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**Paper:**

# Eruption Scenarios of Active Volcanoes in Indonesia

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**Eruption scenarios were prepared as possible sequences in event trees for six active volcanoes in Indonesia, that are located near populated areas or have erupted in recent years (Galunggung, Guntur, Kelud, Merapi, Semeru, and Sinabung). The event trees prepared here show sequences of possible eruption phenomena without probabilities on branches and cover sequences experienced in historical and pre-historical eruptions based on archives and field research results. Changing magma discharge rates during eruption sequences were considered for the event tree of Merapi. This conceptual event tree can also be used as a short-term event tree in which forecasting the coming eruption became possible with geophysical and geochemical monitoring data. Eruption event trees prepared for selected time windows cannot illustrate all plausible hazards and risks associated with an eruption. Therefore, hazards and risks generated from an eruption should be considered in different domains from the event tree.**

**Keywords:** eruption sequence, event tree, volcanic hazard, magma discharge rate, SATREPS

## 1. Introduction

An event tree of a volcanic eruption was previously proposed for evaluating the risks from a coming volcanic eruption [1]. It illustrates plausible eruption phenomena (branches of the tree) with their probabilities based on the eruption history of the volcano. The probabilities of branching to different phenomena could be estimated from real-time monitoring data. The event tree is also important for the long to medium-term forecasting of active volcanoes. Branching is considered for short-term purposes in order to understand and forecast an ongoing crisis and eruption. Most of eruption event trees in previous studies evaluate a single event, i.e., over a short time window, and event tree analysis was performed as the eruption progressed [2–4]. However, eruption and hazards during a single eruption are not unique, and successively different phenomena and hazards may occur during a short time window.

Merapi is one volcano whose eruption history has been studied by many researchers, and an event tree was already proposed [5]. An explosive event occurred soon after a less explosive event during the eruptions at Merapi in 2006 and 2010 [6, 7]. As a result, hazards during a single eruption are different depending on their location within the eruption sequence. Such hazards include dome-collapse-type pyroclastic density current (PDC), fallout ballistics and ash, and lahars during and soon after the eruption. All hazards associated and risks throughout a sequence are impossible to show in a single event-tree chart. At least, possible eruption sequences should be illustrated in the first step of an event tree. On the other hand, the style of magmatic eruption (eruption mode) largely depends on the magma discharge rate [8, 9]. Therefore, branching to different phenomena in the event tree would be better ascribed to a changing magma discharge rates, such as that prepared for the 2006 eruption at Merapi [5].

The SATREPS project "Integrated Study on Mitigation of Multimodal Disasters Cause by Ejection of Volcanic Products" was conducted from 2015 to 2018, focusing on six active volcanoes in Indonesia (Galunggung, Guntur, Kelud, Merapi, Sinabung, and Semeru). We aimed at preparing eruption event trees for these volcanoes based on geological research archives and our field studies. The purpose of constructing an event tree is to input the geological data, including phenomenon, magnitude, and possible hazards regarding a forthcoming or ongoing eruption into the Early Warning System for volcanic eruption. The system is the key platform used in the Support System for Decision Making (SSDM) for governance and disaster management in Indonesia. The SSDM will integrate research from working groups and our studies of those volcanoes. This report presents long to medium-

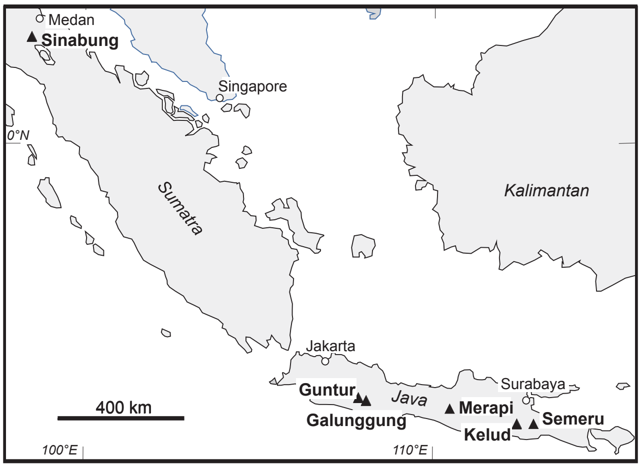


**Fig. 1.** Index map of the six active Indonesian volcanoes studied here.

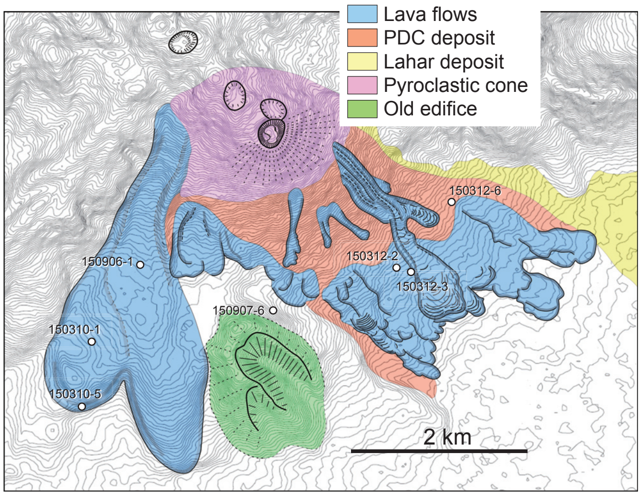


**Fig. 2.** Simplified geologic map of Guntur volcano. See the text for details.

term event trees for Galungung, Guntur, Kelud, Merapi, Sinabung, and Semeru volcanoes based on the newest geological knowledge.

