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Enhancing Preliminary Database of Volcanic Debris Avalanches in Indonesia: A Focus on Morphological Type and Geological Data

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Abstract - Indonesia has many cases of volcanic debris avalanche (VDA), which is fifty-four events from the inventory conducted by MacLeod (1989). However, data on the characteristics of VDA provided is limited, therefore it is necessary to develop detailed information related to these fifty-four cases. This study focuses on morphological and geological inventory of the VDA in Indonesia. Using the DEM database, morphological features were analyzed and four classes were determined, namely (1) volcanoes with horseshoe-shaped scar only; (2) volcanoes with no horseshoe-shaped scar, but has DAD (debris avalanche deposit); (3) volcanoes with no horseshoe-shaped scar, and no DAD; and (4) volcanoes with horseshoe-shaped scar and with DAD. Most of the volcanoes that have VDA are clustered in the first class. From the geological map, three main main pieces of information can be obtained: relative age, rocks/materials, and structure. Of fifty-four reported VDA events, the age of the rocks build the volcano that commonly ranges the Pliocene, Pleistocene, and Holocene. The composition material is relatively uniform, consisting of lava with basalt-andesite rock types. Scar structures are also delineated in some volcanoes. Based on these characterization results, its relationship with volcano types in Indonesia (*e.g.* type A, B, C) was analyzed to determine the potential for reoccurrence of VDA. Further analysis is proposed, along with a more comprehensive characterization of the VDA in Indonesia, particularly at the type A volcanoes, such as Dempo, Galunggung, Gede, Papandayan, Sundoro, and Raung.

Keywords: debris avalanche, morphology, sector collapse, volcanic hazard

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Introduction

Volcanic debris avalanche (VDA) is a gravity-driven mass movement that occurs when a volcanic sector collapses, resulting in the rapid movement of either a portion of the volcanic edifice or a large mass of volcanic material (Bernard et al., 2021). Various factors can trigger the collapse of a volcanic edifice, such as structural instability, hydrothermal alteration, and seismic activity (de

Vries and Davies, 2015; Roverato *et al*., 2021). It is a natural volcano process that is relatively rare in its occurrence, but it may have a far-reaching impact across the landscape around the volcano (Figure 1). The extent of the impact can reach ~100 km (Siebert, 2002; Ui, 1989). Besides having a large size, its mobility to travel up to long distances is the key difference between avalanche and other type of landslides in nonvolcanic areas (Siebert, 2002). VDAs are most common on stratovolcanoes (Suhendro and Haryono, 2023). VDA can transform the structure of a volcano and the surrounding landscape. In the edifice, this process commonly leaves a horseshoe-shaped scar, and in the middle, it can create avalanche walls and undulating structures of hummocky terrain (Siebert, 1984). While in the distal part, it can produce a piedmont shape or can be transformed into alluvial or laharic deposits (Bernard *et al*., 2019). Hummocks are a typical feature in debris avalanche deposits (DAD) (Hunt *et al*., 2018; Siebert, 1984). A global inventory of debris avalanche events has recorded 1001 events from 594 volcanoes in fifty-two countries (Dufresne *et al*., 2021). Among the world archipelagic countries, Indonesia has more than a hundred volcanoes and numerous volcanoes that are contributed to the global inventory list of volcanic debris avalanches. An earliest inventory conducted in Indonesia reported fifty-four VDA cases (MacLeod, 1989). Based on this inventoried data, most of these VDAs are in Java (thirty) and Sumatera (twenty), two are located in Nusa Tenggara, and there is only one of each in Halmahera and the Banda Sea. Following that work, no research has evaluated the data or confirmed the number of VDAs in Indonesia.

