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Characteristics of hummocky terrains in the regionally active fault zone: A case study of Mount Besar in south Sumatra

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Abstract: Mount Besar is one of the stratovolcanoes located in southern Sumatra that possesses clear geomorphological evidence of a debris avalanche event, as reflected by the presence of an amphitheater-shaped escarpment and hummocky hills. This mountain lies in proximity (~10 km horizontal distance) to the Great Sumatran Fault (GSF), suggesting a potential tectonic influence in triggering the debris avalanche event. Therefore, this study aims to identify the morphological characteristics of debris avalanche deposits (DADs) at Mount Besar, assess the potential hazards impacting nearby communities, and emphasize the need for comprehensive disaster risk management strategies in volcanic regions. The DAD of Mount Besar covers an estimated area of 360 km², with a total of 587 identified hummocks. These hummocky hills vary in shape, size, and spatial distribution. Based on observations, polygonal and elongated hummocks dominate the landscape, reflecting complex avalanche dynamics and diverse depositional processes. In order to achieve the stated objectives, an analysis of hummock correspondence was carried out, and the obtained results showed a predominant orientation between 50° and 60° from the north, with significant parallel correspondence indicative of the main flow direction. Larger hummocks were observed to be concentrated near the source area, gradually decreasing in size with increasing distance. This observation is an expression of the diminishing energy of the avalanche as transportation and deposition progressed. The analysis also revealed that the area of DAD coverage and number density of hummocks was about 360 km^2 and 1.6/km^2 respectively. On comparison of the results obtained with those of the previous studies it was observed that the DAD coverage area and the density of hummocks of Mount Besar was less than that of the DADs of eruption-triggered avalanches (e.g., Rinjani, Galunggung, Sindoro), but similar to tectonically triggered DADs (e.g., Mt. Gadung). It is always this similarity that drives towards the likelihood of how the initiation of the Mount Besar DAD could have been triggered by a tectonic but not volcanic eruption, especially the fact that there is no fragmentation or explosive characteristics. Since the above interpretation is correct, it is possible to infer that the lack of fragmentation or explosive activity in tectonically triggered DADs was a major factor in maintaining the larger size of hummocks, and thus, produced a reduced number density of hummocks. In any case, additional field-based studies are also highly demanded to confirm this hypothesis and improve the current body of knowledge about the processes that drive avalanches of debris at Mount Besar.

Keywords: Hummocky hills, debris avalanche, geomorphometry, Mount Besar, volcano-tectonic hazards

INTRODUCTION

Indonesia lies in the active subduction zone of the Eurasian, Indo-Australian and Pacific plates. According to a previous study, this process of subduction has resulted in the development of volcanic arcs due to the continuous nature of the process (Katili, 1975). Several investigations have been conducted on volcanic hazards in Indonesia, including pyroclastic falls, pyroclastic flows, lava flows, and lava dome collapses (e.g., Thouret *et al*., 2000, 2007; Kasbani *et al*., 2019; Kunrat *et al*., 2020; Santoso *et al*., 2022; Suhendro *et al*., 2023, 2024, 2025). Regardless of this fact, Indonesian scholars have not given much attention to other hazards such as landslides and debris avalanches. A debris avalanche can be characterized as a natural process, which is caused by a gravitational collapse or a landslide of volcanic domes (Roverato *et al*., 2021). These natural events are usually caused by the failure of volcanic edifice walls, which is a cyclic phenomenon called volcanic sector collapse, and is capable of moving vast masses of material, in areas as large as tens of square kilometers. Hummocky hills are the key morphological sign of a volcanic sector collapse, which can be found in the locations of Mount Rinjani, Mount Gadung, Mount Sindoro, and Mount Galunggung (Moktikanana *et al*., 2021; Alfin *et al*., 2022;

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Rahayu *et al*., 2023; Malawani *et al*., 2024). To this end, the phenomenon is reported worldwide, especially in the areas of the Pacific Ring of Fire, including the United States, Mexico, Japan, the Philippines, and Indonesia (Yoshida *et al.*, 2012; Yoshida, 2014; Hayakawa *et al*., 2018; Malawani *et al.*, 2024). According to prior research, the records of avalanche deposits (DADs) indicated 1,001 reported events in 594 volcanoes in 54 countries, half of which occurred in Japan, the United States, and Russia (Dufresne *et al*., 2021). Since volcano Mount St. Helens erupted in the 1980s, debris avalanches have come into being a major subject of exploration with particular attention on volcanic hazards, in addition to eruptions and earthquakes caused by volcanoes (Siebert, 1984; Yoshida, 2014).

The morphology of the hummocky hills of the phenomenon makes DADs easily recognizable. It is a signature of the processes of the debris avalanche, a common aspect of the large or highly dissected stratovolcanoes (Suhendro & Haryono, 2023). In Indonesia, a nation located on the Ring of Fire, nearly 70 instances of DAD occurrences have been detected (MacLeod, 1989). These instances include the Mount Gadung in East Java, the Mount Galunggung in West Java, and the Mount Sindoro-Sumbing complex in Central Java (Moktikanana *et al*., 2021; Alfin *et al.*, 2022; Rahayu *et al*., 2023). The mountain Besar in the south of Sumatra is seen to have a characteristic morphological structure that suggests a previous avalanche of debris in the past. Of special interest is that this site is located next to the GSF (see Figure 1b), which is a rare example of a volcano-tectonic interaction not typically present on other Indonesian islands like Java or Bali or the Nusa Tenggara Islands. Accordingly, the older volcanic activities in Sumatra have given rise to seven volcanoes (type C) that are old or dormant, and one of them is Mount Besar (Katili, 1975). This can be proved by the fact that there has been no activity in the destination since about 30 ka (Hochstein & Sudarman, 1993). The Ranau Formation, a geological unit that covers the DAD of Mount Besar, has been dated to an eruptive age of approximately 34 ka, which also supports the interpretation (Natawidjaja *et al*., 2017). These findings indicate that the DAD of Mount Besar is still relatively young, and there is a need to carry out geochronological studies in order to narrow down its eruptive history. In this framework, the broad scar on the

