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Morphometric Analysis and Stress Orientation of Kaba, Daun, and Hulupalik Volcanoes, Bengkulu Province, Indonesia

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Abstract

Bengkulu Province is an area in Sumatra that is surrounded by Bukit Barisan. This research aims to provide information about the horizontal stress orientation data σ_{Hmaxs} on the volcanoes of Kaba, Bukit Daun, and Hulupalik, as well as added information about the slope data in the research location that underlies the volcanic arc on the Sumatra Fault. We conducted this research by mapping the morphology of the mountain and determining the straight line of stress orientation, this research uses DEMNAS data of Geospatial Information Agency (BIG). At Kaba Mountain, the maximum stress azimuth angle (σ_{Hmaxs}) is orientated towards 62° to the East-Northeast/ENE. The direction of plate movement that gives horizontal stress on Kaba volcano is from the east-northeast / ENE and west-southwest / WSW. On Mount Hulupalik determining the azimuth angle of the orientation of the Horizontal stress σ_{Hmaxs}, the azimuth is towards NNE29°. On Mount Daun where the azimuth angle itself is NNE26°. From the azimuth direction of the horizontal stress (σ_{Hmaxs}) of Mount Daun and Hulupalik, the plate stress moves from South Southwest/SSW and North Northeast/NNE. Regardless of the direction of horizontal stress/σ_{Hmaxs} of each mountain, it is influenced by several factors that can cause different stress directions.

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INTRODUCTION

Indonesia is located in the path of four tectonic plates, namely the Indo-Australian Plate, Eurasian Plate, Pacific Plate, and Philippine Sea Plate, the country is highly vulnerable to earthquakes (Ardiansyah & Gustiawan, 2018). Bengkulu Province is an area in Sumatra surrounded by Bukit Barisan, extending from the western part of Sumatra. The formation of the Bukit Barisan is due to the subduction pressure of the Indo-Australian tectonic plate on the Eurasian plate and is named the volcanic arc. The result of this subduction pressure is an elongated fault called the Sumatra fault (Sihombing et al., 2024). Volcanoes have the highest accumulation rate of surface geological features (Pyle, 1997). Volcanoes formed by monogenetic volcanism have a volume of less than 1 km^3 and erupt through one or more small continuous eruptions or many small intermittent eruptions fed by one or more small-volume magma pools (Benamrane et al., 2022). Monogenetic volcanoes around the world have various types of depositional features, such as layers of pyroclastic deposits.

Hot compressible fluid flowing between cold elastic walls is a propagating dike (Rivalta et al., 2015). Volcanic dikes are usually vertical or inclined and form after magma flows through fissures or cracks in the lower layers of rock, then cools and solidifies into hard rock. The effect of dike propagation has been the subject of many studies by researchers and geophysicists, most of which relate to dike propagation away from the surface (Gaffney & Damjanac, 2006). In the study Gaffney (2007), when rising magma passes through the crustal layers in the dike, various rock types that have different geometric configurations are encountered. They found that when magma rising in a dike crosses a narrow ridge or geomorphological trend, the topography responds to the lateral variation of the confined pressure so that it is diverted to the surrounding lowlands before the magma reaches the high topographic surface. Gudmundsson & Philipp (2006) discussed how strong contrasting coatings affect the mechanical properties of dike propagation. They found that dikes may not penetrate thick, low-stiffness layers that are overlapped by thicker, stiffer layers. In addition, if dikes protrude from a magma source through several thin, rigid and regular layers that overlap, the dike trajectory will turn downward rather than propagate in a purely vertical direction. The change in the local stress field caused by the difference in stiffness of the layers causes this effect.

The method of analyzing the dike area, which is formed and located at the crustal-scale extensional cracks that form the horizontal dike stress direction (Figure 1), has some advantages of this method to estimate the horizontal stress orientation/σ_{Hmaxs}: (1) there is no need to utilize earthquake property data, (2) the technique can be applied over a wide range of spatial and temporal scales (Delorey et al., 2021). Using this method can produce the orientation of the main tectonic stresses (σ_{Hmaxs}) derived from the volcanic morphology.