The current list provided by MacLeod (1989) contains only limited information on the characteristics of each VDA, such as the original height of the volcano, the height of the collapse, and the width of the crater (avalanche scar). However, several studies in Indonesia have examined the VDA characteristics further detail, *e.g.,* at Galunggung (Bronto 1989), Raung (Gadung) (Siebert 2002; Moktikanana *et al*., 2021), Papandayan (Pratomo 2006; Nursalim *et al*., 2016; Siebert and Roverato, 2021), Sundoro (Rayahu *et al*., 2023), and Rinjani (Samalas) Volcanoes (Malawani *et al*., 2020; Malawani *et al*. 2024). Considering the limited data on VDAs in Indonesia, more detailed information related to the characteristics of all inventoried VDAs in Indonesia needs to be constructed. Indeed, much more parameters can be used to characterize a VDA and its deposits, *e.g*. age of the event, runout distance (L), drop height (H), friction coefficient (H/L), DAD area, thickness and volume, and the number of hummocks (Siebert, 1984; Bernard *et al*., 2021; Delcamp, *et al*., 2017; Hayakawa *et al*., 2018). However, this research will focus on the morphological feature of VDA and its geological setting. Investigation of the regional geology is valuable to better understand the relative age of the event, the structure of the volcano as well as the avalanche deposit (Malawani *et al*., 2024; Rahayu *et al*., 2023). The combination of these two parameters (morphology and geology) allows a broader perspective on the volcanogenic activity at a particular volcano, and it is useful to examine the potential hazard of volcanic debris avalanches in the future (Gómez-Castillo *et al*.,

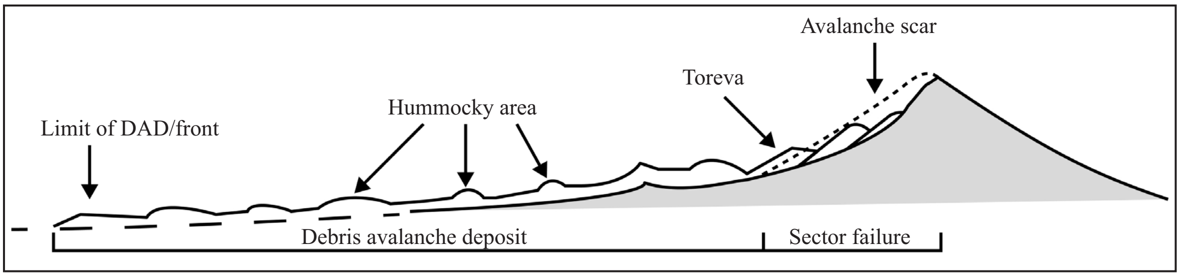
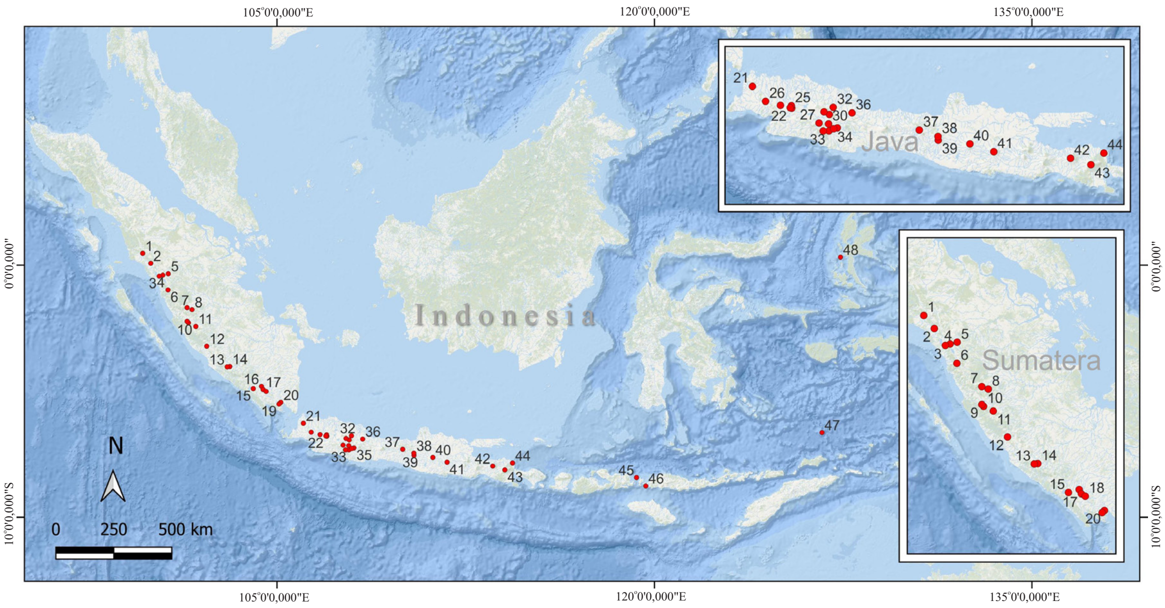


Figure 1. Schematic cross-section of a volcano illustrating the morphological features associated with a VDA process (Source: de Vries and Delcamp, 2015).