## 2. Field Research

Five volcanoes from the SATREPS Project (except Sinabung) were examined; these five volcanoes are high-risk, active volcanoes in Indonesia. Those volcanoes stand near populated cities, and repeated recent eruptions resulted in many fatalities. In 2010, Sinabung erupted for the first time in its history and continued its eruptive activity during the SATREPS project. Two major dome-collapsed-type PDC events occurred, resulting in fatalities. Thereafter, Sinabung was added to the list of volcanoes considered in this project.

Field surveys of six volcanoes (**Fig. 1**) were conducted by the Japan-Indonesia joint geologist team from 2010 to 2018. A field survey at Sinabung started before the present project but soon after the phreatic events in 2010. A field survey at Kelud was conducted in 2014 soon after its Plinian eruption occurred. Merapi from 2011 to 2012, Guntur from 2014 to 2015, Galunggung in 2015, and Semeru from 2016 to 2017. As the periods for our field studies were limited, we attempted to observe exposures with multiple stratigraphic layers and collect charcoal chips in those layers for $^{14}$C dating. Dating of the charcoal samples and bulk chemical analyses of lava and tephra samples were conducted in Japan. Utilizing abundant geological archives before 1995 from the library of the Center for Volcanology and Geological Hazard Mitigation (CVGHM) in Bandung were essential for this study. **Figs. 2** and **3** show an example of field research results from Guntur volcano. Archives of these field data include outcrop information, chemical analyses, and age determination, which are slated for publishing in the Indonesian Journal of Geology in the near future.

## 3. Event Trees

Newhall and Hoblitt [1] showed event trees where the volcanic hazards and risks are sequentially chained for individual eruptions with their probabilities (probability tree). The event tree normally starts from the unrest of eruption and extends through eruption phenomena (events), event scales, extending distances, and sectors affected, ending with risks in order of occurrence. Events included as branching items are plausible phenomena at the target volcano based on its surveyed eruption history, volcanic characteristics from recent eruptions, or simply based on the theoretical volcanological knowledge. In the probability trees adopted by the Volcano Disaster Assistant Program of USGS, as much of the data set as possible was used to consider the probabilities of various phenomena, including in the event trees for the 2010 Merapi eruption [2, 5]. On the other hand, the probability trees used in European countries are based on elicitation of evaluations from team members who were individually weighted in their volcanological experiences and reliabilities [10]. In the Bayesian event tree (BET) method [9], individual monitoring results from multiple monitoring methods were weighted empirically or theoretically, and the total probability at each node was compared with the thresholds for entering different branches.

The eruption scenarios considered in this study simply reflect to event trees for volcanic phenomena and possible eruption sequences for the target volcano. **Fig. 4** shows an example of the event tree with very rough probability values for Sinabung volcano, North Sumatra, which is based on our field research result in 2010 and was prepared soon after the phreatic eruption [11–13].

Putting the probability values in branches is not easy for volcanoes where the eruption histories are not well known. Therefore, we initially aimed at constructing simple eruption scenarios without probabilities. The ages of eruptions recorded recently were put on twigs in the

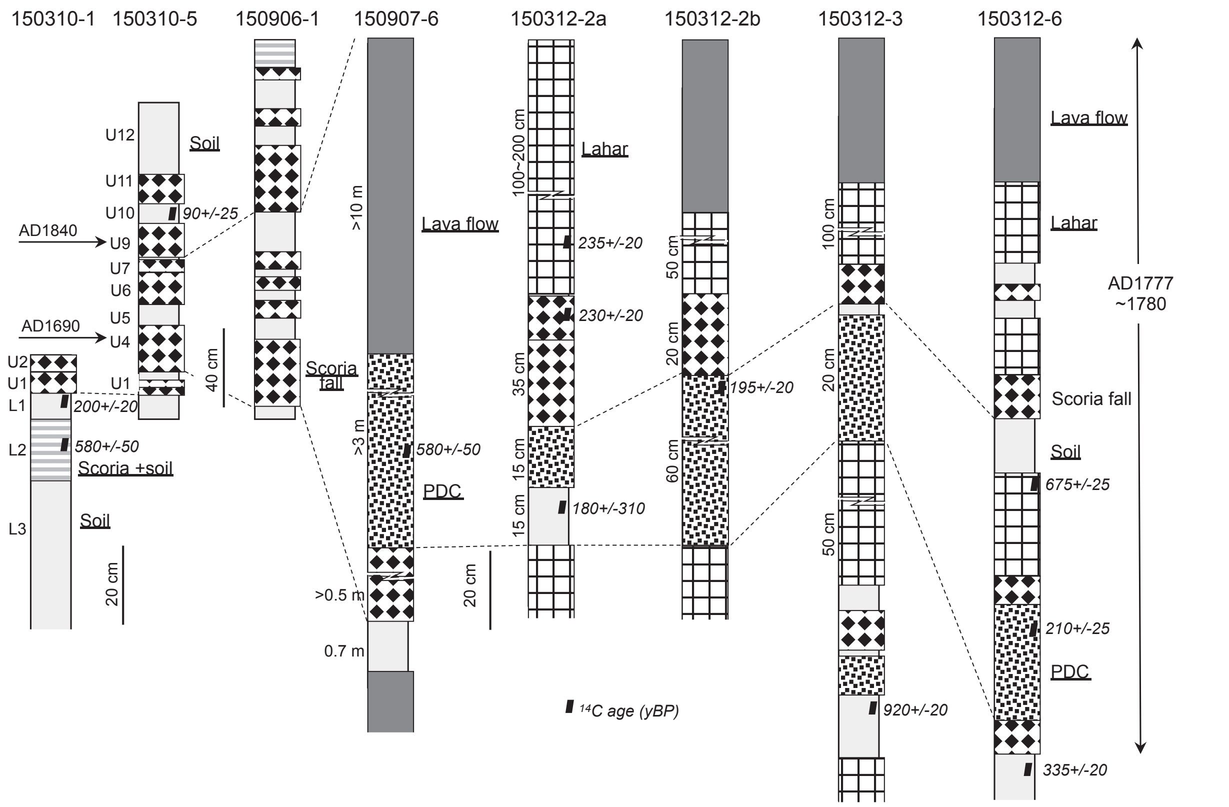


**Fig. 3.** Geologic columnar sections of Guntur volcano. Columns are arrayed from the southern part to the eastern part, as shown in **Fig. 2**.

