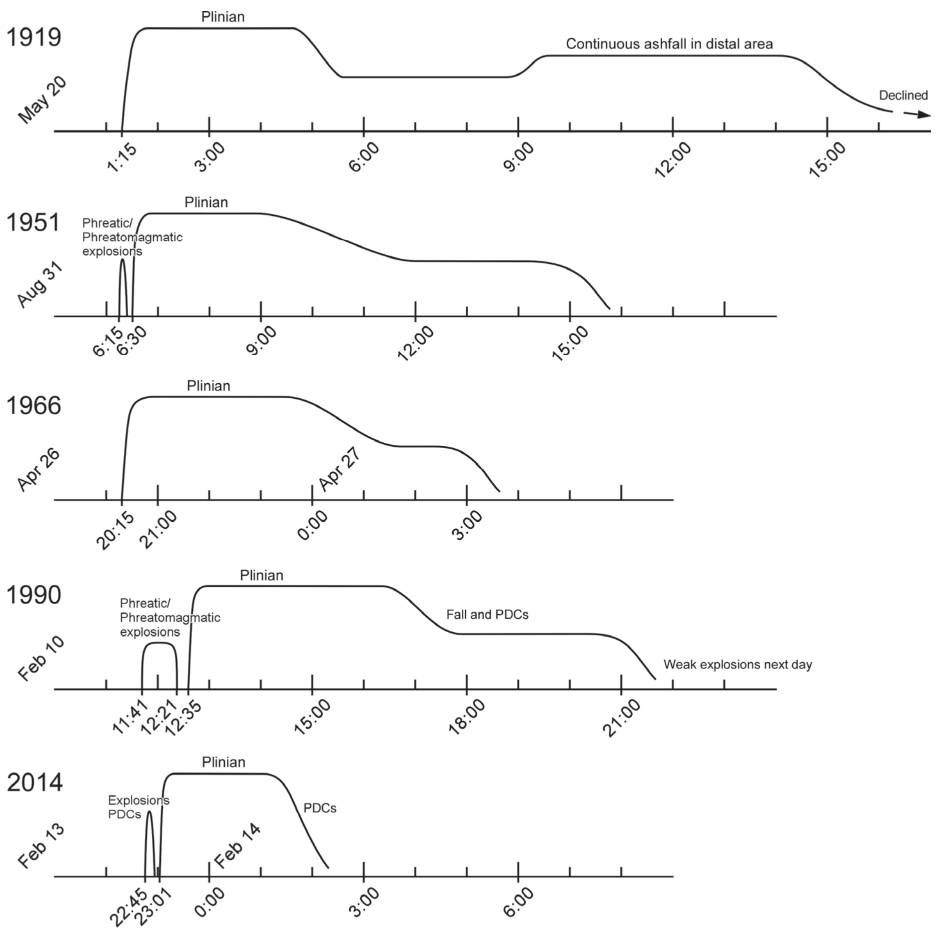

Fig. 2. Sequences of the eruptions at Kelud Volcano in 1919, 1951, 1966, 1990, and 2014. The curves indicate the temporal changes in the eruption intensity inferred from observational records. The vertical scale is qualitative.

2.2. 1919 Eruption

The 1919 eruption occurred at midnight between the 19th and 20th May. The following is a summary of this eruption based on the report by Kemmerling [17] that described his own and other local observations of the 1919 eruption. At approximately 01:15 on 20 May, a very strong roar was heard from the direction of Kelud Volcano. It is inferred that the eruption began at this time (**Fig. 2**). The eruption was also marked by a loud noise heard as far as Borneo. Soon ash began to fall and gravel-sized rocks landed in the plantation area on the volcano's slopes of the Kelud. Most of the roofs of houses were destroyed. Ash particularly spread toward the east. At Malang, ∼35 km E of the volcano, the ash fall was the most intense between 02:00 and 05:00 on 20 May, with 0.75 kg/m^2/h deposited in the area (**Fig. 2**). The depositional rate decreased between 05:00 and 09:00 (to 0.38 kg/m^2/h) and then increased again until 14:00 (0.68 kg/m^2/h). Data of ash weight per unit area was collected every 1 h during the eruption by Dr. Wurth, director of the experimental station at Malang. The ashfall observations and the ash depositional conditions are summarized in [17]. Bali experienced ash fall on 21 May 1919. During this eruption, the ash was distributed to the west and east (**Fig. 1(b)**, [21]). The volume of tephra has been estimated in a previous study as $\sim 190 \times 10^6$ m^3 [17, 26]. The disaster was driven by lahars. Before the eruption, the volume of the lake water in the crater reached 40×10^6 m^3; the water was forced out of the crater at the time of the eruption and combined with the erupted material to form lahars. Approximately 01:30 on 20 May, lahars entered the city of Blitar, ∼20 km SW of the volcano, causing considerable destruction. The 1919 eruption resulted in heavy damage to 104 villages and was thought to have been the greatest volcanic disaster in Indonesia during the 20th century. From 6 to 12 December 1920, a lava dome formed in the summit crater of the Kelud Volcano. The size of the lava dome is not known. This event may have been a later-stage eruption associated with the 1919 eruption.

2.3. 1951 Eruption

The 1951 eruption sequence is summarized in [18] and [26]. The 1951 eruption was among the largest eruptions at Kelud Volcano, occurring after 32 years of dormancy. Two earthquakes occurred ∼3 weeks prior to the eruption. The eruption began in the morning on 31 August 1951 (**Fig. 2**). At 06:15, white smoke appeared from the top of Kelud Volcano accompanied by a roar. At approximately 06:30, an explosive sound was heard, followed by the rising of a thick dark ash column spreading to the south. There was a rain of lapilli, mixed with sand in Kediri, which lasting until approximately 09:00, followed by heavy ashfall which ceased at 16:00. At Blitar, 15 min after the explosion, a shower of sand and gravel fell on the town. By noon the situation returned to normal. Thirty minutes after the first dark ash column appeared, lapilli and ash fell on Margomulyo, at the western foot of the volcano, where the visibility was reduced to 3–4 m. Information from Candi Sewu, 200 kmW of the volcano, mentioned that the 'rain' of rocks lasted $\sim$1 h, and two earthquakes were felt. Ash fall was recorded as far as Bandung, 520 kmW of the volcano. Observations mention that at the time of the eruption a strong westerly wind was blowing and no ashfall was observed on the eastern side of the volcano. It is estimated that $\sim 200 \times 10^6$ m^3 of material was ejected during the eruption [18].