2020). However, morphological analysis of a volcano may also be helpful in predicting the eruption-affected area and inferring information about its tectonics, such as stress orientation and magma-feeding structure (Aravena and Roche, 2022; Hategekimana *et al*., 2024; Marliyani *et al*., 2020). In addition to evaluating and confirming the registered VDAs in Indonesia from a previous study (MacLeod, 1989), this study will improve the current database by adding several parameters (*e.g*. scar width, scar length, scar direction, morphological type, material/rock formation, relative age). Improving the global inventory of volcanic debris avalanches in the world may also be advantageous (Dufresne *et al*., 2021; Siebert and Roverato, 2021).

Datasets

Two main datasets are used as a basic reference for enhancing the characteristics of debris avalanches in Indonesia, *i.e*. the digital elevation model (DEM) data from DEMNAS and the geological map of Indonesia. DEMNAS is available on a nationwide scale at a ~7 m resolution maximum. Geological maps of Indonesia are also available nationwide with two variations of scale, comprising 100,000 and 250,000. The first step performed is identifying the location of volcanoes where VDA has occurred according to the list from MacLeod. Since the data of volcanoes from MacLeod (1989) is not accompanied by coordinates, in the location tracing, a combination of geological map and toponym information from the Indonesian Topographic Map (RBI map) is very helpful in finding a volcano. The distribution of VDAs in Indonesia was then remapped (Figure 2). The identified coordinates of the summit of the volcanoes helped define the row-path of the DEMNAS data. The subsequent steps were to identify the horseshoe-shaped crater or the avalanche scar, the DAD, and hummocks based on the DEM data. In some cases, DAD boundaries



1	Malintang (N)	8	Runcing	15	Kukusan	22	Lingkung	29	Papandayan	36	Cerema	43	Raung
2	Talakmau	9	Raya	16	Balai	23	Salak	30	Guntur	37	Sundoro	44	Baluran
3	Tandikat	10	Kunyit	17	Benatan	24	Gedek	31	Kareumbi	38	Merbabu	45	Gili Banta
4	Marapi	11	Hululuko	18	Ulukubatang	25	Joglok	32	Tampomas	39	Merapi	46	Pulau Rinca
5	Malintang (S)	12	Lumut	19	Pesawaran	26	Sanggabuwana	33	Cikuray	40	Lawu	47	Wetar
6	Talang	13	Dingin	20	Betung	27	Malabar	34	Kracak	41	Wilis	48	Makian
7	Tujuh	14	Dempo	21	Karang	28	Manglayang	35	Galunggung	42	Pinggang		

Figure 2. Geographical distribution of volcanoes in Indonesia that experienced volcanic debris avalanche (VDA). The nomenclature of the volcanoes follows the data presented by MacLeod (1989).

and hummocky terrain information are clearly indicated on geology maps. These three data were utilized to categorize the VDA classifications in Indonesia based on morphological features. However, some volcanoes have multiple VDA events, such as Gede (three events), Guntur, Joglok, Malintang, Papandayan, and Salak Volcanoes which each has two events (MacLeod, 1989). Therefore, the total number of volcanoes listed as having experienced VDA events is forty-eight. Scar morphometry measurements in this research followed the procedure proposed by Bernard *et al.* (2021), but is limited to scar morphology. Each scar was delineated and measured as illustrated in Figure 3.

Age of event is the most critical data in the VDA database both in Indonesia and globally, particularly for events that occurred in the Holocene or earlier. For recent events, the age information is often available, because the event was witnessed and recorded in the global database, for example St. Helens in 1980 (Glicken, 1996). A method to determine the age of the event is by dating the associated deposit of an eruption that triggered VDA (Malawani *et al.*, 2024). In this research, the age was estimated from the geological map, although it is limited based on geological age: Period and Epoch. Another geological feature that can be captured from the geological map is the rock formation. The rock formation provides information on the rock types, surface material, internal structure, and tectonic setting of surrounding volcanoes. In addition to the morphology and geological characteristics, the classification of the volcano type was also considered to assess the potential recurrence. The classification of volcanic activity was performed to complete the inventory of VDA attributes utilizing The Geological Agency of Indonesia, The Ministry of Energy And Mineral Resource (ESDM) database. There are three main categories, *i.e.* group A, B, and C (https://magma.esdm.go.id/v1/edukasi/tipe-gunung-api-di-indonesia-a-b-dan-c). Group A are volcanoes that have records of eruptions since 1600 CE; group B are volcanoes that have records of eruptions before 1600 CE, and group C are volcanoes that have no historical record of eruptions. However, several volcanoes from MacLeod (1989) are not included in the ESDM database, those that are not listed are then assigned to the group D.