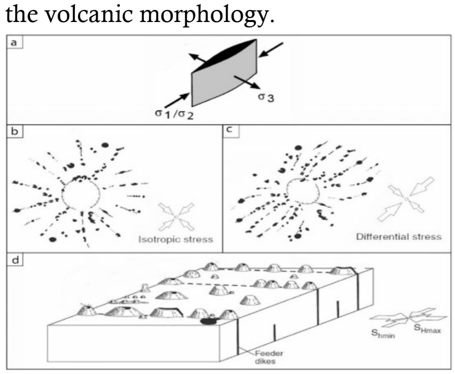

Figure 1. The principle in the figure is the basis for dike placement as well as the orientation of the main stress, a) Model concept of the stress axis relative to the stress. b) Radial dike subjected to a uniform stress field. c) Describe a dike that deforms due to horizontal pressure differences so that embankments and cracks are aligned. d) Circular or elongated alignment of volcanic eruptions parallel to the underground fracture traces, which can help locate vent alignments on a regional scale (Marliyani et al., 2020).

Dikes are positioned sub-vertically according to the medium or maximum main voltage (Figure 1). It is expected that this path can occur in areas that do not have too significant widening, so it can be applied to monogenetic volcanoes and monogenetic fields. Nakamura (1977) conducted previous research on the alignment of volcanic lines as a measure of the main stress that can map cracks, especially based on the position of the hole, connecting the center point of the hole in a circular or elongated shape. Monogenetic volcanoes are characterized by relatively small landscapes and simple mountain ranges. The types of monogenetic volcanoes usually vary from scoria cones, tuff cones, tuff rings, and maars (Gaffney et al., 2007). Polygenetic volcanoes that erupt are mostly considered monogenetic. The pressures generated by local magma pressure sources interact with very rigid rheological boundaries and with physical irregularities such as rock layers and faults (Tibaldi, 2015). A manifestation of this eruption is the surface radial dikes that appear near the main channel of the volcano. Ideally, such dikes are radially orientated, indicating that magmatic pressure is dominant in the main channel over other pressures or that other pressures are not dominant in the desired horizontal direction. Radial dikes are very sensitive to regional magmatic and tectonic stresses, so they may be subject to gravity loads or volcanic emergencies, especially volcanoes and large landforms (Acocella & Neri, 2009).

Convergent boundaries at subduction zones, faults on the arc line often experience strike-slip dominated movement, with the largest and lowest principal stresses ($\sigma1$ and $\sigma3$) being horizontal, as opposed to fault zones where $\sigma3$ is vertical (Nakamura, 1977). Consequently, the situation in the subduction zone favors the ascent of magma along vertical dikes parallel to the direction of maximum horizontal stress (σ_{Hmaxs}) (Nakamura & Uyeda, 1980). The ellipticity ratio of the crater, the long axis of the crater, and the orientation of the rupture are some of the geometry parameters of the cone that can be related to the geometry of the inner structure of the volcano (Corazzato & Tibaldi, 2006; Ferrari et al., 1991).