An isopach map of the products of the 1951 eruption was drawn by [22], including the most distal deposits referred to by [21] (**Figs. 1(c)**, **3(a)**). Wirakusumah [22] divided the deposits into five major units from layer A1 to A5. The total volume of at least 140×10^6 m^3 consists of 1.4×10^6 m^3 of layer A1 (phreatomagmatic explosion origin), 120×10^6 m^3 of layer A2 (mainly pyroclastic air fall deposits which were very widespread) and 16×10^6 m^3 of layers A3 (pyroclastic flow origin), A4 (pumice lapilli air fall from a small eruption), and A5 (ash fall from a small eruption). Hadikusumo [20] also calculated the volume of the ejected material for the 1951 eruption at 200×10^6 m^3. It should be noted that the amount of eruptive products estimated by [20] was based mainly on data of pyroclasts deposited in the rivers and on the slopes of the volcano. The amount of ash carried westward by the prevailing wind and distributed as far as the western part of the island of Java, 700–800 km in distance, was not included in the calculations by [20] and [22]. Reports of the eruption in the local newspapers mention that "the city of Yogyakarta, 250–300 km W of the volcano, was in darkness." This distal ash fall is considered in the map of [21]. It may be safely assumed that the amount of ash blown out of the area during that eruption was considerably high. The eruption killed 7 people and injured 157 people. Approximately 320 hectares of plantation and forested areas were damaged [26]. All the water of the crater lake was ejected during the eruption [20].

2.4. 1966 Eruption

This eruption occurred on 26 April 1966. The seismograph in the volcano observatory (POS) Margomulyo, $\sim$6 km west of the summit crater, recorded an earthquake 15 min before the explosive eruption that began at 20:15 (**Fig. 2**). The eruption lasted approximately 7 h. The ash was blown mainly south and spread over a much narrower area than in 1951. The ash distribution in the distal zone was not constrained because the dispersal axis pointed southward to the Indian Ocean (**Fig. 1(d)**, [21]).

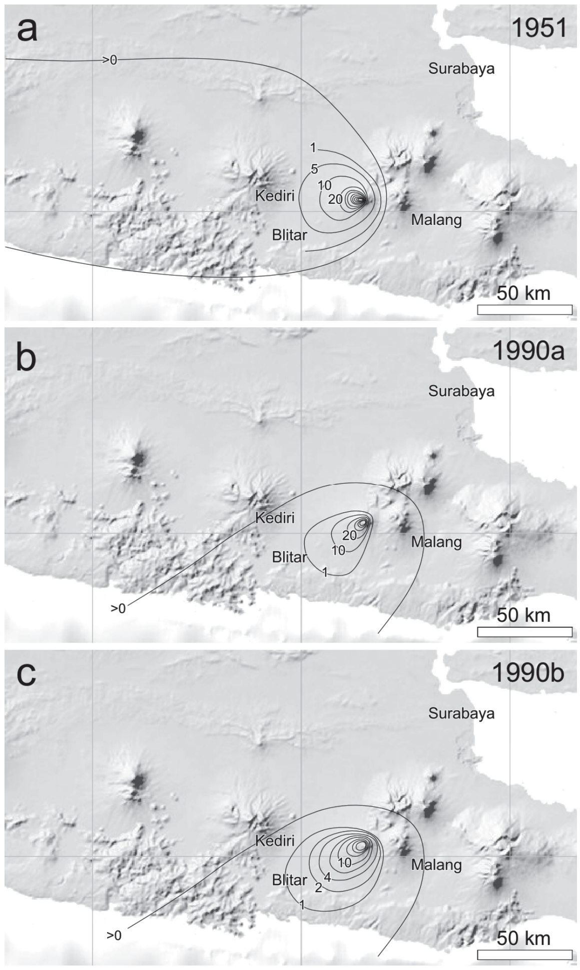

Fig. 3. Tephra distributions for the (a) 1951 eruption [22], (b) 1990 eruption [23], and (c) 1990 eruption [24]. The number unit is [cm].

Based on the proximal distribution of the lapilli and ash, Djoharman [19] estimated the total amount of pyroclastic deposits, including ash fall and pyroclastic material deposited in rivers, probably derived from pyroclastic flows and lahars, at 92×10^6 m^3. The amount of ejected pyroclastic material was estimated by dividing the areas where the deposits remained into two sections around the peak and rivers, and three circular sections. Hadikusumo [20] also estimated a value of $\sim 90 \times 10^6$ m^3 as the volume of the 1966 products. These values by [19] and [20] are based only on the deposits in the proximal zone; therefore, they are the minimum estimation. During the 1966 eruption, all of the water of the crater lake was ejected and 210 people were killed by primary lahars because of the incomplete lake draining system. This is in contrast to the 1951 and 1990 eruptions where no primary lahars occurred and the number of casualties was low because of good drainage of the lake water before the eruptions.

2.5. 1990 Eruption

This eruption occurred on 10 February 1990. The eruption activity began as a volcanic earthquake swarm on

9 February at 12:17. The number of earthquakes rapidly increased and volcanic tremors were noted at 09:32 on 10 February, with increasing amplitude that continued until the eruption event. The eruptions started at 11:41 and continued until 12:21 (**Fig. 2**). This initial phase of the eruption was a phreatomagmatic phase resulting in ash fall, thinly distributed around the peak, while subsequent larger eruptions comprising sand, lapilli, and rocks spread over a radius of 3.5 km^2, approximately 1.5 km to the east and 5 km to the west, northwest and southwest. Loud rumblings were heard after 12:31. The main sustained eruption started at 12:35 according to the seismic record [27] (**Fig. 2**). It was a plinian-style eruption with ash clouds from pyroclastic density currents (PDCs) along the valley in the southwest, extending 5 km from the crater. The total eruption duration was estimated to be 8–9 h but the main explosive plinian phase lasted 4.25 h from 13:30 based on visual and seismic observations [23, 24]. Ash falls were reported in Malang. Satellite tracking of the plume was made difficult by heavy cloud cover in the area. Imagery from Japan's Geostationary Meteorological Satellite (GMS) at 13:00 showed a bright cloud, 53 km across, centered above the volcano. At 13:47, a National Oceanic and Atmospheric Administration (NOAA) polar orbiter image showed that the plume, still approximately circular and centered above the volcano, had grown to $\sim$160 km in diameter. Preliminary temperature analysis suggested that the top of the dense cloud was at $\sim$12 km altitude, although diffuse material could have extended higher. By 16:00, GMS data indicated that the plume had drifted slightly WSW and was $\sim$310 km long. The next day at 13:47, very diffuse-appearing material could be seen extending to the NW coast of Australia, $\sim$1400 km from the Kelud, on an NOAA polar orbiter image. Dispersed remnants of the plume were traced on GMS images until 19:00 on 10 February.

A tephra distribution map was constructed by [23] and [24] (**Figs. 1(e)**, **3(b)**, **3(c)**). The ash fall destroyed approximately 500 houses and 50 school buildings. The 10-cm isopach extends for a maximum distance of $\sim$15 km from the crater. Roof collapse was the main cause of the 32 deaths recorded for this eruption [24, 28]. The eruption was of medium intensity with an ejected tephra volume of $\sim 130 \times 10^6$ m^3, including PDC deposits [24]. Wirakusumah and Hendrajaja [23] and Bourdier et al. [24] used the methods of Pyle [29] and Fierstein and Nathenson [30], respectively, to estimate eruptive material. Because they had no distal tephra data (**Fig. 3**), they calculated the tephra volumes assuming the same tephra-thinning trend extending to the sea area as that on-land. The damage was limited to a small area, within a radius of $\sim$2 km from the crater; however, ash was distributed over a much wider area, estimated to be 1700 km^2.