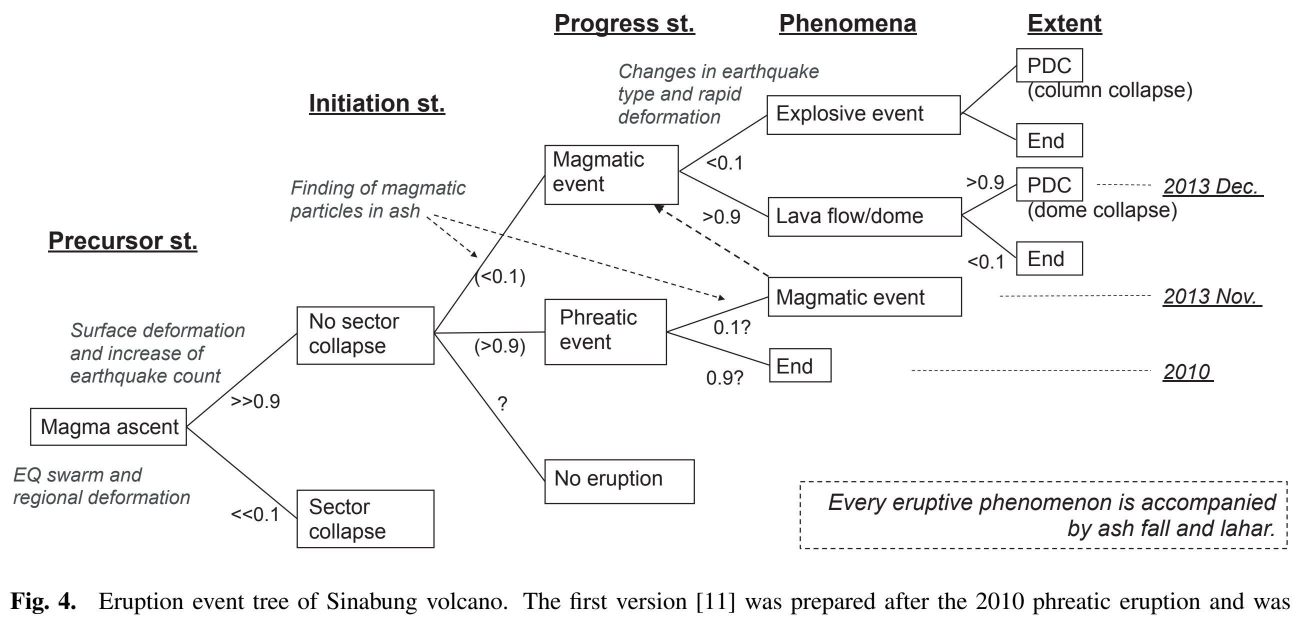


**Fig. 4.** Eruption event tree of Sinabung volcano. The first version [11] was prepared after the 2010 phreatic eruption and was subsequently modified [12].

event trees. Six event trees and their short explanations are shown hereafter (**Figs. 4** to **9**).

### 3.1. Sinabung Volcano

Sinabung (2,460 m asl) is a Pleistocene-to-Holocene stratovolcano with many lava flows at its flanks. The phreatic eruption in 2010 was the first event recorded at Sinabung volcano [14, 15]. As there was no geologic map of this volcano, the joint team of Indonesia and Japanese geologists conducted a field survey soon after the eruption in 2010 [13, 16]. The eruption at Sinabung resumed in September 2013; a lava dome appeared in December 2013 and grew to a lava flow complex [17, 18]. This eruption continued in June 2018. The site of the eruption and its sequence were very close to those of the eruption in the 9–10th century, which was confirmed by the field study [13, 14, 16]. When the event tree was prepared by our team [11], it was considered that juvenile particles appear in the volcanic ash of phreatic events once the magmatic stage is entered. Indeed, the presence of juvenile particles in the volcanic ash from the 11 November 2013 Vulcanian events was confirmed [17]. This event tree did not include the sequence from the lava dome/flow event to a more explosive event. In reality, the explosive stage was accompanied by repeated Vulcanian events beginning in the summer of 2015 [17]. It is common that lava dome eruptions are simply and dominantly effusive throughout eruptions, except for short-lived explosive events in the beginning or midway through the sequences, where the magma discharge rate suddenly increases or a large collapse of the dome occurs. The lava dome eruption at Mount Unzen from 1991 to 1995 [19] was used to prepare the event tree for Sinabung volcano soon after its 2010 eruption. This event tree is shown in **Fig. 4**.

### 3.2. Guntur Volcano

Guntur is a complex of several overlapping stratovolcanoes located approximately 10 km northwest of the city of Garut. It consists of a young large pyroclastic (scoria) cone (2,249 m asl) and basal lava flows with pyroclastic materials, which extend only in the southeastern part. The young cone started its activity about 50,000 years ago [20, 21]. It is obvious that the morphology shows an accumulation of relatively fresh lava flows with levees, which came from the middle flank of the young cone (**Fig. 2**).