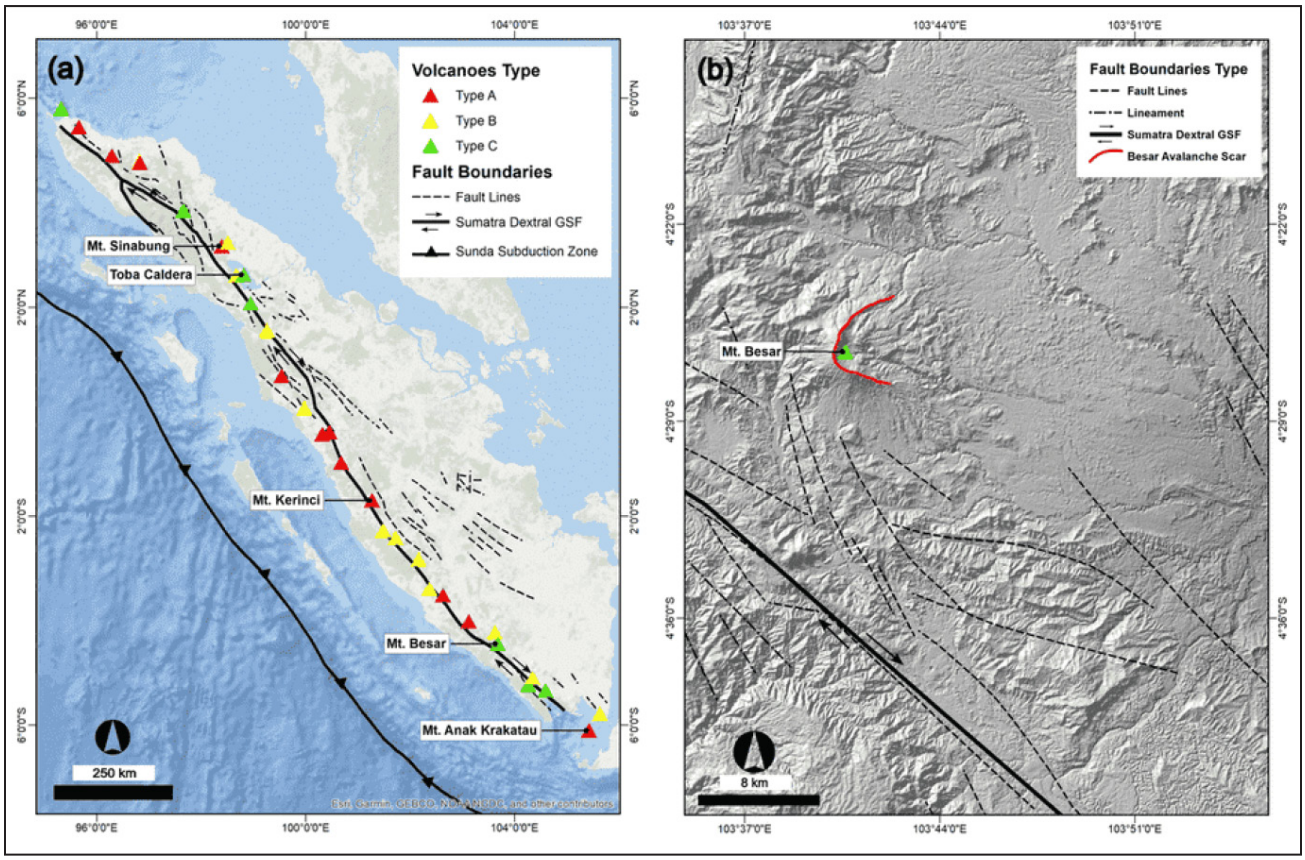


Figure 1: a) The map shows the regional tectonic setting and the distribution of active volcanoes in Sumatra, where volcanoes in Indonesia are classified into type A (erupted after 1600 AD), type B (no recorded eruptions after 1600 AD but still showing volcanic activity), and type C (no recorded eruptions since 1600 AD and no signs of volcanic activity) (modified from Natawidjaja & Triyoso, 2007; Acocella *et al.*, 2018); b) A map showing the location of Mt. Besar in the GSF fault area. Source: DEMNAS (National Digital Elevation Model) data obtained from Inageoportal BIG (available at http://tide.big.go.id).

edifice of the volcano and the availability of distal DAD deposits are likely to be linked to the presence of the tectonic activity along the Sumatran Fault.

The DAD of Mount Besar is an important aspect of geology capable of adding considerable knowledge to the processes of DAD formation, which are led by the volcanic-tectonic interaction. These effects may cause the failure of up to fifty percent of a volcanic structure, which results in massive deposits. Within this context, the peculiarities of the hummocky hills and their spatial distribution are considered the necessary data to comprehend the processes of the debris avalanche and evaluate the risks of each process (Malawani *et al*., 2024). As mentioned in the discussion above, this study aims to (1) determine the features of the DAD at Mount Besar in relation to faults and tectonic activity systems and (2) examine the possible risks that these features have on the neighbouring areas. The regions close to volcanoes, i.e, the ones located in flat land which normally act as the downstream areas of DADs, are more susceptible. According to previous reports, these lands frequently serve as residential or agricultural premises (Hayakawa *et al*., 2018). To that end, comprehensive data concerning the past occurrences of the DAD is needed to formulate proper measures of mitigating the hazards and improving the resilience of communities in the area of volcanic activities.

Regional geology

Sumatra Island was formed as a result of the subduction between the Eurasian and Indo-Australian plates. According to a previous report, the ongoing convergence of these two plates produced the Great Sumatra Fault system, a 1,650 km-long strike-slip fault extending from the Sangihe–Banda Aceh region to Semangko Bay (Natawidjaja & Triyoso, 2007). This extensive fault system has generated significant geotectonic activity, giving rise to approximately 95 active volcanoes that have erupted intermittently since around 1500 AD. The majority of these volcanoes are located approximately 100–200 km from the subduction zone (Hall, 2009). As stated by Natawidjaja & Triyoso (2007), the Great Sumatra Fault is divided into three main regions, namely northern, central, and southern (Figure 2). Mount Besar lies on the southern part of the fault system, near the Komering fault segment and the Manna fault segment. According to historical accounts compiled by Visser (1922), the last time that a disastrous 7.2 magnitude earthquake hit the segment of the Manna fault on June 12, 1893, it caused devastating impacts on the central part of the area (Harukawa *et al*., 2014).

The Sumatran fault segment has a unique seismic characteristic, namely the potential for a double mainshock (two main earthquakes close together) due to the stepover fault configuration (overlapping fault sections), in which an