2.6. 2007–2008 Eruption

From September to October 2007 the color and temperature of the crater lake water changed, and seismic activity and ground deformation significantly increased. On 4 November 2007 a lava dome emerged in the crater lake. The lava dome remained active throughout November and December 2017, although the seismic activity gradually decreased [25, 31]. By 12 May 2008, the crater lake was nearly entirely depleted. By this time, the lava dome was considered to have stopped growing, having reached an estimated size of $\sim$260 m in height, $\sim$400 m in width at its base, and 3.5×10^7 m^3 in volume [25, 32]. The nature of this effusive eruption was different from that of the previous explosive plinian eruptions.

2.7. 2014 Eruption

During January 2014, the number of volcanic earthquakes around the Kelud Volcano began to increase. Their number and magnitude further increased from 2 February onward, and continued to increase until the eruption on 13 February 2014. The eruption was directly observed by eyewitnesses and recorded by a network of geophysical instruments, including satellites and remote seismic and acoustic stations. At 22:46 (local time, 15:46 UTC) on 13 February 2014, the seismic signal recorded at the near-crater station abruptly disappeared, indicating the onset of the explosive event (**Fig. 2**). Observers in the POS Margomulyo reported that the real-time camera on the crater rim captured ballistic ejecta as its final image at $\sim$22:45. Therefore, the erupting materials must have hit the seismic stations at this time. The explosion was followed by the rise of a plinian column. A satellite first detected the umbrella cloud at 16:09 UTC; the height of the cloud was 22–26 km above sea level (a.s.l.) 30 min after its detection [33]. The eruptive cloud radially and continuously spread at 17–18 km a.s.l., and its diameter reached 300 km within 1.5 h. The circular plume then drifted westward across the island of Java, retaining nearly the same radius 3 h after the eruption, while slightly expanding in both the down- and cross-current directions. Satellite images indicate that the vigorous plinian plume continued for $\sim$2.5 h, but remote seismo-acoustic signals suggest that the eruption plume weakened by 18:00 UTC and the resonant oscillation between the atmosphere and the ground continued for another hour [34, 35]. These observations indicate that the eruption lasted 2–2.5 h. Nine hours later, the center of the eruption cloud had drifted $\sim$600 km westward over the Indian Ocean. The tephra distribution is generally consistent with the development of the eruptive plume, but no major ashfall was observed in the eastern and southern areas of the volcano (**Fig. 1(g)**). The eruption deposits can be divided into four major depositional units (units A, B, C, and D), corresponding to the main phases of the 2014 event [36].

3. Estimation of Tephra Volume and Mass Discharge Rate

Using the relationship between the area covered by tephra and the thickness of the deposit, we estimated the volume of the fallout tephra deposits. Here, we used

Table 1. Tephra data for the 1919 eruption at Kelud Volcano by Kemmerling [17].

Observation	Average thickness [m]	Area [km^2]
Hardly visible	0.0001	34000
1/4–1/20 mm	0.00013	42000
3–1/5 mm	0.0016	16700
15–3 mm	0.009	5450
50–15 mm	0.0325	2250
450–50 mm	0.25	500

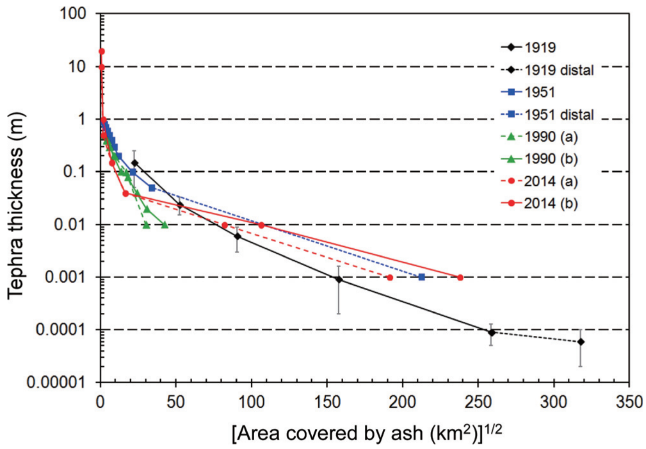

Fig. 4. Tephra thinning trends from representative eruptions at Kelud Volcano in the last 100 years. The 1919 eruption [17] (error bars indicate the variation in the thickness measurement); the 1951 eruption [22]; the 1990 eruption (a) [23], (b) [24]; and the 2014 eruption (a) and (b) [36].

tephra data for the eruptions of 1919, 1951, and 1990 [17, 21–24] to calculate their volumes (**Fig. 3**). In previous studies, tephra volumes have been estimated based on deposits, but different estimation methods were used in the various studies, and oversimplified or unclear assumptions were applied in some cases. For example, for the 1919 eruption, Kemmerling [17] estimated the total tephra volume by summing the volumes for multiple sections, each one calculated from the average thickness multiplied by the area covered by ash. However, this simplified method can cause a large error. In this study, we applied two methods for fitting and integrating the tephra thinning trends: exponential fitting [30] and Weibull fitting [37]. These methods do not set proximal and distal limits for the tephra distribution.

For the 1901 eruption, we have no detailed data of the deposit distribution. It is therefore difficult to construct the relationship between the thickness of the ash and the area covered by the ash; hence, we used the volume from the reports of [16] and [26] but treated it only as a reference value.

For the 1919 eruption, we used the tephra data by [17], in which the relationship between the ash thickness and the ash-covered area is summarized (**Table 1**). We assumed two tephra-thinning trends; one including the most distal data (average 0.0001-m thickness) and the other excluding these data. The distal data were thought to include a relatively large uncertainty because they had been based on observations of very thinly distributed ash that is barely visible. The variation in the thickness measurement in [17] was also considered (**Fig. 4**). We obtained 0.19–0.63 km^3 with the exponential fitting method and 0.25–1.1 km^3 when using the Weibull fitting method (average 0.53 km^3) (**Table 2**). When the most distal data and the average thickness for each area were included, we obtained the maximum volumes. PDCs also occurred during the eruption but their distribution and timing are unknown. Therefore, for the total DRE volume in **Table 2**, PDCs are not included. Based on witness observations of the tephra fall [17], the major phase of the eruption lasted ~13 h. Using the deposit volume and the eruption duration, the average mass discharge rate was estimated to be 1.6×10^7 kg/s (**Table 3**).