According to the archives of the Global Volcanism Network at the Smithsonian Institution (GVN) (https://volcano.si.edu [accessed on July 31, 2018]), Guntur volcano has 12 confirmed eruptions, with the largest eruptions being VEI 3 (volcano explosivity index [22]) in 1690 and 1843. Lava flow eruptions were recorded in 1780 and 1840. In the latest eruption, a basalt lava flow reached the Cipana village, 4 km southeast of the summit crater (at the top of young cone). More than 170 years have passed after the last eruption. In contrast to this superficially quiet activity, seismic activity occurred frequently under the summit and surroundings [23].

The sequences of recent eruptions are not well known. Our field survey on Guntur volcano revealed deposits from many eruptions (**Fig. 3**). $^{14}$C dating showed at least 12 eruptions over this three hundred year period. In this study, the presence of extensively-distributed PDC and lahar deposits together with the stratigraphical relationship between lava flows and scoria falls became clear. The eruption sequences could be summarized as follows. First, a scoria fall event was dominated in 1690. Two eruptions during 1777–1780 started with a scoria fall event, followed by a PDC event and further scoria fall events, and finally concluding with a lava flow event. Eruptions from 1803 to 1847 began with scoria fall events, followed by lava flow events. The event tree has a node corresponding to the vent location before the eruption phenomena depending on the magma discharge rates (**Fig. 5**). A phreatic event was not considered here because clear phreatic events were not confirmed in the field (**Fig. 3**).

### 3.3. Galunggung

The eastern slope of Galunggung volcano (2,168 m asl) is cut by a large horseshoe-shaped caldera that breachs to the southeast [24]. The hummocky surface with many hills characterizing the debris avalanche is distributed within the caldera and the eastern foot up to about 23 km from the caldera headwall. Collapse is considered to have occurred approximately 4,200 years ago [25]. Historical eruptions such as those in 1822 and from 1982 to 1983 were restricted to the central vent near the caldera headwall. We attempted to find the eruption evidence before the 1822 eruption and after the horseshoe-shaped caldera collapse, and we attempted to determine the age of caldera. Unfortunately, the deposits from such a period and charcoal samples suggesting the caldera collapse and old activities after the former were not found.

Among the eruptions at Galunggung recorded since the early 19th century in the GVN archives, the eruption in 1822 was VEI 5, in which PDC and lahar events occurred with approximately 4,000 fatalities, and the eruption from 1982 to 1983 was VEI 4, in which PDC and lahar events followed the explosive event with heavy ash fall according to the GVN archives. The latter eruption continued for approximately 10 months, and the sequence was divided into three phases [26]. In phase 1, explosive events generated PDC events; in phase 2, phreatomagmatic explosive events opened the present maar crater; in phase 3, Strombolian events occurred with lava flow. The eruption columns during this eruption reached 10 to 20 km above the crater. An aircraft incident is considered to have occurred within the ash cloud due to a groundwater-related explosive event early in phase 2 [27]. In the event tree (**Fig. 6**), the crater was treated as the first node because the presence of crater water was essential for the eruption style (labelled "Phenomena").

### 3.4. Kelud

In Kelud volcano (1,731 m asl), a cluster of lava domes cut by numerous craters exhibits a very irregular profile at the summit. According to the GVN archives, the summit crater was frequently filled with water, and devastating lahars were repeated by direct ejection of the crater water during eruptions. PDC events from violent explosive events and lahars during recent eruptions caused widespread fatalities and destruction. This resulted in more than 5,000 deaths in the 1919 eruption and more than 200 deaths in the 1966 eruption. The recent activity in Kelud is characterized by explosive eruptions spreaded by approximately 10 year intervals [28, 29]. A few eruptions forming lava domes without explosive events occurred (e.g., from 2007 to 2008) [28–30]. An explosive