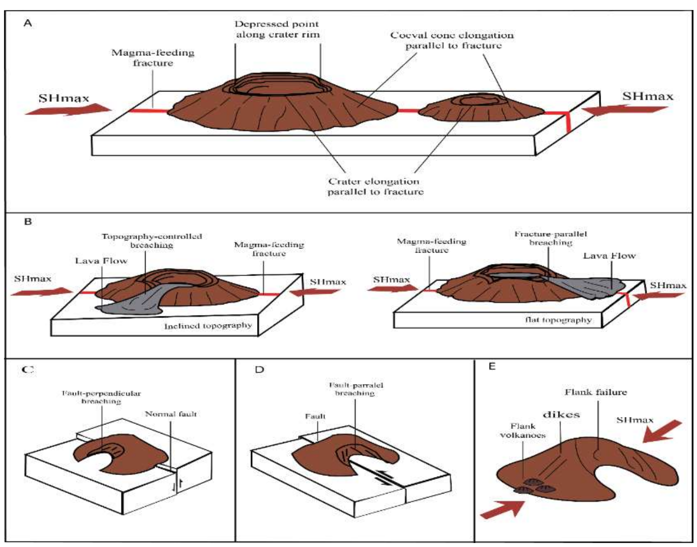

Figure 2. Sketches of morphometric characteristics of measured pyroclastic cones associated with faults. (A) The alignment of the fault crater extenders, crater rim pressure points, and maximum horizontal stress (σ_{Hmaxs}) orientated aligned cones that are on the same magma fracture line. (B) The illustration of breakthrough is affected by topography, where the topographic slope (N10°), topography controls the fault orientation regardless of the fracture geometry. Defined direction angle is horizontal straight as clockwise from north. (C) Normal faults that are in the up and down direction. (D) Faults undergoing parallel sliding or sliding, regardless of the fault type (may be strike-slip or dip-slip). (E) The collapse on the flank of the mountain is a lava breakthrough, which is perpendicular to the maximum horizontal stress. (Marliyani et al., 2020).

Figure 2 describes a sketch of the morphometry and its relation to the direction of maximum horizontal stress (σ_{Hmaxs}). The orientation of the breach crater is measured on polygenetic and monogenetic cones. The breach azimuth is the slope direction of the dividing line of the collapsed amphitheatre (Figure 2). For consistency, the azimuth is rotated clockwise from north. Cracks are usually horseshoe-like basin, often associated with lava flows (Figure 2). Breaches (Figure 2b) are generally associated with the weakest side of the cone or the presence of a decreasing substrate; the dip of the underlying fault may also be a factor (Tibaldi, 1995). As a result, the breakout direction may be the same as the orientation of the largest horizontal principal stress or it may be different (Tibaldi, 1995). Therefore, unless the cone lies on an immersed surface, the fault is usually parallel (Figure 2B right), or perpendicular (Figure 2C) to the shape of the magma-filled fracture. If the substrate is dipping, its dispersion will be limited to the downhill part of the slope, increasing the likelihood of slope collapse (Wooller et al., 2004).

For many scientific questions, the stress state of the Earth's crust is critical. In recent decades, a number of techniques have been developed to determine the current orientation of the maximum compressive horizontal stresses (σ_{Hmaxs}) in the Earth's crust (Reiter, 2020). It has been concluded that the forces driving plate motion also govern the orientation of S_{Hmaxs} on a regional scale. S_{Hmaxs} are used to assist and indicate the direction of horizontal stress. This is true in many regions around the world, according to S_{Hmaxs} orientation data collected by the World Stress Map (WSM) project (Heidbach et al., 2016). With the ever-increasing amount of data, it has become possible to identify fault stress directions in several mountain regions around the world (Reiter, 2020).

In this study, we mapped monogenetic volcanoes and parasitic vents associated with a polygenetic volcano, analysed morphological data and analysed the crater to determine the orientation of the dike, the purpose of determining the orientation to recognise spatial stress. This study aims to provide information about the orientation data of σ_{Hmaxs} stress at the Kaba, Bukit Daun, and Bukit Hulupalik volcanoes, and we add information about the slope data at the study site underlying the volcanic arc on the Sumatra fault.

METHOD

We conducted this research by mapping the morphology of the mountain and determining the direction and straight line of stress orientation, as well as the distribution of small mountains around Kaba, Daun, and Hulupalik Volcanoes. To identify the trend of the underlying cracks, we used the Geospatial Information Agency (BIG) DEMNAS data. The parameters we documented were: (1) monogenetic cone distribution; (2) volcanic crater diameter; (3) orientation of crater fragment direction; (4) fault stress direction. Our research focuses on several monogenetic volcanoes in Bengkulu province.

Morphometry is a statistical and analytical method, which consists of measuring various morphological parameters of volcanoes to identify: the degree of erosion and the relative age of volcanoes within a region (Grosse et al., 2012; Hooper & Sheridan, 1998; Kereszturi & Németh, 2016) the geodynamic context (Fornaciai et al., 2012; Tibaldi, 1995; Uslular et al., 2021) the implied eruption style (Bemis & Ferencz, 2017; Favalli et al., 2009); the evolution of the volcanic landscape the most likely eruption type in a region and the assessment. The results of our morphometric data are presented in (Table 1).