For the 1951 eruption, we used the tephra data of a major fallout deposit (5- to 90-cm contours for unit A2, **Fig. 3(a)**) by [22], which comprises $>$ 90% of the total tephra volume, and assumed two cases; one included the 0.1-cm contour for the distal limit of tephra distribution (**Fig. 1(c)**), the other did not use any contours for the distal zone (**Fig. 4**). We obtained 0.22–0.50 km^3 when using exponential fitting and 0.21–0.49 km^3 using Weibull fitting (average 0.36 km^3) (**Table 2**). When the distal contour was included, the eruptive volumes reached maximum values. PDCs also occurred during the eruption but their distribution and timing are unknown. Therefore, for the total DRE volume in **Table 2**, PDCs are not included. Based on witness observations of the tephra fall [18, 26], the major phase of the eruption lasted ~8.5 h. Using the deposit volume and the eruption duration, the average mass discharge rate was estimated to be 1.6×10^7 kg/s (**Table 3**).

For the 1966 eruption, the tephra volume was estimated as ~0.092 km^3 by [19], dividing the areas where the deposits remained into two sections around the peak, rivers, and three circular sections in the distal zone, and adding the volumes for each section calculated as the average thickness multiplied by the area. The tephra in the sea area was not considered; therefore, this estimation indicates a minimum value. If we assume a similar tephra distribution to the 1990 eruption (**Fig. 1**) and also assume exponential decay [30], the tephra volume in the sea area is 10–20% of the total tephra volume. Here, we adopt the value of [19], but also consider +20% error in the maximum. Hence, the total tephra volume is assumed as 0.09–0.1 km^3. The duration of the eruption was ~7 h [11, 26]. Using the deposit volume and the eruption duration, the average mass discharge rate was estimated to be 5.3×10^6 kg/s (**Table 3**).

For the 1990 eruption, we examined two datasets by [23] and [24] (**Figs. 1(e)**, **3(b)**, **3(c)**), and re-evaluated their volumes. The exponential fitting method yielded a volume of 0.079–0.102 km^3 and the Weibull fitting

Table 2. Volumes of the eruptions at Kelud Volcano since 1900.

Date	Eruption type	Tephra volume [$\times 10^6$ m^3] This study (Fall) Exponential max	min	Weibull max	min	Average	Other studies PDC	Fall+PDC	DRE volume*1 (This study) [$\times 10^6$ m^3]	Mass [$\times 10^9$ kg]	Magnitude*2 [M]	References for tephra volume*3
22–23 May 1901	Explosive	-	-	-	-	-	?	200	112	280	4.4	1, 2
20–21 May 1919	Explosive	629	185	1051	246	528	?	190	296	739	4.9	2, 3
6–12 Dec 1920	Effusive	-	-	-	-	-	-	-	small	-	-	2
31 Aug 1951	Explosive	502	223	488	208	355	?	200	199	497	4.7	2, 4, 5
24 Apr 1966	Explosive	-	-	-	-	-	?	90–92	53	133	4.1	2, 4, 6
10 Feb 1990	Explosive	102	79	107	79	92	20	120	63	156	4.2	7, 8
4 Nov 2007 to Apr 2008	Effusive	-	-	-	-	-	-	-	35	88	3.9	9
13 Feb 2014	Explosive	431	279	447	237	349	30	-	212	530	4.7	10, 11

*1: DRE (dense rock equivalent) volume was calculated assuming the deposit density 1400 kg/m^3 (as measured for the 2014 deposit) and magma density 2500 kg/m^3.
*2: Eruption magnitude (M) was calculated using the equation, $M = \text{Log (Mass, kg)} - 7$
*3: References 1) Houwink (1901), 2) Badang Geologi (2011), 3) Kemmerling (1921), 4) Hadikusmo (1974), 5) Wirakusumah (1991), 6) Djoharman (1966), 7) Wirakusumah and Hendrajaja (1992), 8) Bourdier et al. (1997), 9) Hidayati et al. (2009), 10) Maeno et al. (in press), 11) Global Volcanism Program (2014).

Table 3. Volumes of the eruptions at Kelud Volcano since 1900.

Date	DRE Volume [$\times 10^6$ m^3]	Mass [$\times 10^9$ kg]	Duration [h]	Peak duration [h]	Average discharge*1 [m^3/s]	Average discharge*1 [kg/s]	Max. discharge*2 [m^3/s]	Max. discharge*2 [kg/s]	Death tolls	Notes on disasters	Refs*3
22-23 May 1901	112	280	?	-	-	-	-	-	Many	Pyroclastic flows, lahars, flood at Blitar, destruction on summit ridge	1, 2, 12
20-21 May 1919	296	739	13	-	6.3E+03	1.6E+07	-	-	5160	Roof collapse, over 9000 houses damaged, 104 villages to be severely damaged, 135 km^2 of agricultural land destroyed by lahars	2, 3
6-12 Dec 1920	small	-	168	-	-	-	-	-	0		2
31 Aug 1951	199	497	8.5	-	6.5E+03	1.6E+07	-	-	7	Pyroclastic flows, destruction of summit ridge, 157 injured. 320 hectares of plantation and forestry areas are damaged.	2, 4, 5, 12
24 Apr 1966	53	133	7	-	2.1E+03	5.3E+06	-	-	211	210 killed by lahars. 50 km^2 agricultural land destroyed by lahars.	2, 4, 6
10 Feb 1990	63	156	8.5	4.25	2.1E+03	5.1E+06	4.1E+03	1.0E+07	32	Roof collapse, About 500 houses and 50 school buildings were damaged, lahars	2, 7, 8
4 Nov 2007 to Apr 2008	35	88	4200	1300	2.3E+00	5.8E+03	7.5E+00	1.9E+04	0		9
13 Feb 2014	212	530	2.75	2.25	2.1E+04	5.4E+07	2.6E+04	6.5E+07	7	Roof collapse, Damage to infrastructure included 3,782 houses, 20 government buildings, 251 schools, 9 hospitals, and 36 churches.	10, 11

*1: Average discharge was calculated using mass (DRE volume) and duration.
*2: Maximum discharge was calculated using mass (DRE volume) and peak duration.
*3: References 1) Houwink (1901), 2) Badang Geologi (2011), 3) Kemmerling (1921), 4) Hadikusmo (1974), 5) Wirakusumah (1991), 6) Djoharman (1966), 7) Wirakusumah and Hendrajaja (1992), 8) Bourdier et al. (1997), 9) Hidayati et al. (2009), 10) Maeno et al. (in press), 11) Global Volcanism Program (2014), 12) Thouret et al. (1998).

method resulted in 0.079–0.11 km^3. Maximum volumes were obtained using the data by [24] (**Table 2**). The total eruption duration was estimated at 8.5 h but the main explosive plinian phase lasted 4.25 h based on visual and seismic observations [23, 24]. Using the deposit volume including the PDC volumes ($\sim$0.02 km^3, [24]) and the eruption duration, the average mass and maximum discharge rates were estimated as 5.1×10^6 kg/s and 1.0×10^7 kg/s, respectively (**Table 3**).