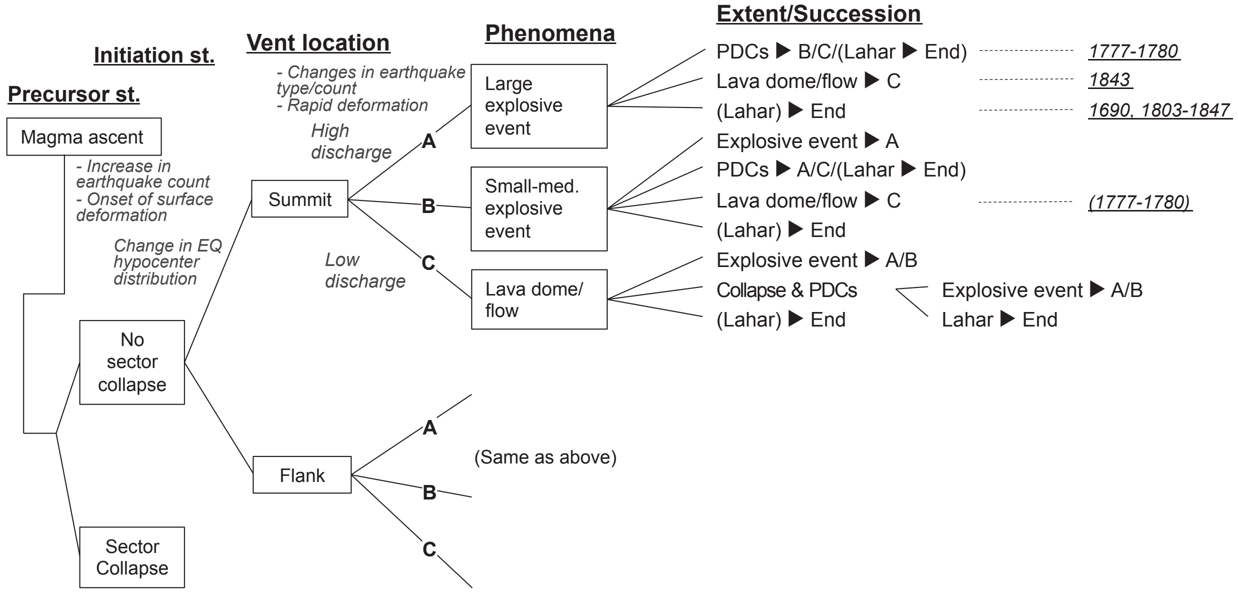


**Fig. 5.** Eruption event tree of Guntur volcano. "Vent location" (summit or flank) is considered after "Initiation stage," as related hazards are different. Branches with A, B, and C correspond to different magma discharge rates. These are also considered in "Succession" after "Extent" phenomena (after triangle arrows). A/B indicates development to either A or B. "Progress stage" in **Fig. 4** is involved in "Phenomena." A phreatic event is not considered as a phenomenon for brevity.

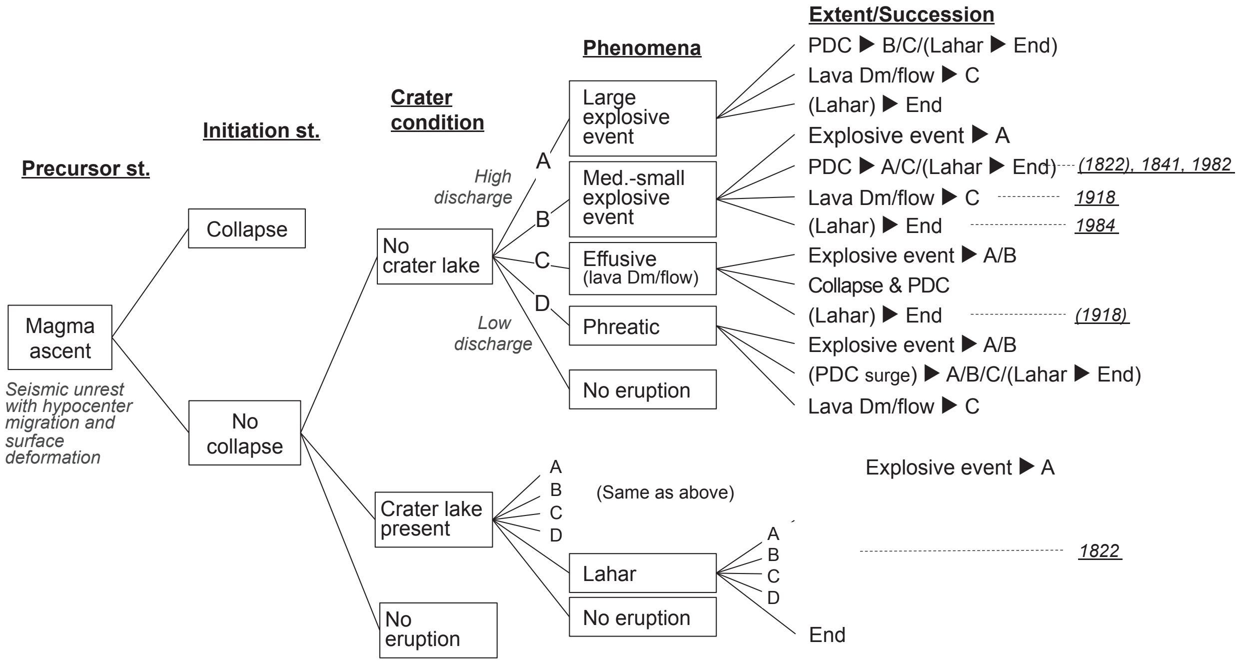


**Fig. 6.** Eruption event tree of Galunggung volcano. "Crater condition" is considered after the "Initiation stage," as the existence of crater water introduces a phreatomagmatic explosive event. Branches with A, B, C, and D are termed with different magma discharge rates and are also considered in "Succession" after "Extent" phenomena (after triangle arrows). A phreatic event is treated here in "Phenomena."

eruption occurred on February 13, 2014 [31]. Before the 2014 eruption, the summit crater was plugged by the lava dome from 2007 to 2008. The 2014 eruption started by breaking of the lava dome with the Vulcanian event accompanied by lateral blasts, which was preceded by a huge eruption column in the Plinian stage that reached as high as ~25 km asl [31]. The chemical composition of the lava dome and pumices from the Plinian stage are nearly identical (basaltic andesite). Considering the historical disaster on this volcano, **Fig. 7** shows that the presence of a crater is one branching node, just as in the Galunggung event tree.