The location of this research is Gunung Kaba, which is located on the border of Rejang Lebong and Kepahiang Regencies at the coordinates of 3°33‘S, and 102°06’E, and Gunung Daun and Hulupalik which are at the coordinates of 3°23‘S and 102°22’E which are administratively located on the border of Rejang Lebong, Lebong, and North Bengkulu Regencies.

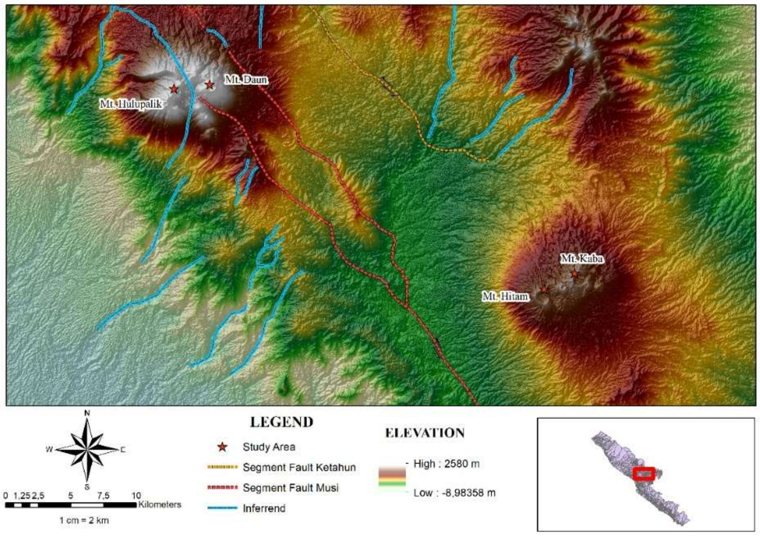

Figure 3. Location Map of the Kaba, Daun and Hulupalik Mountain Research Area.

Numerous small monogenetic cones or mountains formed along fissures produced by subsurface dikes (Nakamura, 1977). Mapping the linear arrangement of the many monogenetic volcanic vents can allow the trend of the underlying cracks/dikes to be estimated. This allows the direction of the maximum horizontal stress during a volcanic eruption to be known. Consequently, the minimum horizontal stress is directed perpendicular to the maximum stress, and the maximum horizontal stress occurs in the same direction as the alignment and elongation. (Figure 1 and Figure 2). In this research, we manually identified the stress (σ_{Hmaxs})/S_{Hmaxs} straight line, which is formed by several monogenetic volcanoes that are several kilometres to tens of kilometres apart from each other. In general, the ages of the volcanoes are different from each other and have similar surface roughness.

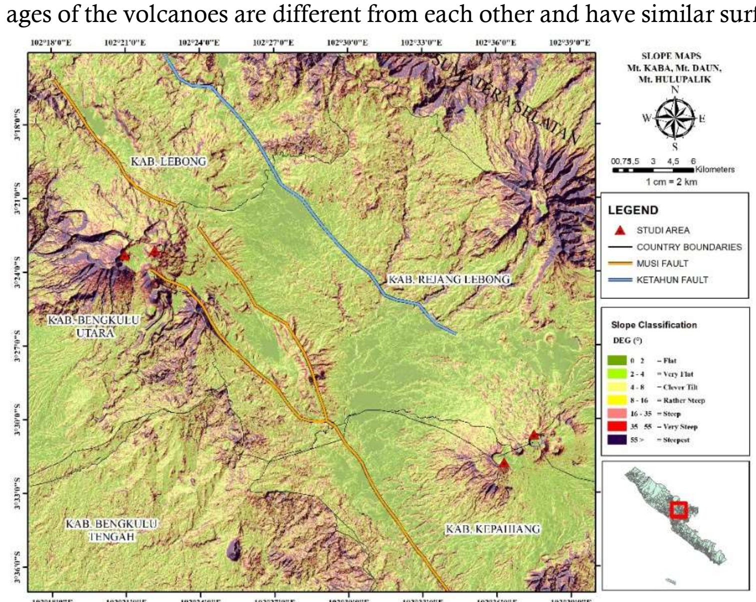

Figure 4. Map of slope in the research study area, according to Van Zuidam 1983 classification

We also measured the slope of the study area to add data to support our research. We refer to Van Zuidam (1983) for slope classification, where areas indexed 0-2° (dark green) are flat areas, while areas with a slope of 55°>> are steep areas or ravines.