Results and Discussion

Morphological Features

Identification of the morphological features is essential in evaluating the existing list of VDAs in Indonesia. The typical morphological characteristic of volcanic debris avalanches (VDA) includes a horseshoe-shaped crater or scar on

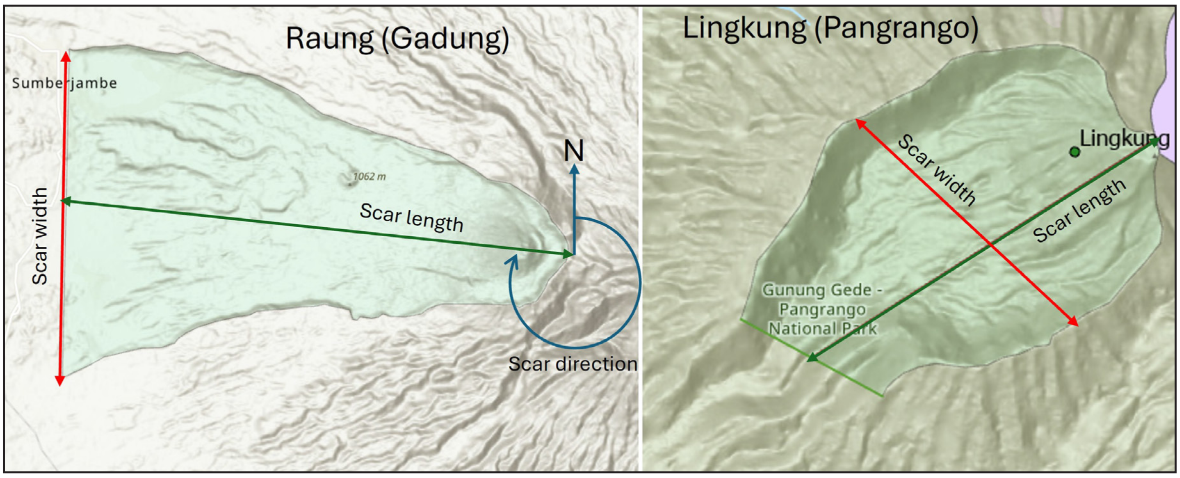


Figure 3. Procedure for several morphometric measurements (maximum width, length, and direction) of the avalanche scar.

the upper slopes of the volcano, along with a debris avalanche deposit (DAD) at the base, featuring hummocky terrain. However, most of the volcanoes on the existing list are identified by their scar of avalanche feature only (Table 1). A few have large horseshoe-shaped scar such as Lingkung/Pangrango Volcano in West Java Province (~2.8 km wide on average), and a few have smaller horseshoe-shaped scar like Wetar in the Banda Sea (~380 m wide on average). There are forty-four volcanoes that only display scar morphology. In this group, some volcanoes have experienced multiple DAD forming events (slope failures), *e.g.* Malintang (Sumatera), Gede and Guntur Volcanoes (West Java). Three volcanoes with the most typical morphological features (horseshoe-shaped scar with DAD) are Galungung (West Java), Raung (East Java), and Tandikat Volcanoes (Sumatera). These volcanoes have horseshoe-shaped scars and DAD areas on the flank of the volcanoes that are recognized through DEM and satellite imagery. There are also hummocks in the middle and lower parts of these volcanoes.