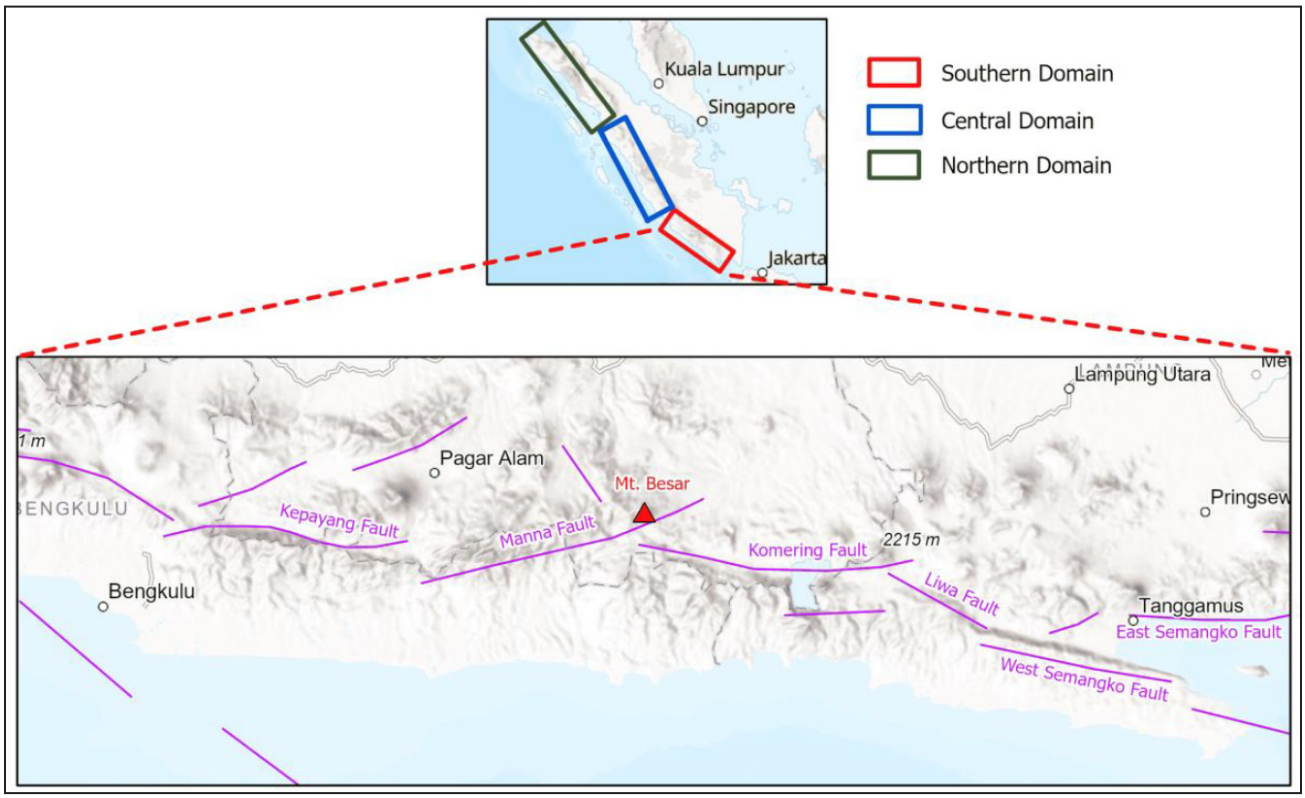


Figure 2: Fault segments in Sumatra Island are divided into three regions, namely, northern, central, and southern. The position of Mount Besar is in the southern region, an area surrounded by several fault segments, some of which are nearby faults, specifically the Komering and Manna fault segments. Adapted from Sieh & Natawidjaja (2000) in "Neotectonic of The Sumatran Fault, Indonesia".

earthquake occurring on one segment can transfer energy and trigger another mainshock in the adjacent segment (Natawidjaja & Triyoso, 2007). The Sumatra fault has a very high potential hazard, especially in densely populated areas around the fault. The Sumatra fault is classified as a highly active fault with a movement of 10-27 mm/year (Natawidjaja & Triyoso, 2007). According to Natawidjaja & Triyoso (2007), the strain accumulation in each segment of the Sumatra Fault will accumulate earthquake energy of 7.2 – 7.4 Mw. The activity of fault segments and fractures in Sumatra Island, especially in the area around the study site, has a history of major earthquakes. Earthquakes associated with this zone have medium to strong intensity with a shallow depth potential of less than 20 km (Edward, 2015). The Komering segment is one of the active fault segments near Mount Besar, spanning 150 km through Lake Ranau, Lampung Province, and South Sumatra Province. Historical disasters include the Liwa earthquake on July 24, 1933, with a magnitude of 7.5 Mw, and on February 16, 1994, with Mw 6.8 (North Lampung Geophysical Station, 2023). These earthquakes resulted in many casualties, as many as 2000 people were injured, 207 people died, and physical damage to buildings (Arifin, 2014).

Natawidjaja & Triyoso (2007) divided the Sumatra fault into 20 major segments. Based on this division, Mount Besar is located on the northern side of the Komering Fault segment and administers South Ogan Komering Ulu Regency, South Sumatra Province. Northwest of the Komering Fault segment, there is a morphological feature known as a contractional or restraining bend zone (Natawidjaja & Triyoso, 2007). The restraining bend acts as a barrier to the propagation of seismic activity but can also accumulate seismic activity with high magnitudes (Shaw, 2006). In addition to releasing seismic energy, this fault configuration has been observed to facilitate mechanisms of segment rupture and activation within the restraining bend zone (Harris *et al*., 2002). From a regional geological perspective (Figure 3), Mount Besar is composed primarily of Quaternary Garrangang andesite–basalt (Qvg), and its volcanic formation is underlain by the Quaternary Ranau Tuff (QTr; Ranau Formation), representing the caldera-forming deposits of the Ranau caldera that erupted approximately 34 ka (Natawidjaja *et al*., 2017). This stratigraphic relationship suggests that the DAD at Mount Besar is probably older than 34 ka. As a result, Mount Seminung, which is the post-caldera volcano of Ranau (Gunawan & Suhendro, 2023), and Suoh Crater remain the only two active volcanic edifices in the vicinity. The most recent eruption of Mount Seminung has been identified as a sub-Plinian event, evidenced by a thick (~3 m within 4 km of the vent) pumice- and scoria-bearing pyroclastic deposit, although its precise age has yet to be determined (Gunawan & Suhendro, 2023). On the flip side, a phreatic eruption was recently recorded at Suoh Crater on May 24, 2024 (Global Volcanism Program, 2024).

METHODOLOGY

The morphological data used in this study were taken from the DEMNAS (National Digital Elevation Model) and converted further into the hillshade data by using procedures outlined in previous studies (Moktikanana *et al*., 2021; Alfin *et al.*, 2022; Malawani *et al*., 2024). Accordingly, topographic and geological maps were also adopted to identify the lithological characteristics of the study area, particularly in the DAD zone. All data processing and spatial analyses were performed with Geographic Information System (GIS) software. The morphometric analysis implied the integration of several variables, i.e. shape, size, area, distance from source, direction, elongation ratio, displacement angle, relative height and the H/L ratio (i.e. the ratio between the height of the mountain H, and the maximum length of the DAD L). In addition, the hummock frequency and number density were also studied (Salinas & López-Blanco, 2010; Hayakawa *et al*., 2018). These analyses were conducted as an attempt to determine important morphological parameters in the interpretation of DAD characteristics and hummocky hill formation, which will give an insight into the correlation between depositional patterns, flow dynamics and geomorphological processes.

Hummock correspondence was analyzed in two ways, which were the rose diagram and displacement angle methods (Yoshida, 2014). The main direction of flow was determined qualitatively by the observation of the opening of the avalanche-shaped (horseshoe-shaped) amphitheatre relative to the most distal hummocks on the same axis. From the rose diagram, the displacement angle was calculated as the difference between the main flow direction angle and the major axis angle for each hummock. Furthermore, the angle was determined based on the variation between the major axis orientation of individual hummocks and the individual flow direction, as is shown in Figure 4. The Individual Flow Direction was used to represent the azimuth of a line that linked the centroid of each hummock to the source of the avalanche (i.e., the distance from the source). In accordance with this, hummocks with a displacement angle of less than 45° were categorized as parallel-aligned, and those with a displacement angle greater than 45° were categorized as perpendicular-aligned (Yoshida, 2014). It is further important to understand that this analysis was only done on the morphometric data based on DEMNAS, as investigations in the field were not possible. Regardless, the obtained remote-based results represent a valuable framework that should be further substantiated through detailed field observations in future studies.