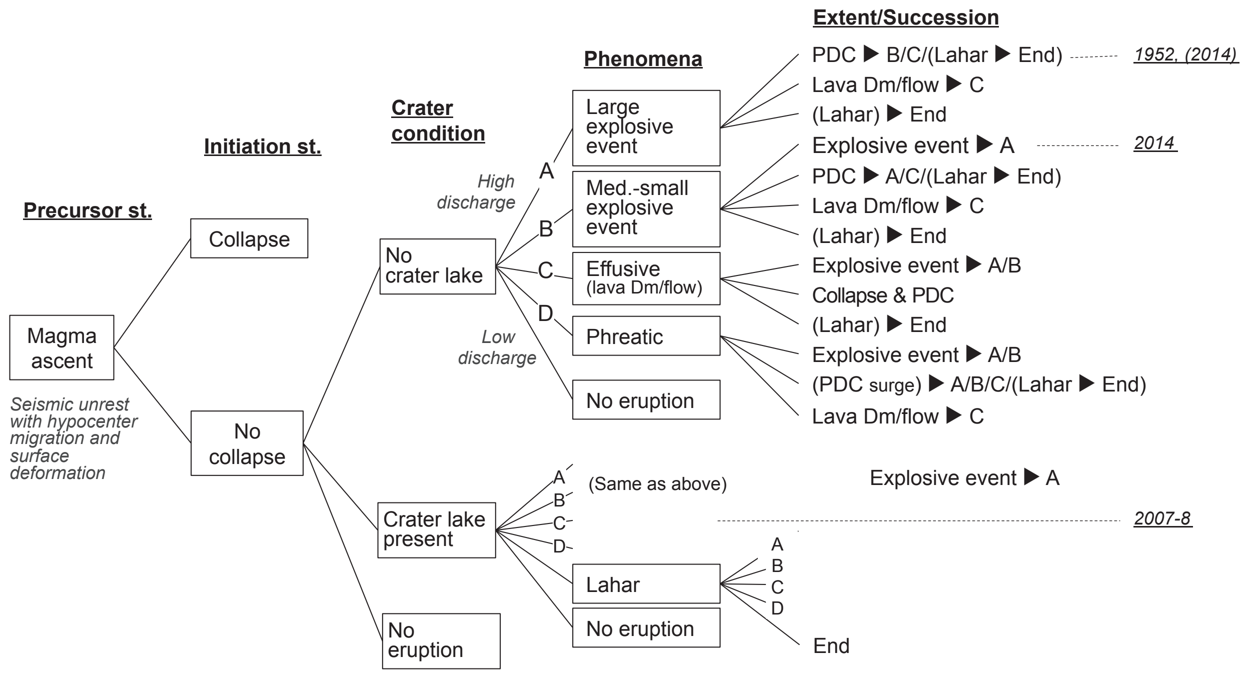


**Fig. 7.** Eruption event tree of Kelud volcano. "Crater condition" is considered after "Initiation stage" as the existence of crater water introduces lahar disasters, as is obvious in historic eruptions [29].

### 3.5. Semeru

Semeru is the highest active volcano in Java Island with elevation of 3,676 m asl, located in the southern end of the Bromo-Tengger-Semeru volcanic massif. According to the summary by Siswowidjoyo et al. [32], Thouret et al. [33] and the GVN archives, about 40 eruptions have been recorded since the early 19th century, ranging up to VEI 3. PDC events recurred every 5 years on average. In 1884–1885, lava flowing at the summit generated landslides, explosions at the summit crater, PDC, and lahar events. The eruption during 1910 to 1912 (VEI 3) started with the explosive event at the summit, which was followed by lava flow, PDCs, and lahars. Since 1967, frequent small-to-moderate explosive events were repeated, and large explosions sometimes generated PDCs and lahars. Lava dome growth at the summit and its disruption by explosions and collapse also occurred during the recent activity. The eruptions in 1895 and from 1941 to 1942 produced lava flows at the southeastern flank. At least five large-scale lahars that exceeding 5 million $m^3$ have occurred since 1884.

Our field study revealed the existence of tephra and PDC deposits from relatively large explosive events at the summit and flank, as well as the ages of these activities [34]. Subplinian to violent Strombolian events larger than recent events were repeated from the 3rd to 11th centuries. Around the 16th century, relatively large eruptions occurred on the southwestern slope with accumulation of thick scoria falls and generation of PDCs that destroyed the temple of the Majapahit Kingdom at Candi Jawar (about 5.5 km southwest of the present summit crater). There are morphological characteristics suggesting pre-historical lava flow and scoria cone-building events mainly on the south to southwestern lower slopes. The eruption sequence, from the lava flowing to an explosive event, should be considered to occur in the near future.

The magma chemistry of Semeru volcano is bimodal (andesite and basalt). Before the 3rd century, andesite magma produced explosive events near the summit. Basaltic magma eruptions were common at the flank during the 3rd to 11th centuries. Andesite magma dominated after the 11th century, and the summit eruptions over these past 1,000 years are characterized by andesite. The event tree (**Fig. 8**) treats the initial vent location as the node of branching, considering the geological records of eruptions.

### 3.6. Merapi

Merapi volcano (2,910 m asl) lies immediately north of the major city of Yogyakarta. Merapi is one of the most active volcanoes in Indonesia. There are many geological research results on its volcanic history [35, 36]. Merapi has erupted every several years since the 16th century. Hazards associated with these eruptions are PDC and lahar events during the growth and collapse of the summit lava dome. Eruptions in 1872 and 2010 were largest among recent frequent eruptions with VEI 4, according to the GVN archives. During the eruption in 2010, laterally-directed explosions occurred repeatedly due to collapses of the summit lava dome, which grew while sealing the upper conduit of magma. This generated pyroclastic flows that cascaded about 16 km from the summit. As a result, at least 386 people were killed and