Table 1. Morphological Features of The Volcanic Debris Avalanches in Indonesia

Morphological features	Count / number of events (n)
Horseshoe-shaped scar only	44
No horseshoe-shaped scar, have DAD	3
No horseshoe-shaped scar, no DAD	4
Horseshoe-shaped scar with DAD	3

A volcano that had experienced a VDA event can also be identified by the presence of DAD and hummocky terrain on the middle and lower slopes, even if there is no visible trace of a crater or avalanche scar, as seen in Gede Volcano (southeast DAD) (Figure 4a). Other volcanoes with similar feature are Sundoro (Central Java) and Tampomas (West Java). The remaining volcanoes are those that have neither a scar nor a visible DAD. Volcanoes with this characteristic are unlikely

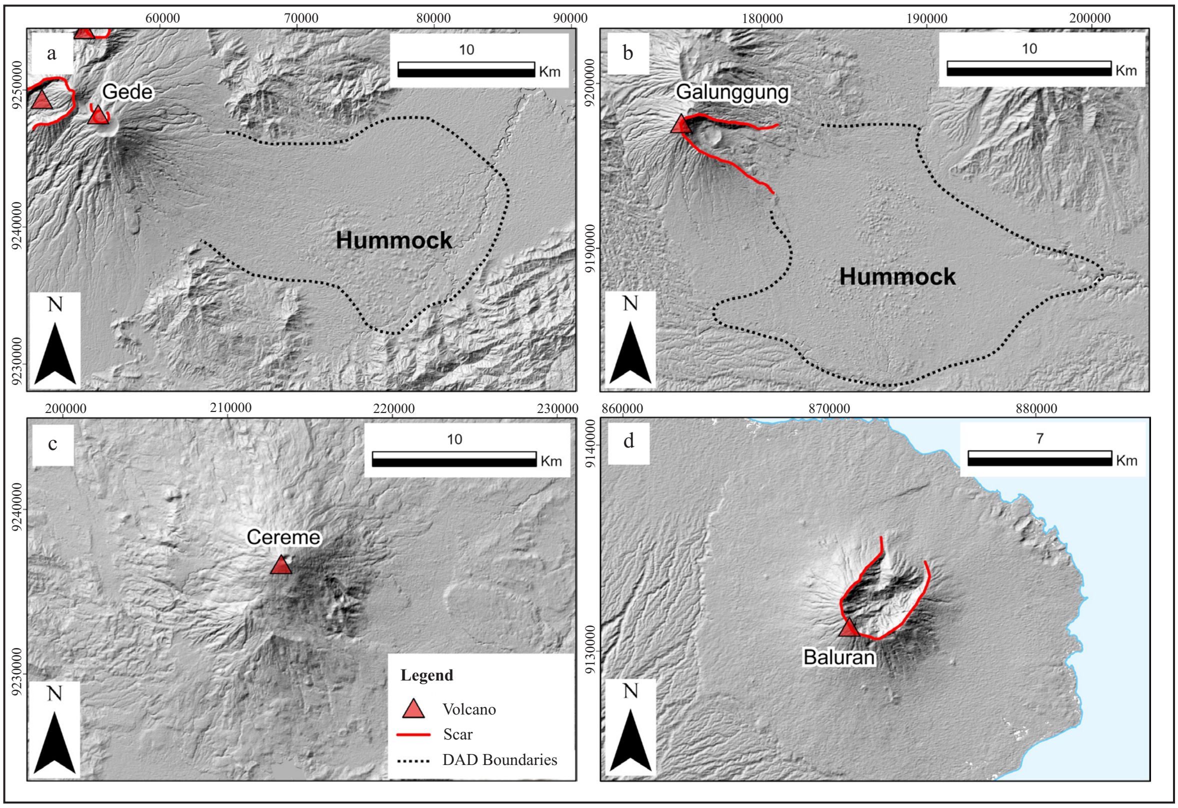


Figure 4. Variety of morphological features of some VDAs. Gede (southeast) (a) has no crater/scar but has DAD; Galunggung (b) has both crater/scar and DAD; Cereme (c) has neither scar nor DAD; and Baluran in East Java (d) only has crater/scar.

to be categorized as having a history of a VDA event in recent times, because the crater has been filled by a new dome or filled by the post-DAD edifices. However, the DAD of these volcanoes is no longer visible. Therefore, it is challenging to recognize both their craters and deposit trails. Example of these volcanoes are Cereme/Ciremai, Guntur, (West Java), and Merapi (Central Java). It is necessary to conduct specific exploration to confirm a VDA event on these volcanoes, because morphological identification fails to confirm that they have a VDA event. However, a recent study suggests that Merapi Volcano has a VDA directed toward the south (Bronto *et al*., 2023). The scars left by the avalanche process suggested by Bronto *et al*. (2023) are not clearly visible, possibly due to subsequent volcanic growth and the complex eruption history of Merapi Volcano. In addition, the associated DAD boundaries are difficult to recognize, and the distribution of undulating hills (suspected as hummocks) is sparse. Therefore, it is reasonable to include Merapi in this classification. A full list of morphological features of the VDA in Indonesia is provided in the Supplementary Material.