In the 2007–2008 eruption, a lava dome grew during the period of volcanic activity which lasted nearly 6 months, but the main dome growth occurred from 4 November to the end of December 2007 [25]. The volume of the dome reached 3.5×10^7 m^3 [32]. Therefore, if we assume that most of the dome formed during the first 2 months, the mass discharge rate was estimated as 1.9×10^4 kg/s while the average mass discharge rate over the 6-month period was 5.8×10^3 kg/s (**Table 3**).

For the 2014 eruption, we used tephra data by [36]. The total deposit volume of the fallout tephra was estimated as 0.24–0.47 km^3. The volume of the PDC deposit was estimated as ~0.03 km^3. Therefore, the total volume, including the fallout and PDCs, was 0.26–0.48 km^3 (**Table 2**). The data of proximal fallout deposits shows a steeper thinning trend than that of the other eruptions (**Fig. 4**), but the volume for this area is only 5–10% of the total tephra volume. Based on satellite data and remote seismic records [34, 35], the duration of the development of the plinian column was estimated as 2.25–2.75 h. Using the deposit volume and the eruption duration, we calculated the average magma discharge rate as 6.5×10^7 kg/s for the maximum discharge during the plinian eruption [36] and 5.4×10^7 kg/s for the average mass discharge rate (**Table 3**).

4. Magma Reservoir

The chemical composition of the magma for each eruption and its changes during the last 100 years is not well constrained, because of poor preservation of the erupted materials, except those from recent eruptions (since 1990). The whole-rock chemical and mineral compositions of the recent products (1990, 2007–2008, and 2014 eruptions) are similar to one another [24, 36, 38], although the texture and glass composition are slightly different; the pumice in 2014 is more vesicular and its glass composition is less evolved. The whole-rock composition is 55–56 wt% in SiO_2. The matrix glass composition is dacitic to rhyolitic with 69–70 wt% in SiO_2. The erupted materials are basically highly porphyritic basaltic andesite with ~50–60 vol% of phenocrysts of plagioclase, clinopyroxene, orthopyroxene, and titanomagnetite. It is important to understand the effects of influences such as magma differentiation and mixing on changes in the magma reservoir condition and eruption process throughout the history of Kelud Volcano. However, the petrological and mineralogical characteristics of the older products (from the 1901 eruption to that in 1990) have not been analyzed; thus, it is still unclear whether the condition of the magma reservoir has changed during the last 100 years. The 2007–2008 lava dome provides evidence of a complex magmatic system comprising a deep-crustal storage region ($>$ 15 km depth), a mid-crustal storage zone (~10 km depth), and an upper crustal zone ($<$ 10 km depth) likely composed of multiple magma storage zones and pockets [38]. Similarities between the magma compositions since 1990 imply that the contrasting eruption styles of Kelud Volcano are not the result of geochemical evolution. Rather, differences in the degassing behavior, as a function of ascent rate, have likely played a role in the eruptive behavior of the volcano [38].

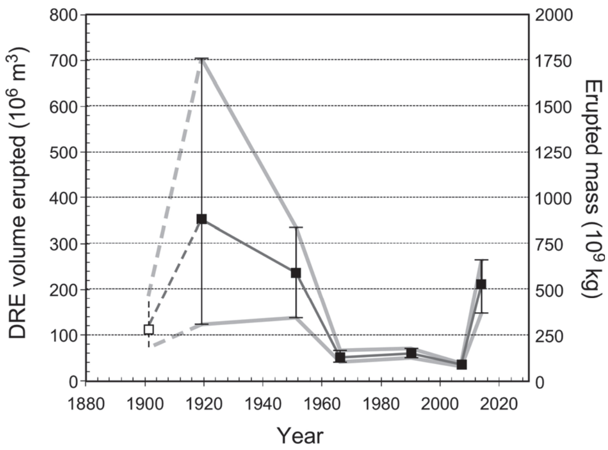

Fig. 5. Temporal variation in the DRE volume or mass of erupted materials from the eruptions at Kelud Volcano in the last 100 years. Errors are derived from the uncertainties in the tephra data and estimation methods. The volume of the 1901 eruption is referred from [16], in which the error is not evaluated.

5. Discussion

5.1. Eruption Pattern

The recent eruptions at Kelud Volcano were considered VEI 4-scale explosive plinian-style or smaller-scale dome-building eruptions. Our results agree with these models of the eruption style of Kelud Volcano. However, the tephra fallout volumes of the 1919 and 1951 eruptions estimated in this study using improved estimation methods (0.53 km^3 and 0.36 km^3, respectively) significantly deviate from previously estimated values (0.19 km^3 and 0.20 km^3, respectively) (**Fig. 5**). The volumes of PDCs are not included in these estimations. If we assume the same PDC/fallout volume ratio as the 1990 and 2014 eruptions, the total volumes may increase 10–20%. We also estimated the mass discharge rates for the plinian eruptions, considering the duration of the eruption (or peak duration), and constrained based on descriptions and records of eruption sequences with time marks (**Fig. 2**). The average (or maximum) mass discharge rates were estimated to be on the order of 10^7 kg/s for the 1919, 1951, and 2014 eruptions and 10^6 kg/s for the 1966 and 1990 eruptions (**Table 3**). These values are within the typical range of mass discharge rates for sub-plinian and plinian eruptions (e.g., [39, 40]) (**Fig. 6**). In **Fig. 6**, the errors caused by uncertainties in the total tephra volumes with/without PDCs and the durations of the eruptions, are

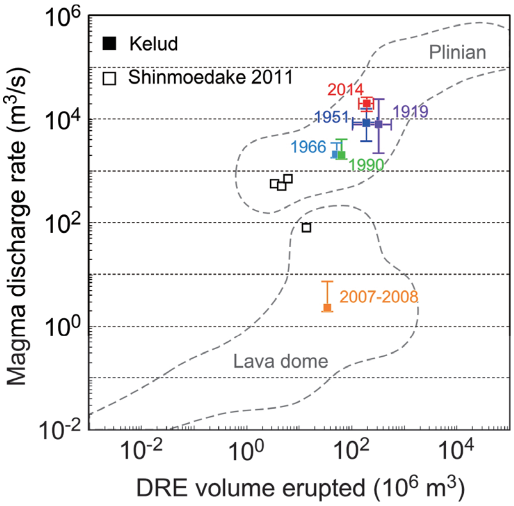

Fig. 6. The relationship between DRE volume and magma discharge rate for the eruptions at Kelud Volcano in the last 100 years. Broken lines show the compiled data for the plinian eruptions (upper) and dome-building eruptions (bottom), summarized by [40]. The data for the subplinian eruptions at Shinmoedake volcano in 2011 [40] are also plotted. The error bars are derived from uncertainties in the eruption duration (average vs. peak) and tephra volume. The maximum discharge rates for the 1919, 1951, and 1966 eruptions are indicated, assuming a peak duration of 4 h based on observed sequences (**Fig. 2**).