RESULTS

Morphology of hummock, size, and distribution

Mount Siedang on Mount Besar has a wide distribution of hummocks of different sizes, shapes and morphology (DAD). The two-dimensional (2D) outlines of the hummocks were interpreted according to respective individual

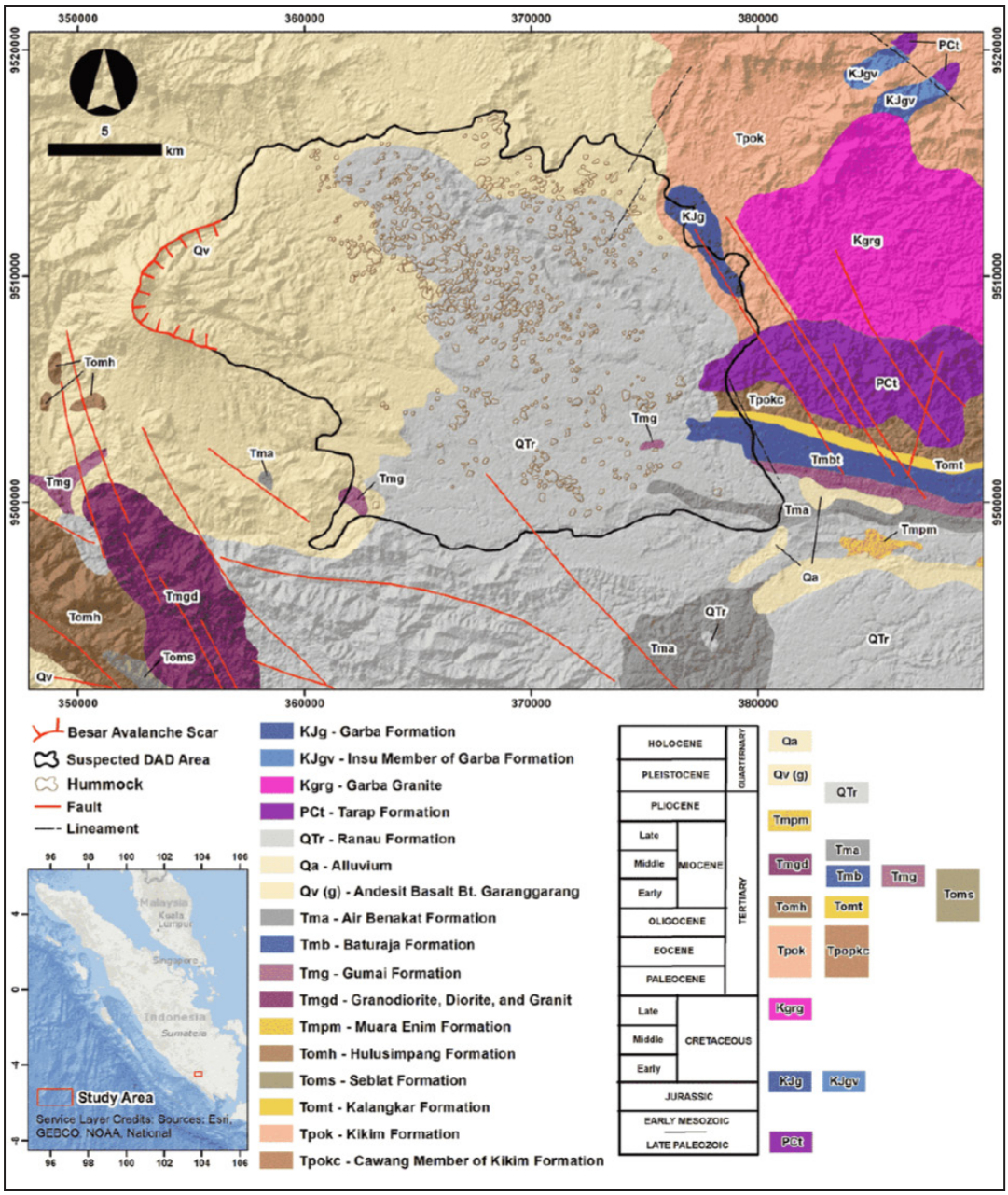


Figure 3: The DAD of Mount Besar's coverage area is shown by the black-solid line. Observe that the DAD is situated on Qv(g), i.e., the Garanggang andesitic eruption is recently overlain by the QTr (Ranau formation) formed at ~34 ka. Source: Geological Map of Baturaja Quadrangle, Sumatera (Gafoer *et al*., 1993).

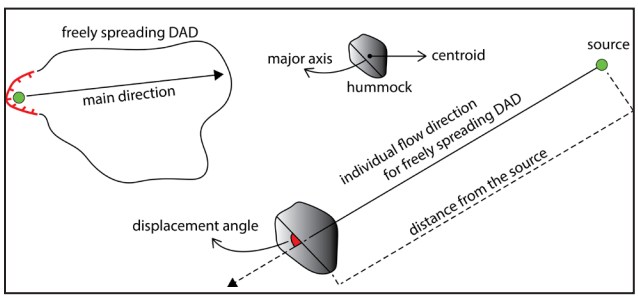


Figure 4: Morphometric parameter for freely spreading DAD, adapted from Yoshida (2014).

boundaries reflecting four principal shape types, including rounded, elongated, polygonal and rectangular. Among the 587 hummocks, 224 (38%) had polygonal or irregular shapes and 181 (31%) were elongated with a corresponding preferred correspondence that represents the predominant avalanche flow direction (Figure 5a). In three-dimensional (3D) form, the hummocks were observed to be predominantly conical and ridge-shaped, representing 45% and 39% of the total, respectively. Cubical and pyramidal hummocks accounted for smaller proportions, at 9% and 7%. Based on the spatial distribution shown in Figure 6a, these various

hummock shapes were evenly dispersed across the DAD, having no distinct correlation with distance from the source area. It can also be observed from the figure that diverse hummock morphologies occurred consistently from the midsection to the distal zones of the deposit.

Based on the size distribution, the hummock hills were classified into two types, namely small (<0.1 km²) and large (>0.1 km²) (Figure 5b). Based on observations, the hummock size generally correlates with the distance from the avalanche source, extending between 9 km and 27 km. However, the majority of hummocks were concentrated within a range of 10–20 km from the source, as shown in Figure 6d. It is also important to state that larger hummocks typically occur closer to the debris

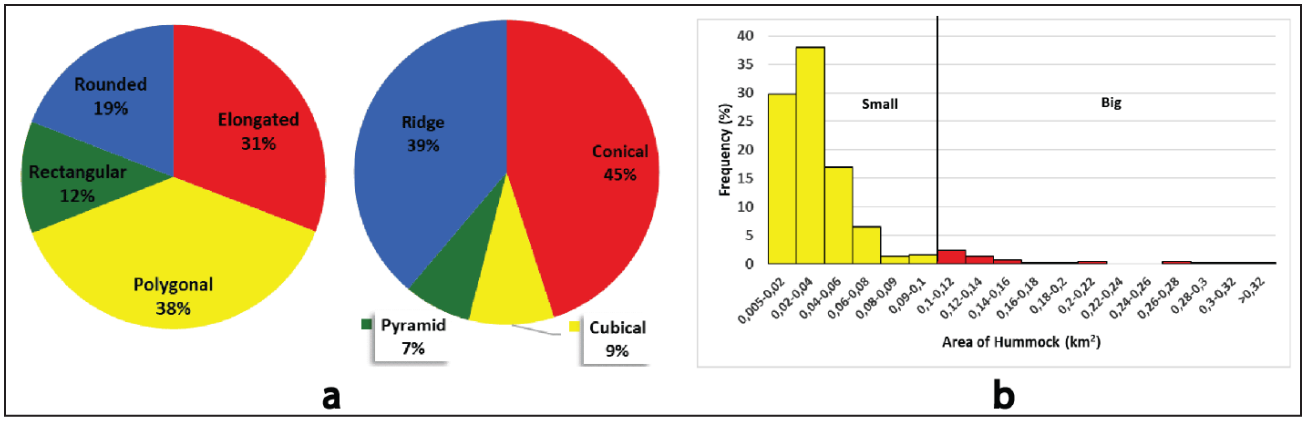


Figure 5: (a) The Pie charts on the left represent the percentage of the hummock 2D shape, while that on the right denotes the hummock 3D shape; and (b) the histogram of hummock area vs percentage of hummock frequency.