Geological Properties: Structure and Material from Geological Maps

The analysis of geological properties is based on the geological map of Indonesia. The results of the geological inventory provide several information, including the age, rock types, surface materials, and the structural characteristics of the surrounding volcanoes (Supplementary Material). From the fifty-four VDA events in forty-eight volcanoes, the age of the rocks that build the volcano edifices is commonly in the range of Pliocene, Pleistocene, and Holocene. The composing material is relatively uniform, which is constituted by lava with basalt-andesite type of rocks, and laharic materials. Rock names may be inaccurate, because the names on the geologic maps are acquired from petrographic data and not consider geochemical data.

Several sheets of geological maps specifically mention the characteristics of DAD, for example in the Cianjur Sheet (Sudjatmiko, 2003). The southeast DAD of Gede Volcano is identified as the Qyc rock formation, which is conical hills mainly composed of basaltic rocks. Although not specifically referred to as hummocks or DAD, this indicates the presence of a VDA event from Gede Volcano even though the trace of crater is missing in the southeast direction. Similar characteristics are also detected in the Magelang-Semarang Sheet (Thanden *et al*., 1996). The Old Sundoro Volcanic (Qos) rock formation is described as intensely weathered volcanic detritus that formed conical hills. Although not specifically referred to as avalanche deposits, the feature of conical hills in volcanic areas provides key information to suggest that they are hummocks of DAD. In both sheets, the individual conical hill is delineated relatively accurate, and their distribution is observable throughout the map. In the Tasikmalaya Sheet (Budhitrisna, 2010) the evidence of VDA is clearly informed. This map sheet specifically informs that the Galunggung volcanic breccia (Qvb) rock formation is the result of volcanic avalanches which formed conical hills up to 1 km in size and tens of meters in height. Although it does not delineate the individual hummock, the boundary of the Qvd sufficiently indicates the presumptive boundary of the DAD.

The majority of the geological maps contain structural information that indicates the occurrence of avalanches, *i.e.* the delineation of avalanche scar. For instance, the Bogor Sheet (Effendi *et al.*, 2011) covers four VDA events from Salak, Lingkung/Pangrango, Gede, and Joglok Volcanoes, but the VDA occurrence is only captured by the structure information (scar delineation). The rock formation does not indicate avalanche deposits. However, all craters of avalanche or horseshoe-shaped scars from the four volcanoes in this map sheet are clearly delineated in the map. Based on this analysis, it can be inferred that data in the geological map is very useful for building the database, particularly as a foundational resource for detecting and characterizing debris avalanches in Indonesia.

Volcano Type

The classification of volcano types that have experienced VDA events shows that the majority are in group D, which are volcanoes that are not included in the ESDM database of active volcanoes. These volcanoes are either already extinct or have no evidence of recent volcanic activity (Figure 5). The total number in group D is twenty-four volcanoes. The classification of group D is an additional classification in this research, apart from the official classification of the Geological Agency of Indonesia/ESDM. The remaining VDA events occurred in volcanoes that are identified by The Geological Agency as registered active volcanoes in Indonesia, and categorized into groups A, B, and C. Based on the results of this classification, it can be recognized that almost 50% of volcanoes are in the group D, indicating that the VDA history on those volcanoes has occurred in the past, or at least has not occurred in the last two millennia. It is important to consider the potential for VDA recurrence at the group A volcanoes, as they are still active. Some volcanoes in this group include Dempo (Sumatera), Galunggung, Gede, Papandayan, Sundoro, and Raung (Java). Besides these volcanoes are active, they also experienced historical VDA events, as confirmed by the presence of avalanche scars or debris avalanche deposits (DAD). Therefore, it is important to remain cautious about the potential for future VDA occurrences.