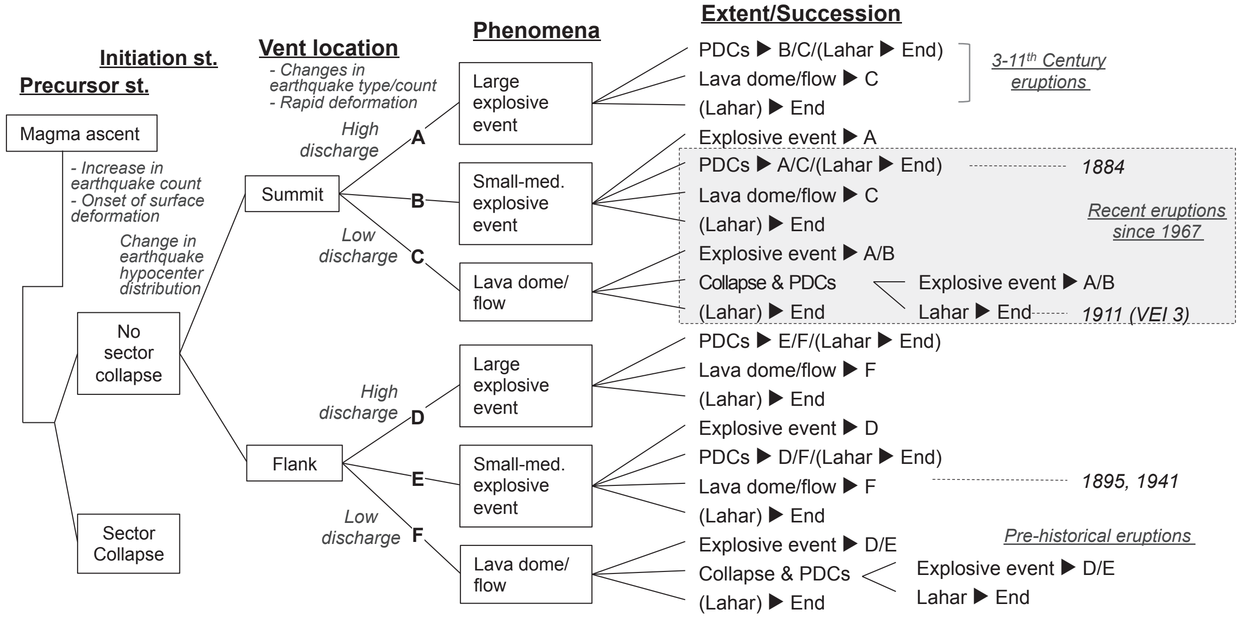


**Fig. 8.** Eruption event tree of Semeru volcano. "Vent location" (summit or flank) is considered after "Initiation stage" as related hazards are different, as is obvious in historic eruptions. Therefore, branches with A, B, and C and those for D, E, and F are considered for different vent locations. A phreatic event is not shown here for brevity.

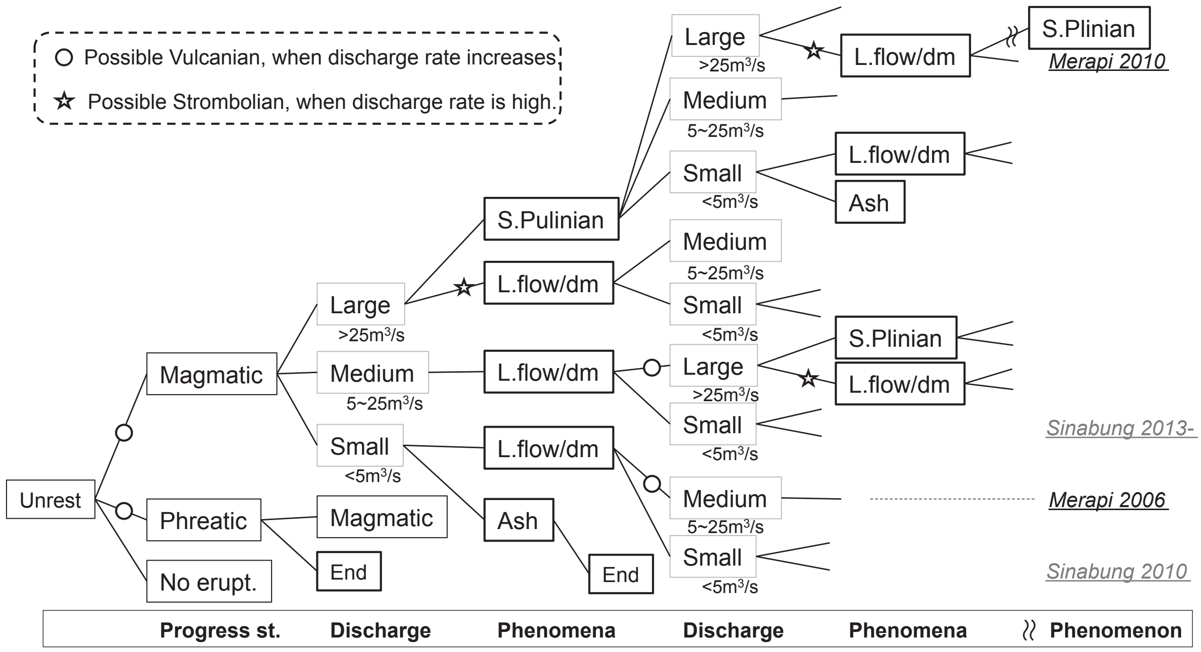


**Fig. 9.** Eruption event tree of Merapi volcano with variable magma discharge rates. Vulcanian events are possible when the crater opens in phreatic eruptions and by pulse-like increases in the magma discharge rate. Eruption scenarios for Sinabung volcano can also be considered in this event tree.

more than 300,000 people evacuated [2, 5, 37, 38].

The event tree shown in **Fig. 9** is a rather conceptual diagram reflecting changes in the magma discharge rate as an eruption advances. The eruptions in 2006 and 2010 are examples in which the magma discharge rate increased during the later stage of the eruption. In other words, the eruption phenomenon changed from normal lava dome growth with collapsed-type PDC events to explosive events with sustainable towering of the eruption column [3, 5].