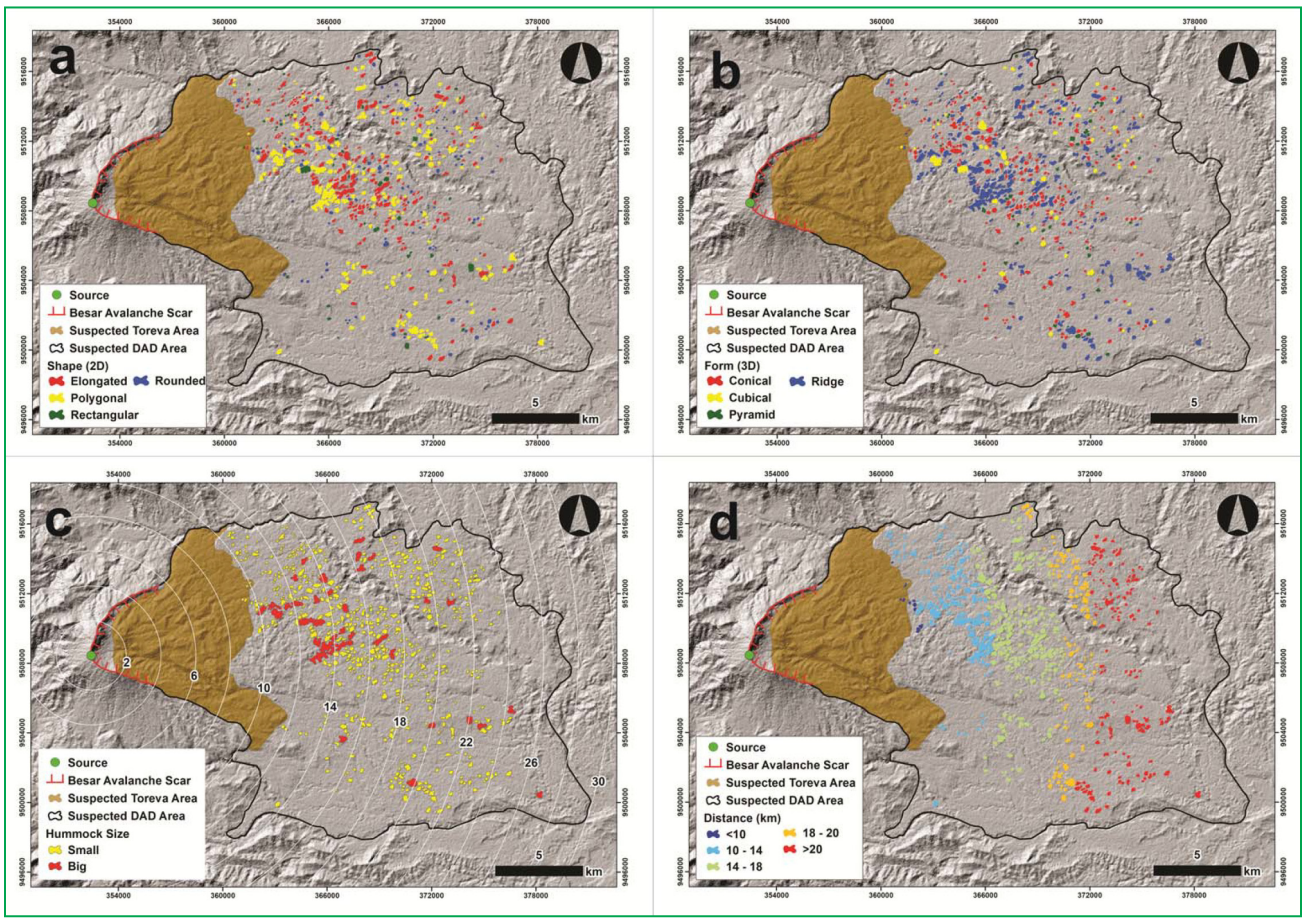


Figure 6: Map of morphological characteristics of individual hummocks: (a) shape; (b) form; (c) size; and (d) distance.

avalanche source, while smaller ones are more common in distal areas. In the case of Mount Besar, this trend was not strictly observed. The hummock distribution was irregular, with variations in size, including six significantly large hummocks identified as far as 20 km from the landslide source.

Hummock correspondence and displacement angle

Rose diagrams in Figure 7a show that most hummocks in Mount Besar's DAD are oriented between 50° and 60° from north, with displacement angles of <45°, particularly in the central and northern areas, reflecting a predominantly parallel alignment. Meanwhile, the rest have displacement angles >45° (perpendicular hummock alignment) and are mainly found from the central to southern parts of the DAD. Displacement angle data for each hummock is then interpolated using the Natural Neighbor Interpolation method to determine its distribution.

Morphometric data of the hummocky hills

The DADs of Mount Besar have 587 hummocky hills covering 360 km^2. This number is not significantly different from Mount Gadung, Mount Galunggung, and Mount Sindoro-Sumbing in Java. Accordingly, a negative correlation was observed between the size of the hummocks and their distance from the landslide source (Figure 8a), where larger hummocks tend to be located closer to the source area, and smaller hummocks were found further away. A positive correlation is shown between the H and L variables (Figure 8b), indicating that the greater the height of the volcano, the farther the landslide distribution extends, and vice versa. A negative correlation was also observed between the average hummock size and hummock density. This ratio reflects that the larger the area occupied by hummocky hills, the lower the density of hummocks tends to be, as wider distributions are generally dominated by fewer but larger hummocks (i.e., hummocks with greater average area), whereas higher hummock densities are typically associated with smaller average hummock areas (Figure 8c). Based on (Figure 8d), the H/L value of Mount Besar is relatively similar to that of Mount Gadung and is significantly higher than those of Mount Rinjani, Mount Sindoro, and Mount Galunggung. The relationship between hummock density and H/L ratio was found to possess a positive correlation trend (Figure 8e), reflecting that higher hummock densities were generally associated with higher H/L values. Accordingly, the comparative ratios of hummock density and H/L between Mount Besar and Mount Gadung showed relatively similar values, specifically when compared to Mount Sindoro, Mount Galunggung, and Mount Rinjani. The present analysis is, however, limited to morphometric data derived from DEM, without field-based lithological verification. The absence of detailed information on the presence of primary eruptive components interbedded within the DAD of Mount Besar renders the interpretation of a non-eruptive trigger tentative. Therefore, future investigations including detailed field surveys and petrological analyses are required to determine whether lithological evidence supports a purely tectonic origin.