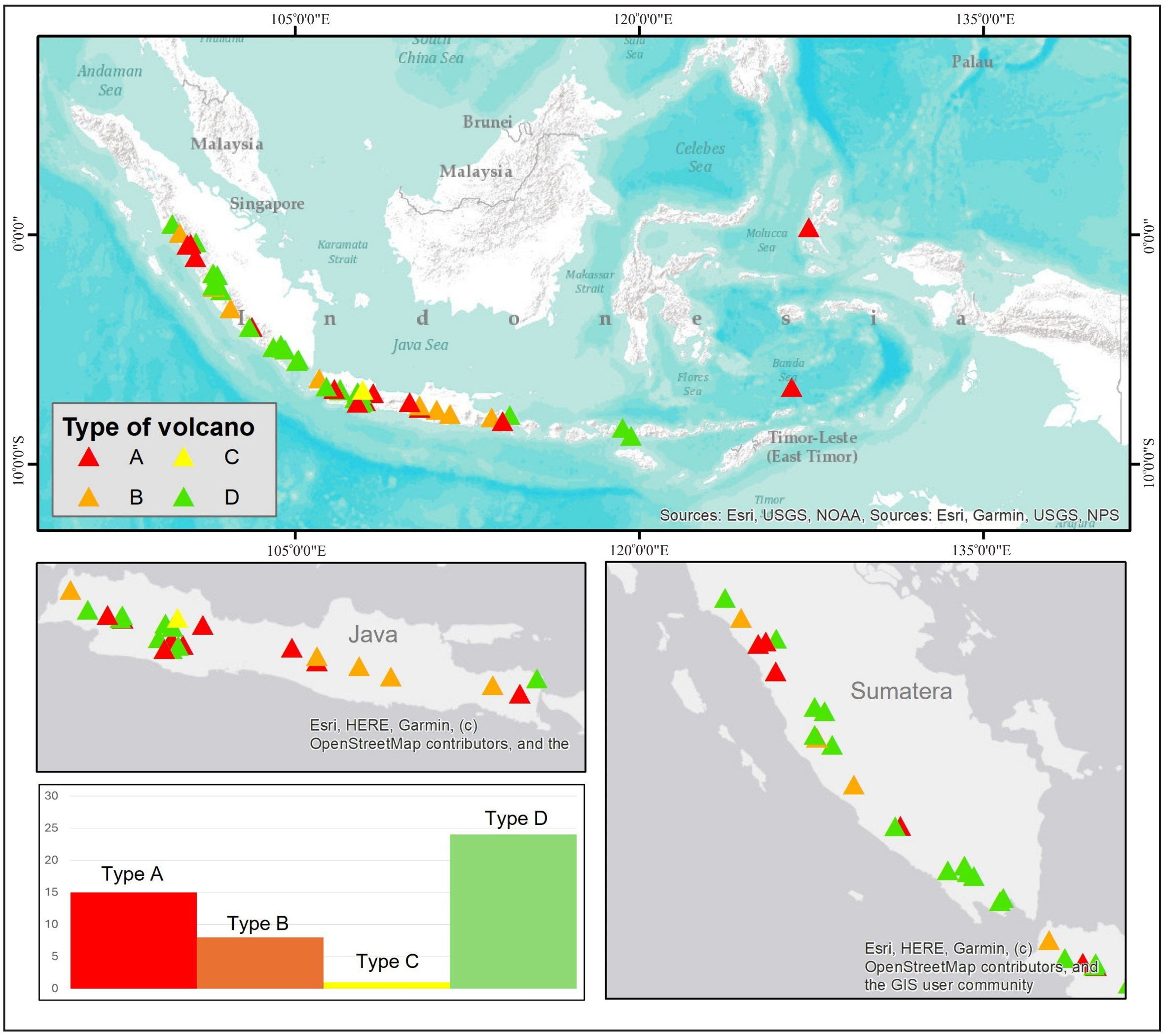


Figure 5. Classification of volcano types that have history of volcanic debris avalanche (VDA) events (list from MacLeod, 1989).