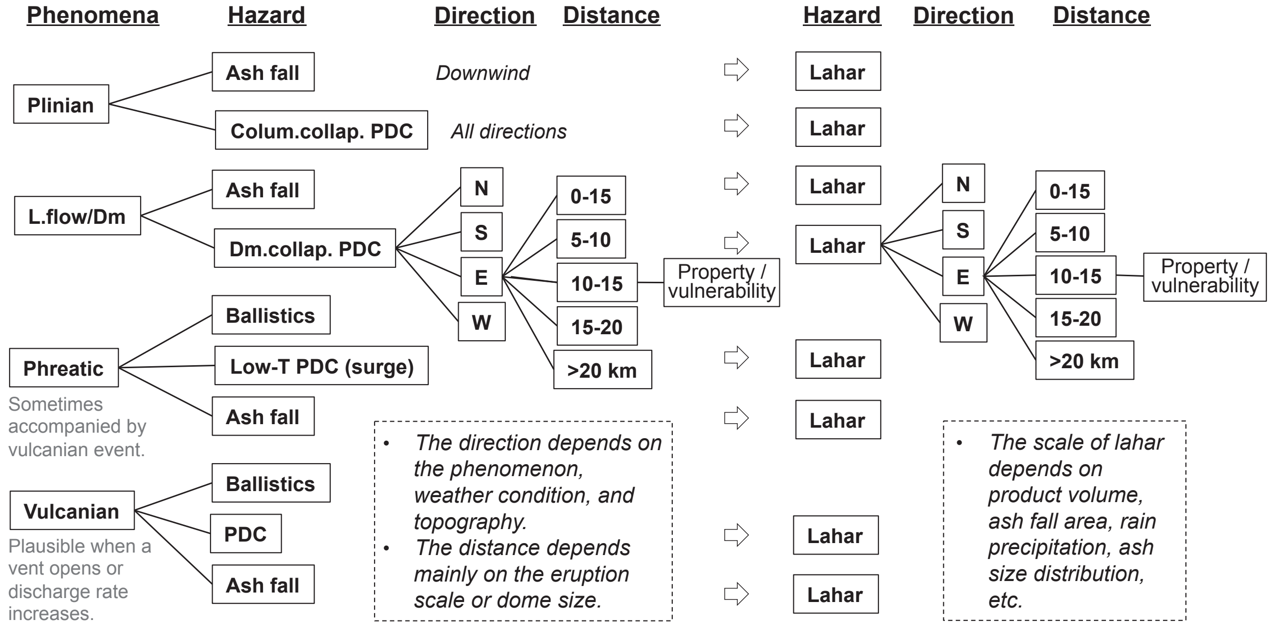


**Fig. 10.** Risk evaluation trees for hazards developed from each volcanic phenomenon. Lahar is a secondary hazard possible for most primary hazards.

## 4. Discussion

The event trees prepared here consist of eruption phenomena from individual volcanoes that were already experienced or are plausible. We could not put values of probabilities for those individual events due to the incomplete database of eruption histories. Instead, the ages of recent eruptions are shown at the right ends on the charts. From this information, we could understand roughly how the past eruptions advanced and what types of branching were possible along the way. This information is very helpful for anticipating upcoming eruptions. The conceptual event tree prepared for Merapi volcano (**Fig. 9**) may be used as a short-term event tree. For example, escalation in seismicity and EDM distance changes just before the 2010 eruption at Merapi were much different from those of the 2006 eruption [2], and the manner of seismicity just prior to the eruption onsets at Kelud in 2014 was different from that in 2007 [39]. As in the BET method [40] or the idea already proposed at Sakurajima volcano [41], those geophysical monitoring data prior to the eruption onset can be used to determine the magma discharge rates, which are used in an event tree such as that shown in **Fig. 9**.

As already discussed, volcanic phenomena are variable, even during a single eruption sequence. They may include ash fall, PDC (surge and pyroclastic flow), lahar, lava flow, ballistics, and tsunamis. The direction, distances, and areas impacted by those phenomena are also variable, depending on the intensities, weather conditions, and geomorphological characteristics. The area affected by volcanic ash is extensive without the strong effect by geomorphology but is determined significantly by wind conditions. Therefore, the impacted areas should be considered when assessing individual upcoming hazards. Lahar is a secondary disaster and is always accompanied by ash falls from the primary hazards, such as explosive magma, phreatic eruptive events, and PDC events. Multiple hazards with related risks during a single eruption are difficult to illustrate within an event tree. **Fig. 10** shows an idea where possible hazards and risks are considered in domains that are different from the eruption event tree. Multiple hazards are shown as branches from each eruption phenomenon, which are followed by branches to assess the impact of hazards and lahar. In this assessment, the exposure and vulnerability for each hazard (direction and distance) should be considered when evaluate the risks, though these details are not discussed here. This shows only a conceptual image on how we should consider the risks from possible hazards that can arise from an eruption event tree.

## 5. Concluding Remarks

We prepared the event trees that include possible eruption sequences for Sinabung, Guntur, Galunggung, Semeru, Kelud, and Merapi based on the geological archives and results from our field study. It is difficult to illustrate multiple hazards that can possibly occur during a single eruption sequence. In the event trees of both Guntur and Semeru volcanos, the branching node on vent locations (presence or absence of water in the crater) was considered first. The branching node for phenomena (eruption styles) were considered next, which depend primarily on the magma discharge rate. In the scenarios of Galunggung and Kelud volcanoes, the branching node on crater conditions was considered first, and the branching node on phenomena was considered next. For Merapi volcano, the magma discharge rate was considered to vary during the eruption sequence, and the event tree can be used as a short-term event tree. Catching changes in the magma discharge rate may be possible when monitoring seismic, geodetic and chemical data. This conceptual event tree together with hazard assessments in different domains may be necessary for considering eruption sequences for most volcanoes.

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