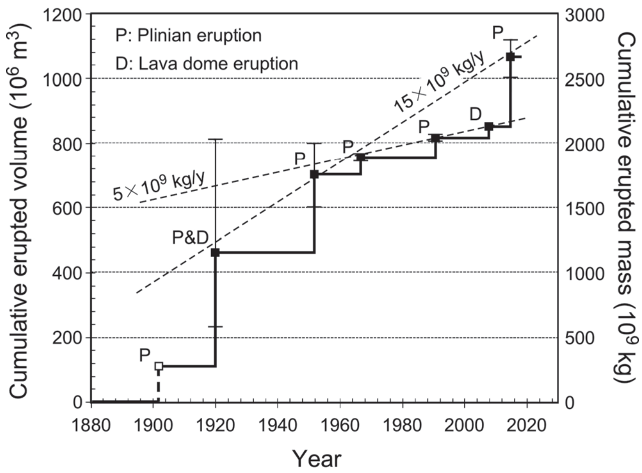

Fig. 7. Step diagram showing the temporal variation in the cumulative erupted volume/mass in the last 100 years at Kelud Volcano. There are two possible long-term mass discharge rates; 15×10^9 kg/year in the last 100 years and 5×10^9 kg/year in the last 50 years before the 2014 eruption. The volume of the 1901 eruption is referred from [16], where the error is not evaluated.

indicated. Even if these errors are considered, the 2014 eruption has the highest mass discharge rate among all the eruptions that have occurred in the last century. In the 1919 eruption, tephra fall from the eruption plume continued for more than 10 h with some fluctuations in discharge and sedimentation rates (**Fig. 2**). The tephra dispersal axis also changed during the eruption. This is in contrast to the 2014 eruption, which lasted only ~3 h. The eruption sequence of the 1919 eruption was more complicated and its impact was probably more widespread than that of the other historical eruptions.

The plinian eruptions at Kelud Volcano were accompanied by PDCs or dome building. The detailed descriptions of the eruptions enabled us to reconstruct the eruptive pattern at Kelud Volcano. The eruptions generally occur in the following phases: they start with an explosive phreatic phase, followed by a phreatomagmatic phase when the crater lake water mixes with the pyroclastic materials. This is followed by a magmatic phase characterized by the ascent of an eruptive column with an umbrella cloud and surges sometimes preceding column-collapse fed PDCs, ashfalls and lahars. PDCs are commonly produced by phreatomagmatic explosions during the earlier phase, or by column collapse during the later phase, as recorded in the 1990 and 2014 eruptions [24, 36].

5.2. Long-Term Magma Discharge Rates

The tephra volumes of the plinian eruptions in the last century have been on the order of 10^8 m^3. This scale of eruption is defined in terms of eruption magnitude (M) as M4.1–M4.9 (**Table 2**), the largest being the 1919 eruption at M ~4.9. Using volume or mass data for these eruptions, the variation in the cumulative erupted volume or mass with time in the last 100 years was calculated and illustrated in a 'step diagram' (**Fig. 7**). From this diagram, we can propose some possible long-term mass discharge rates. One possible magma discharge rate is ~5×10^9 kg/year with a linear relationship between the repose period and volume (**Fig. 7**) as proposed by [14]. They reviewed published data of erupted volumes in the last century [15]. Although this mass discharge rate fits our step diagram excluding the 2014 eruption (**Fig. 7**), it does not explain the eruptions of 1901, 1919, and 1951. Moreover, the volume of the 2014 eruption cannot be predicted based on this mass discharge rate. Another possible mass discharge rate is ~1.5×10^{10} kg/year, which fits the volume data for the larger eruptions in 1919, 1951, and 2014; however, the smaller eruptions may not be explained by this mass discharge rate. The difference between these mass discharge rates ([14] and this study) is mainly caused by improvement in the tephra volume estimates for the 1919 and 1951 eruptions. There is also a possibility that the variation in eruption volumes has a more complex, non-linear relationship as it gradually decreased from 1919 to 1990; this idea should be further investigated by analyzing eruption records or deposits at a much longer time-scale. When we assume a steady-state magma supply system during the last 100 years, the mass discharge rate of ~1.5×10^{10} kg/year (~6 km^3/ky) may best explain the relationship between the repose period and eruptive volume.

The reported mass discharge rates for explosive activity over the last 0.1–10 ky at basaltic-andesitic volcanoes in subduction zones are on the order of from 0.1 km^3/ky (e.g., 0.8 km^3/ky, Lamongan [4]; 0.31 km^3/ky, Colima [5]) to 1 km^3/ky (e.g., 1.75 km^3/ky for Cerro Negro [8]; $\sim$2 km^3/ky for Agung [9]). Kelud Volcano underwent a period of a relatively high magma discharge rate in its recent past. This also indicates a higher magma production rate, thus a higher heat flux, in the deep crustal to upper mantle region beneath the volcano, although the magma genesis and crust-mantle structure in this area must be investigated by thorough geochemical and geophysical studies.

Assuming that the magma discharge rate has been constant in the last 100 years, the relationship between the repose time and erupted volume may be represented as a volume-predictable relation. This relation may be expected if the eruptions cease when the magmatic pressure decreases to some constant value related to the thickness of the overburden and the degree of magma differentiation [2]. This behavior may also occur if the volume of magma leaked is a large fraction of the total volume of the reservoir that is resupplied at a constant rate. Mafic to intermediate magmatic systems with well-established conduits may approach periodic eruptive behavior (with a regular interval and constant volume) – for example, at Izu-Oshima Volcano [1], where eruptions may start and stop at critical values of the same variable. In the case of Kelud Volcano, the periodic behavior and magma discharge rate may be controlled by a more complex magma supply system, which extends from the upper crustal to the deep crustal region with multiple magma storage zones and pockets [38].

5.3. Potential Hazards at Kelud Volcano

The scale and intensity of the eruption represented by the volume and mass discharge rate are important for estimating the impacts and hazards around the volcano. The intensity of the eruption determines the height of the eruption plume, which is also related to the extent of the area covered by fallout deposits. The widespread tephra distribution observed in the 1919, 1951, and 2014 eruptions was caused by a high eruption plume with a high mass discharge rate. This feature is probably also common in the smaller-scale plinian eruptions at Kelud Volcano (**Fig. 1**, [17, 21, 22]). However, the well-observed 2014 eruption provided an important opportunity to study in detail the sequence of plinian eruptions and associated hazards. Ash fall from the spreading eruption cloud caused damage to infrastructure and more than 3,000 houses [41]. In the proximal area (for example, Ngantur, 8 km NE of the volcano), roof collapse occurred shortly after the major phase of the eruption. The eruption cloud spread as it drifted to the west and reached the Indian Ocean 7 h after the eruption began. Data obtained immediately after the beginning of the eruption can be used to estimate the time-scale of hazards caused by ash fall.