Outlook for VDA Research in Indonesia

The current list of VDAs in Indonesia is based on the identification of MacLeod (1989), who conducted identification based on the identified sector failures of volcanoes. The issue regarding the data is that at least forty-four events have no evidence of debris avalanche deposits. The most likely reason is because it occurred a long time ago, and is covered by more recent deposits making the former deposits no longer visible. In addition to the list provided by MacLeod (1989), three additional events were introduced, namely Mount Besar in Sumatera, Arjuno in Java, and Samalas (Rinjani) in Lombok. Mount Besar and Samalas are large VDA events with extensive DAD areas, and have a significant number of hummocks. A significant caldera of avalanche is found in Arjuno Volcano, but it has a smaller DAD area and less hummocky hills. The age of the event in Mount Besar and Arjuno has not yet been identified, while Samalas has been proposed to have occurred around ~3500 BCE (Malawani *et al*., 2024). By the addition of three events at these volcanoes, the total number of VDA events in Indonesia is to be fifty-seven across fifty-one volcanoes.

Many VDA events have no information on their age, because dating VDA events is challenging. Paleosols that are usually used as the basis for dating are commonly lost due to erosion processes of avalanche transport. However, the dating can be performed by conducting material dating above and below the DAD deposits as demonstrated at Gede (southeast DAD) and Rinjani Volcanoes (Samalas DAD) (Belousov *et al*., 2015; Malawani *et al*., 2024). Alternatively, lithological matching can be performed as conducted in the case of Godean DAD, a deposit from The Merapi Volcano (Bronto *et al*., 2023). This gigantic debris avalanche is highly interesting to be investigated further, as it is suspected to be the event of Merapi Volcano, which is estimated to have occurred ~110,000 years BP, with a covered DAD area up to ~390 km^2, with a maximum volume of ~8 km^3 (Bronto *et al*., 2023). Among the fifty-four inventoried VDA events from MacLeod (1989), there are only several events with proper dating, namely Gede, Galunggung, and Papandayan. The debris avalanches on Gede Volcano are directed toward the northeast (NE) and southeast (SE). The SE debris avalanche is a massive deposit with hummocky terrain, covering the Cianjur area, and is estimated to have occurred between 43–12 kyr BP. In contrast, the NE debris avalanche is younger, estimated to have occurred around 1,000 years BP (Belousov *et al*., 2015). Two debris avalanche events were identified at Galunggung, one confirmed through radiocarbon dating that produced the hummocky terrain in Tasikmalaya (4,200 yr BP: Bronto, 1989) and another smaller event in 1822 that was observed through direct observation (Junghuhn, 1854). The chronology of the debris avalanche in Papandayan is confirmed through field reports aftermath of the eruption. A clear account describes that Papandayan experienced a debris avalanche in 1772 CE resulting in a vast deposit that buried several of the surrounding villages on the lower slope of the volcano (Horsfield, 1816; Neumann van Padang, 1983). This event destroyed at least forty villages and caused 2957 fatalities. Another event at Papandayan is the 2022 debris avalanche, recorded as only distributed near the summit (Nursalim *et al*., 2016). Two renowned volcanic debris avalanche (VDA) occurrences that remain undated are Raung (Gadung) and Sundoro (Java). The VDA cases of Arjuno and Tandikat could also potentially be extremely interesting to investigate. There is no comprehensive information available regarding the morphology, internal structure, or dating of these two examples from Java and Sumatera.

Conclusions

The results of this study provide a more detailed description of the inventoried VDA events in Indonesia, focusing on their morphological characteristics and geological context. A huge number of VDA events in Indonesia are characterized mainly by their craters or horseshoe-shape scar morphology; some of them, such as Galunggung, Lingkung/Pangrango, Raung (Gadung) have large scars, while other like Wetar, bears smaller scar. In this study, the morphological characteristics that were examined only allowed for the classification into four classes: (1) volcanoes with horseshoe-shaped scar only; (2) with no horseshoe-shaped scar but have DAD; (3) with no horseshoe-shaped scar, and no DAD; and (4) with horseshoe-shaped scar and DAD. The geological maps turned out to be very essential in the identification of the occurrence of avalanches. These maps, therefore, greatly assist in preliminary assessments of the VDA occurrences and characteristics of deposits. However, the age information remains limited. Further exploration focusing on the radiocarbon dating for determining the age of VDAs in Indonesia is essential to conduct, given only a small number of them are dated. Besides this morphology-based and basic geological characterization, it is important to further investigate the potential recurrence of VDA, particularly on type A volcanoes.

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