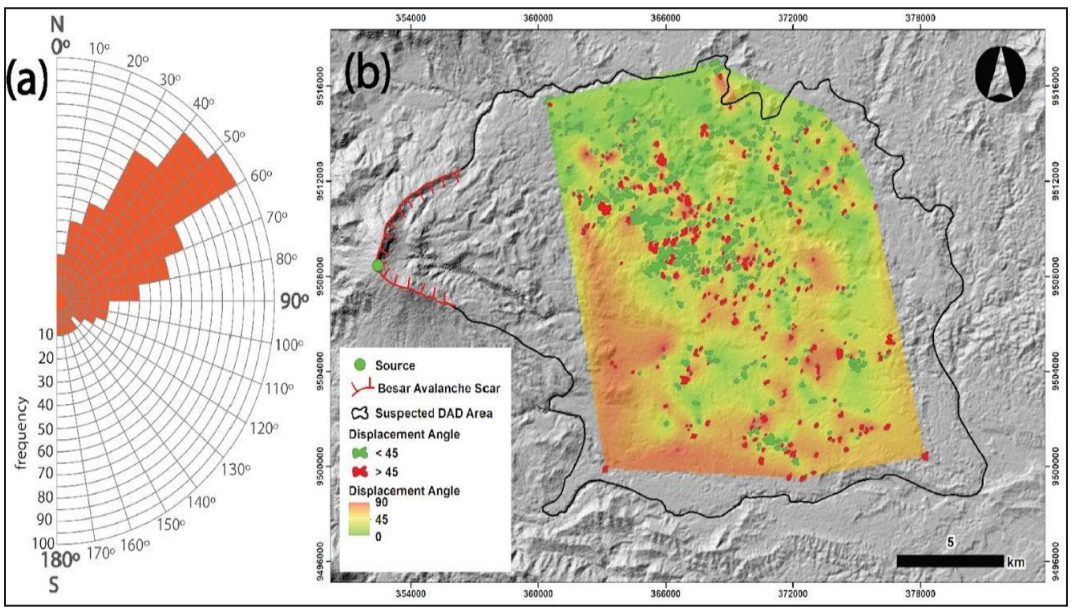


Figure 7: (a) Rose diagram shows the directional trend of hummocks. (b) The map reflects the spatial distribution of hummocks within the suspected DAD area of Mount Besar, where the colour gradient is green (low, below 45°), red (high, above 45°), and yellow (moderate, around 45°).

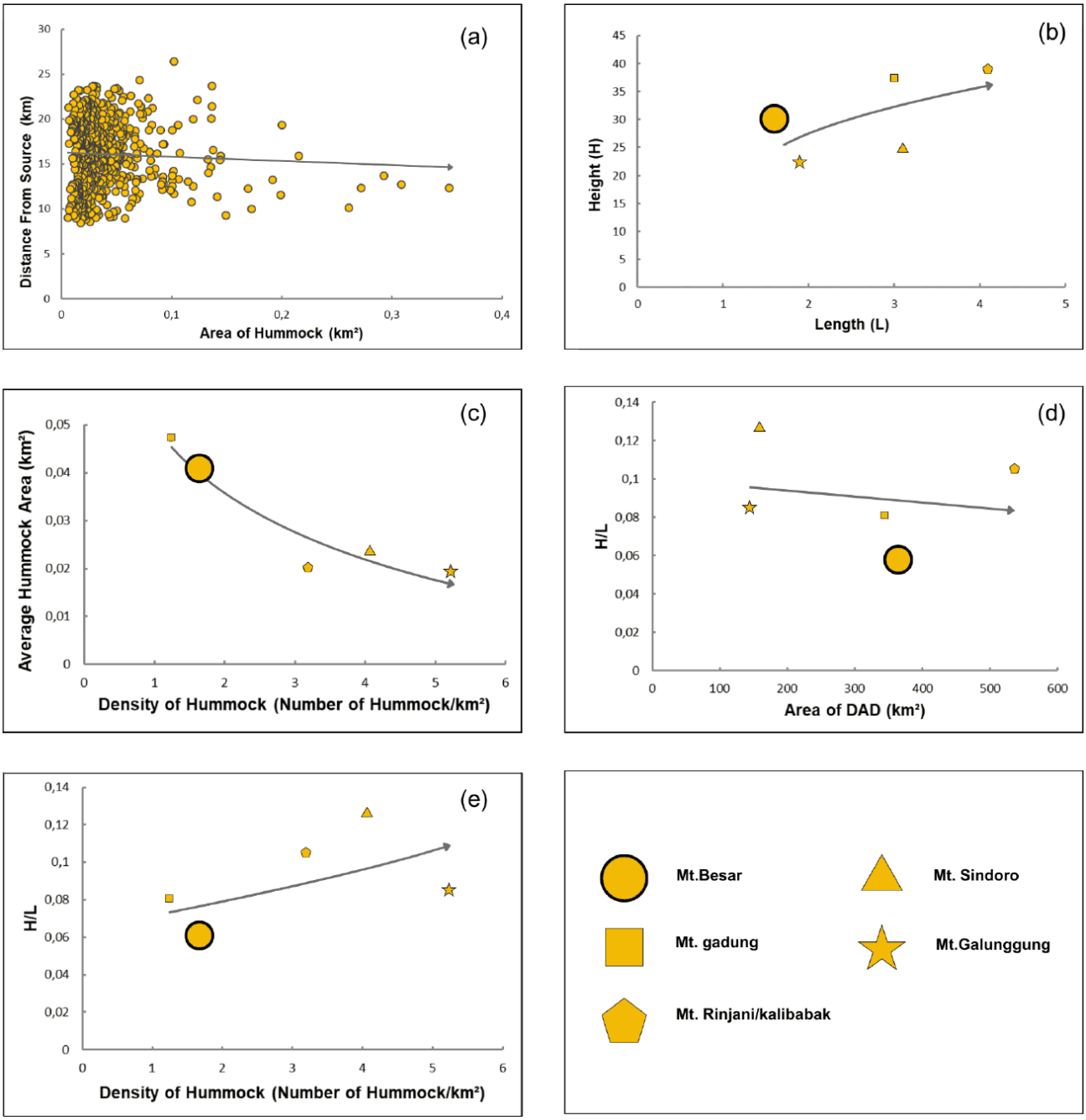


Figure 8: (a) Bivariate plot between the area of hummocky hills and their distance from the source; (b) Bivariate plot between H and L; (c) Bivariate plot between H/L and the area of DAD; (d) Bivariate plot between the average and density of hummocky hills; and (e) Bivariate plot between H/L and the density of hummocky hills. (Data source for comparison in this figure: Moktikanana *et al*., 2021; Alfin *et al*., 2022; Rahayu *et al*., 2023; Malawani *et al*., 2024).