The data show that the fallout tephra from Kelud Volcano is generally significantly affected by the prevailing and local winds and that the tephra is dispersed over a wide area of Java. In the 1919 eruption, the eruption plume had two lobes spreading to the east and west. The records of the 2014 eruption show that in Java, the higher eruption plume was affected by easterly winds while the lower plume was more likely affected by westerly winds [36]. If the eruption plume develops and remains at a lower level for a relatively long duration, ash fall may occur on the eastern side of the volcano. Therefore, the eruption plume with two lobes observed during the 1919 eruption probably reflects the change in the plume height in the different phases of the eruption that lasted at least 12 h. This behavior of the eruption plume has important implications for hazards from ash fall during a prolonged eruption. In addition to the effects of the eruption volume and wind on the tephra dispersal pattern, the crater condition at the summit is another key factor influencing the course of the eruption and its impact. The presence of a lava dome may affect the pathway of the ascending magma and result in generation of high-energy PDCs as observed during the 2014 eruption [36]. Additionally, the crater lake at the summit area has a high potential to trigger dilute PDCs and lahars during the explosive phase of the eruption [42] (**Table 3**).

The recurrence history of plinian eruptions and dome formation at Kelud Volcano indicates that eruption of a type and scale similar to those of previous events in the last century can occur in the future. The magma discharge pattern (**Fig. 7**) can help predict the volume of future eruptions based on the dormancy period. Deeper knowledge of the products from the recent well-observed eruptions (the 1990, 2007–2008, and 2014 eruptions), including satellite and geophysical monitoring data, will improve our understanding of the eruptive features, thus expanding our ability to predict the activity patterns and assess the hazards posed by the volcano. The knowledge and findings from studies of eruptions occurring in the last century will have important implications when we construct more sophisticated event trees and assess future volcanic hazards of Kelud Volcano, as well as other active volcanoes with the potential to generate both explosive and effusive eruptions.

6. Conclusions

In this study, we reconstructed the relationship between the repose period and cumulative volume of the erupted material over the past 100 years at Kelud Volcano, Indonesia, and estimated the long-term magma discharge rate; based on our analysis we evaluated the volcano's future eruptive potential. Historical documents and tephra data were used to calculate the volume and mass discharge rate for each eruption. The DRE volumes of the 1901, 1919, 1951, 1966, 1990 and 2014 eruptions were estimated to be from 51 to 296×10^6 m^3, corresponding to eruption magnitudes ranging from 4.1 to 4.9. The accuracy of the volume estimates of the 1919 and 1951 eruptions was significantly improved compared to that of previous studies. The temporal variation in the cumulated erupted mass, reconstructed based on tephra data, indicates a plausible long-term magma discharge rate in the last century of $\sim 1.5 \times 10^{10}$ kg/year ($\sim 6 \times 10^6$ m^3/year). This value provides a better fit than previous estimates to the relationship among the larger-volume eruptions (1919, 1951, and 2014), although it does not explain the variation on the erupted volume of the smaller eruptions (1966 and 1990). The estimated long-term mass discharge is relatively high compared to that of other typical basaltic-andesitic subduction-zone volcanoes. This mass discharge rate based on the relationship between the erupted volume and the dormancy period provides important insights into the evolution of magmatic systems and can help predict the scale, timing, and hazards of future eruptions at Kelud Volcano.

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References:

[1] K. Nakamura, "Volcano-stratigraphic study of Oshima volcano, Izu," Bull. Earthquake Res. Inst. Tokyo Univ., Vol.42, pp. 649-728, 1964.

[2] C. R. Bacon, "Time predictable bimodal volcanism in the Coso range, California," Geology, Vol.10, pp. 65-69, 1982.

[3] G. Wadge, "Steady stage volcanism: evidence from eruption histories of polygenetic volcanoes," J. Geophys. Res., Vol.87, No.B5, pp. 4035-4049, 1982.

[4] S. A. Carn, "The Lamomgan volcanic field, East Java, Indonesia: physical volcanology, historic activity and hazards," J. Volcanol. Geotherm. Res., Vol.95, pp. 81-108, 2000.

[5] J. F. Luhr and I. S. E. Carmichael, "The Colima volcanic complex, Mexico: III, ash- and scoria-fall deposits from the upper slopes of Volcan Colima," Contrib. Mineral. Petrol., Vol.80, pp. 262-275, 1982.

[6] L. Civetta, Y. Cornette, P. Y. Gillot, and G. Orsi, "The eruptive history of Pantelleria (Sicily Channel) in the last 50 ka," Bull. Volcanol., Vol.50, pp. 47-57, 1988.

[7] C.-Y. King, "Volume predictability of historical eruptions at Kilauea and Mauna Loa volcanoes," J. Volcanol. Geotherm. Res., Vol.38, pp. 281-285, 1989.

[8] B. E. Hill, C. B. Connor, M. S. Jarzemba, P. C. La Femina, M. Navarro, and W. Strauch, "1995 eruptions of Cerro Negro volcano, Nicaragua, and risk assessment for future eruptions," Geol. Soc. Am. Bull, Vol.110, pp. 1231-1241, 1998.

[9] K. Fontijn, F. Costa, I. Sutawidjaja, C. G. Newhall1, and J. S. Herrin, "A 5000-year record of multiple highly explosive mafic eruptions from Gunung Agung (Bali, Indonesia): implications for eruption frequency and volcanic hazards," Bull. Volcanol., Vol.77, No.59, doi:10.1007/s00445-015-0943-x, 2015.

[10] Global Volcanism Program, "Kelut volcano (263280)," E. Venzke (ed.), Volcanoes of the World, v.4.7.0, Smithsonian Institution, 2013, https://volcano.si.edu/volcano.cfm?vn=263280, doi: https://doi.org/10.5479/si.GVP.VOTW4-2013 [accessed July 3, 2018]

[11] K. Kusumadinata, "Catalogue of references on Indonesian volcanoes with eruption in historical time," Volcanol. Surv. Indon, p. 820, 1979.

[12] J.-D. Thouret, K. E. Abdurachman, J.-L. Bourdier, and S. Bronto, "Origin, characteristics, and behavior of lahars following the 1990 eruption at Kelud volcano, eastern Java (Indonesia)," Bull. Volcanol., Vol.59, pp. 460-480, 1998.

[13] C. G. Newhall and S. Self, "The volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism," J. Geophys. Res., Vol.87, C2, pp. 1231-1238, 1982.

[14] K. Ishihara, Surono, M. Hendrasto, and S. Hidayati, "Long-term forecasting of volcanic eruption in case study of Kelud volcano, Indonesia," Annul. Disas. Prev. Res. Inst., Kyoto Univ. 54-B, pp. 209-214, 2011 (in Japanese with English abstract).

[15] Direktorat Vulkanologi, "Data Dasar Gunungapi Indonesia," 1990.

[16] L. Houwink, "Verslag van den onderzoek naar aanleiding van de uitbarsting van den vulkaan Keloet in den nacht 22 op den 23 mei 1901," Mijnwz Nederlands Oost-Indie Jaarboek, pp. 126-136, 1901.

[17] G. L. L. Kemmerling, "De uitbarsting van den G. Keloet in den nacht van den 19den op den 20sten Mei 1919," Vulkanol. Meded., No.2, 1921 (translated to English).