DISCUSSION

A proposal for tectonic-triggered debris avalanche: Evidence from morphology

MacLeod (1989) reported that numerous Indonesian volcanoes have experienced debris avalanche events, as evidenced by the presence of hummocks and amphitheater-shaped escarpments. According to another previous study, almost all of these DADs originated from large, mature stratovolcanoes (Suhendro & Haryono, 2023). Several explorations, including those by Watt (2019), Suhendro & Haryono (2023), and Rahayu *et al*. (2023), have discussed possible reasons why large, mature stratovolcanoes are particularly susceptible to DAD formation. Among the observed reasons are, first, the volcanoes typically possess well-developed magmatic systems with more differentiated magma compositions, increasing the probability of large

explosive eruptions that may lead to edifice collapse. Second, these volcanoes often undergo prolonged hydrothermal alteration and intense weathering processes, which weaken the volcanic structure and make it prone to gravitational collapse, even in the absence of eruptive activity. The reasons provided showed that the formation of a DAD can be either eruption-triggered or non-eruptive in origin.

Previous investigations by Bronto (1989) and Malawani *et al*. (2024) confirmed that DAD events at Mount Galunggung and Mount Rinjani were associated with explosive eruptions (VEI 5) that occurred around ~4.2 ka cal BP and 7000–2600 BCE, respectively. Similarly, Rahayu *et al*. (2023) suggested that the DAD event at Mount Sindoro was also eruption-triggered, but the precise age and eruptive style remain uncertain. These eruption-triggered DADs were observed to possess comparable morphological characteristics, namely, dominantly small hummock sizes and high hummock number densities (Figure 8c). The stated features are dissimilar to those of Mount Gadung's DAD, which is characterized by larger hummock sizes and lower densities (Figure 8c), representing a case of a non-eruptive, tectonically triggered DAD (Moktikanana *et al*., 2021). The DAD of Mount Besar yields identical morphological characteristics to the DAD of Mount Gadung (Figure 8); hence, it may support the idea that the DAD of Mount Besar was not triggered by an eruption and possibly generated by the fault system (i.e., tectonic-triggered DAD). The fact that Mount Besar is situated only ~10 km to the east of the Great Sumatran Fault may support this idea (Figure 1). The next question is, why does the eruption-triggered DAD yield different morphological characteristics from the tectonic-triggered DAD?

Understanding why eruption-triggered DAD possess morphological characteristics that differ from those of the tectonic-triggered DAD is essential. It is generally known that explosivity is proportional to the fragmentation index, and a higher degree of fragmentation index facilitates the formation of the more prevalent fine particle sizes. Thus, it is very possible that the small hummock sizes and the high hummock number density at Mount Galunggung and Mount Rinjani (and possibly Mount Sindoro too) were facilitated by the intensive fragmentation during an explosive event. This means that if a DAD lacks a magmatic fragmentation event, the kinetic energy should be theoretically low and consequently result in the formation of a dominantly large hummock size and small hummock number density, such as

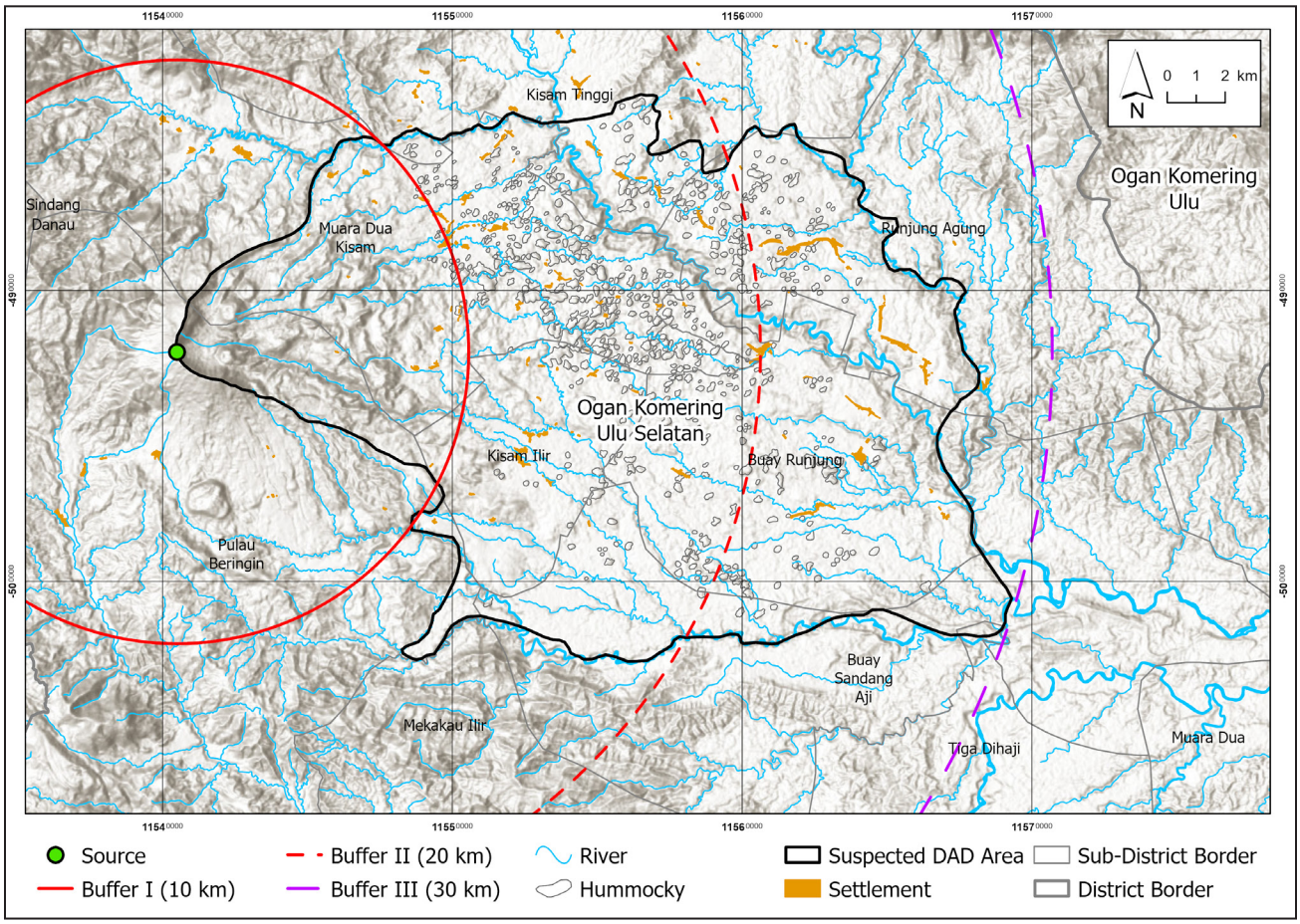


Figure 9: The hazard map of the DADs of Mount Besar.

the case of Mount Gadung and Mount Besar. Furthermore, several previous studies (e.g., Siebert & Reid, 2023; Rollwage *et al*., 2024) have shown that the Great Sumatran Fault (GSF) can produce >7 Mw earthquakes. Such strong earthquakes can release a large amount of seismic energy, hence disrupting the stability of volcanic edifices. As a result, this process can lead to the collapse of the volcano (even without eruptions), ultimately resulting in the formation of DADs. One example in this case (i.e., tectonic-triggering DAD) is the collapse of the Mayuyama-dake in 1792 because the volcano collapsed after a >7-magnitude earthquake hit Nagasaki Prefecture (Ohta, 1969). Therefore, Mount Besar's proximity to the numerous active fault segments (see Figure 3) strongly suggests that geological structures can play a major role in the generation of DAD. Previous studies have demonstrated that the configuration of geological structures, particularly fault systems and fracture orientation, strongly controls the morphology of volcanic edifices and the occurrence of sector collapse (Corazzato & Tibaldi, 2006; Marliyani *et al*., 2020; Hategekimana *et al*., 2024). Furthermore, fault orientations and fracture alignments are often expressed in the asymmetry of v,olcanic edifices, the orientations of amphitheater-shaped collapse scars, and the distribution of hummock deposits (Corazzato & Tibaldi, 2006; Marliyani *et al*., 2020; Hategekimana *et al*., 2024). In this context, the proximity to major fault segments of the GSF, the orientation of subsidiary fractures, and local fault alignments around Mount Besar, both at regional and local scales, should be considered in evaluating whether DAD was primarily triggered by tectonic activity or volcanic activity. This implies that both the occurrence of DAD and the resulting morphological expression of the collapse are not only a function of eruptive or non-eruptive triggers, but also of the regional and local tectonic framework that governs edifice growth and stability.

Hazards of debris avalanche

The collapse of a volcanic sector is a low-frequency disaster event that produces large and highly destructive debris avalanches with volumes ranging from 0.05 to 45 km^3 (Roverato *et al*., 2014). The flow can reach initial speeds of up to 100 m/s, travel tens of kilometers, and spread over the surrounding areas (Siebert *et al*., 1987). A volcano can reach a critical point of instability when it exceeds its sides, which can cause partial collapse, and the result of this slope collapse is a large and rapid mass movement known as a catastrophic landslide or debris avalanche. Many factors can cause sector collapse during an eruption process, including destabilizing factors such as earthquakes (tectonic faults), magma intrusion, hydrothermal activity, gravitational loading, and progressive shifting (Reid *et al*., 2000).

The sector collapse activity on Mount Besar resulted in DADs stretching up to 30 km with an area coverage of 360 km^2. Similarly, other mountains previously studied, such as Mount Gadung, stretch up to 37.2 km with an area coverage of 340 km^2, Mount Galunggung stretches up to 22.4 km with an area coverage of 140 km^2, DAD Kalibabak Mount Samalas stretches up to 39 km with an area coverage of 530 km^2, and Mount Sindoro stretches up to 24.6 km with an area coverage of 150 km^2.

Considering the fact that the range of DAD on several mountains in Indonesia reaches > 20 km, hazard potential mapping may be necessary to include the DAD hazard variable, particularly on active mountains in Indonesia, with a radius of 20-30 km as potential areas that might be affected by DAD. As seen in Figure 9, although the formation of DAD deposits occurred before residential activities developed, this shows that the DAD range can reach as far as ~30 km, covering several sub-districts in Ogan Komering Ulu Selatan Regency, including the sub-districts of Muara Dua Kisam, Runjung Agung, Buay Runjung, and Kisam Ilir. This indicates that the impact of the DAD landslide on the current conditions may cause many casualties and significant losses. However, in Indonesia official Volcano Hazard Zone Map the DAD or debris avalanche is not included. Although only by adding the radius of debris avalanche runout as proposed on the map that we created (Figure 9), it may cause a public uproar. Therefore, this debris avalanche potential notice is only suitable if presented in scientific research papers.

It was found that the runout distance and a covered area of the debris avalanche from Mount Besar are strongly affected by topographic constraints since the DAD is limited by preexisting mountains (Figure 3). These topographic barriers will invariably restrict the distance and direction of debris avalanche spread and will inevitably bring out the importance of hazard assessment to consider the path and potential debris avalanche distribution. Within this context, the size and spread of a debris avalanche can be estimated before it happens to allow the mapping of potentially impacted areas for the evacuation planning. In addition, it is assumed that the hazards mitigation must also take into account a high probability of large eruption co-occurring with the debris avalanche, possibly coinciding with the movement of tectonic faults. In the context of Disaster Risk Reduction (DRR) in Indonesia, which is regulated by national and regional regulations, it has been identified four main stages for volcanic hazards in Indonesia, which are monitoring, mapping, emergency response and recovery (Malawani *et al*., 2021). Most of the volcanoes on the island of Sumatra are located along the active Sumatra Fault Zone which underlines the need of permanent monitoring for DAD potential in this area. Based on the potential of exposure to pyroclastic flows, lava flows, volcanic ejecta, toxic gases, rockfalls, ashfall, lahar floods and pyroclastic surges, volcanic disaster risk management of the National Disaster Management Authority (BNPB) classified hazard zones into three levels (KRB III, KRB II and KRB I). Although the potential risk of DAD is rather high, existing KRB studies in Indonesia do not

include DAD as a hazard variable. The implementation of DAD hazards into DRR is necessary in Indonesia by using specific technical methodologies (Legros, 2002; Kelfoun & Druitt, 2005; Hayakawa *et al*., 2018; Malawani *et al*., 2021; Alfin *et al*., 2022). The introduction of these methods will, without doubt, help enhance the scientific reliability of volcanic hazard zonation (KRB) maps and guarantee that DAD-related hazards are clearly addressed in disaster preparedness and mitigation planning. Moreover, given that governments in Indonesia can observe that there are many active volcanoes in the areas where many people reside, future disaster risk management strategies need to clearly integrate DAD hazards. The history of tectonically induced DAD at Mount Besar reflects that DAD phenomena can cause serious damage to multiple sub-districts, therefore it is very urgent to include it.

CONCLUSION

The collapse of Mount Besar's walls resulted in the formation of Debris Avalanche Deposits (DAD) characterized by the creation of hummocky hills. The main geomorphometric characteristics of DAD and hummocky hills were identified from DEMNAS data using several variables (shape, size, area, distance to source, direction, elongation ratio, displacement angle, relative height, H/L ratio, number of hummocks, and density of hummocks).

The obtained results showed that tectonically triggered DADs, such as the DAD observed at Mount Besar, had larger hummock sizes and lower hummock number densities compared to eruption-triggered DADs. The absence of magmatic fragmentation may explain this phenomenon, as the lack of gas pressure inhibited the fragmentation of hummocks into smaller components. The results also showed that despite the absence of gas pressure in tectonically triggered DADs, the coverage area and maximum runout distance of each occurrence were comparable to those of eruption-triggered DADs. The findings suggest that both types posed substantial hazards to human settlements. It is important to understand that the identification of volcanic threats in the study of KRB (Disaster-Prone Areas) has not yet included the potential hazard of DAD. Therefore, DAD analysis becomes an essential part of the disaster risk reduction (DRR) studies on volcanoes, considering the reach of deposits that can extend 20-30 km from the mountain's peak. Although the results that would be obtained may not be suitable for public dissemination, each observation is highly valuable for informed decision-making and the development of effective mitigation strategies.

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AUTHORS CONTRIBUTION

APR- conceptualized and led the study project, performed all analysis, interpreted and curated the data, visualized all figures, and wrote the manuscript. LRS and KWW- performed all analysis, interpreted and curated the data, visualized all figures, and wrote the manuscript. IS, MNM, and MAS- supervised the study and validated the interpretation. All authors contributed to writing-editing-reviewing the manuscript.

CONFLICT OF INTEREST

The authors declare there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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