[18] D. Hadikusumo, "Report on the volcanological research and volcanic activity in Indonesia for the period 1950-1957," Volcanol. Surv. Indon. Bull., Vol.100, pp. 54-63, 1957.

[19] L. Djoharman, "Laporan taksiran djumlah piroklastika letusan Gn. Kelut tanggal, April 26, 1966," Direktorat Vulkanologi, 1966 (translated to English).

[20] D. Hadikusumo, "The rise and drop of Mt. Kelut crater bottom after paroxysmal eruptions," Tectonophysics, Vol.23, pp. 341-347, 1974.

[21] M. Alzwar, "Gunung Kelud," Berita Berkala Vulkanologi, Edisi Khusus, 108, Direktorat Vulkanologi, Volcanol. Surv. Indonesia, Bandung, p. 60, 1985.

[22] A. D. Wirakusumah, "Some studies of volcano, petrology and structure of Mt. Kelut, East Java, Indonesia," Ph.D. Thesis, Victoria University of Wellington, p. 460, 1991.

[23] A. D. Wirakusumah and L. Hendrajaja, "Evolution of the 1990 Kelut eruption energy based on the volume of ejected volcanic materials," Direktorat Vulkanologi, 1992.

[24] J.-L. Bourdier, I. Pratomo, J.-C. Thouret, G. Boudon, and P. M. Vincent, "Observations, stratigraphy and eruptive processes of the 1990 eruption of Kelut volcano, Indonesia," J. Volcanol. Geotherm. Res., Vol.79, pp. 181-203, 1997.

[25] S. Hidayati, A. Basuki, K. Kristianto, and I. Mulyana, "Emergence of lava dome from the crater lake of Kelud volcano," J. Geologi Indonesia, Vol.4, No.4, pp. 229-238, 2009.

[26] Badan Geologi, "Data Dasar Gunungapi Indonesia," 2nd edn. 981, 2011.

[27] Ph. Lesage and Surono, "Seismic precursors of the February 10, 1990 eruption of Kelut volcano, Java," J. Volcanol. Geotherm. Res., Vol.65, pp. 135-146, 1995.

[28] Global Volcanism Program, "Report on Kelut (Indonesia)," L. McClelland (ed.), Bulletin of the Global Volcanism Network, Vol.15, No.9, Smithsonian Institution, doi: http://dx.doi.org/10.5479/si.GVP.BGVN199009-263280, 1990.

[29] D. M. Pyle, "The thickness, volume and grainsize of tephra fall deposits," Bull. Volcanol., Vol.51, pp. 1-15, 1989.

[30] J. Fierstein and M. Nathenson, "Another look at the calculation of fallout tephra volumes," Bull. Volcanol., Vol.54, pp. 156-167, 1992.

[31] E. De Belizal, F. Lavigne, J. C. Gaillard, D. Grancher, I. Pratomo, and J.-C. Komorowski, "The 2007 eruption of Kelut volcano (East Java, Indonesia): Phenomenology, crisis management and social response," Geomorphology, Vol.136, pp. 165-175, 2012.

[32] L. Siebert, T. Simkin, and P. Kimberly, "Volcanoes of the World," 3rd edition, University of California Press, Los Angeles, p. 551, 2011.

[33] N. I. Kristiansen, A. J. Prata, A. Stohl, and S. A. Carn, "Stratospheric volcanic ash emissions from the 13 February 2014 Kelut eruption," Geophy. Res. Lett., Vol.42, pp. 588-596, 2015.

[34] C. Caudron, B. Taisne, M. Garces, L. P. Alexis, and P. Mialle, "On the use of remote infrasound and seismic stations to constrain the eruptive sequence and intensity for the 2014 Kelud eruption," Gephy. Res. Lett., Vol.42, pp. 6614-6621, 2015.

[35] Y. Nakashima, K. Heki, A. Takeo, M. N. Cahyadi, A. Aditiya, and K. Yoshizawa, "Atmospheric resonant oscillations by the 2014 eruption of the Kelud volcano, Indonesia, observed with the ionosphereic total electron contents and seismic signals," Earth Planet. Sci. Lett., Vol.434, pp. 112-116, 2016.

[36] F. Maeno, S. Nakada, M. Yoshimoto, T. Shimano, N. Hokanishi, A. Zaennudin, and M. Iguchi, "A sequence of a plinian eruption preceded by dome destruction at Kelud volcano, Indonesia, on February 13, 2014, revealed from tephra fallout and pyroclastic density current deposits," J. Volcanol. Geotherm. Res., (in press).

[37] C. Bonadonna and A. Costa, "Estimating the volume of tephra deposits: a new simple strategy," Geology, Vol.40, pp. 415-418, 2012.

[38] A. J. Jeffery, R. Gertisser, V. R. Troll, E. M. Jolis, B. Dahren, C. Harris, A. G. Tindle, K. Preece, B. O'Driscoll, H. Humaida, and J. P. Chadwick, "The pre-erupting magma plumbing system of the 2007-2008 dome-forming eruption of Kelut volcano, East Java, Indonesia," Contrib. Mineral. Petrol., Vol.16, pp. 275-308, 2013.

[39] S. Carey and H. Sigurdsson, "The intensity of plinian eruption," Bull. Volcanol., Vol.51, pp. 28-40, 1989.

[40] T. Kozono, H. Ueda, T. Ozawa, T. Koyaguchi, E. Fujita, A. Tomiya, and Y. J. Suzuki, "Magma discharge variations during the 2011 eruptions of Shinmoe-dake volcano, Japan, revealed by geodetic and satellite observations," Bull. Volcanol., Vol.75, No.695, 2013.

[41] Global Volcanism Program, "Report on Kelud (Indonesia): February 2014," R. Wunderman (ed.), Bulletin of the Global Volcanism Network, Vol.39, No.2, Smithsonian Institution, 2014.

[42] A. R. Mulyana, A. Nasution, A. Martono, A. D. Sumpena, Purwoto, and M. S. Santoso, "Volcanic hazards map of Kelud volcano, East Java Province," Direktorat Vulkanologi dan Mitigasi Bencana Geologi, 2004.

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• "Development of an automatic volcanic ash sampling apparatus for active volcanoes," Bulletin of Volcanology, Vol.75, No.773, https://doi.org/10.1007/s00445-013-0773-7, 2013.
• "Vesiculation path of ascending magma in the 1983 and the 2000 eruptions of Miyakejima volcano, Japan," Bulletin of Volcanology, Vol.68, No.549, https://doi.org/10.1007/s00445-005-0029-2, 2006.

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• "Contribution of monitoring data to decision making for evacuation from the 2014 and 2015 eruptions of Kuchinoerabujima Volcano," J. of Natural Disaster Science, Vol.38, pp. 31-47, 2017.
• "Volcanic activity of Sakurajima monitored using GNSS," J. Disaster Res., Vol.13, No.3, pp. 518-525, 2018.

Academic Societies & Scientific Organizations:
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• American Geophysical Union (AGU)