At polygenic pyroclastic volcanoes, recent volcanic products often overlie the bases of neighboring monogenic volcanoes or flank the cone, preventing the measurement of important parameters needed to determine the geometry of magma-flow fractures. However, in crater regions, lava or erupted volcanic products do not cover the crater, and its shape may be closer to the volcano than to the base of the cone (Tibaldi, 1995). For Scoria cones, Analyse parameters related to the configuration of the magma conduction system, such as measuring the ellipticity and elongation axes of the crater, as well as the dividing line through the crater. To evaluate the region of maximum compressive stresses, it is necessary to analyze the dominant directions of all these indices.

In this study, we measured the ellipticity (dmin/dmax), the ratio of minimum and maximum crater diameters, for craters with fairly continuous rims, breaching bisectors, coeval conealignment breaching (Figure 5) and the results of the measurement data are presented in Table 1. The crater that underwent extensive breaching in (Figure 2) was not included in the measurements.

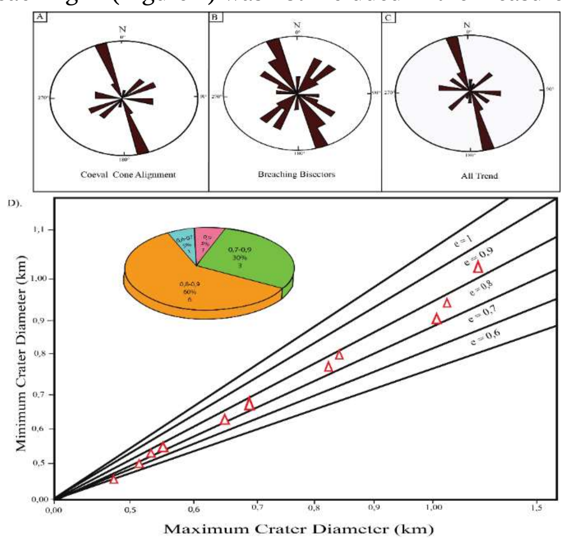

Figure 5. Rose diagrams associated with trends (a-c): (a) maximum crater elongation axis; (b) cone crater alignment; (c) all trends measured in this study; (d) The ellipticity graph (the ratio of minimum and maximum crater diameters) of monogenetic and polygenetic volcanic craters has a relatively moderate percentage, and most craters are close to circular or almost circular with a ratio between up to, the percentage of elliptical shapes is only 60% of all observed mountains. And the percentage that is close to circular shape is 5%. (Benamrane et al., 2022; Marliyani et al., 2020)

All trends from the measurements are illustrated on the rose diagram (Figure 5), where the measurement data from the trends illustrated from the rose diagram and volcano morphometry are presented in Table 1. In table 1. is the measurement result of the morphometry of the volcano that we made the centre of this research. We get crater diameter data from Google Earth by plotting the crater area of each mountain. In the Breaching bisectors data, we measure by calculating the direction of the breakthrough of the lava coming out of the volcano. And on the Coeval cone Alignment, we get it by drawing a straight line azimuth from the direction of horizontal stress ($\sigma Hmaxs$) / SHmaxs in a clockwise direction whose centre is North.

Geological documentation of the volcano from the field focused on the scoria cone complex each considered in the context of geoeducation and geologically preserved features of the volcano (Lakroud et al., 2019).

Table 1. Morphometric data of volcanoes in the Sumatra volcanic arc.

Mountain Name	Figure	Max Crater Diameter (KM)	Min Crater Diameter (KM)	Crater Ellipticity Ration (Min/Max Diameter)	Breaching bisectors (Deg)	Coeval Cone Alignment Breaching (Deg)
Kaba	6	Mg	1.18	0.94	0.797	-
Kaba flank	6	Mg	0.45	0.4	0.889	-
Biring	6	Mg	0.41	0.37	0.902	-
Hitam	6	Mg	1.1	0.98	0.891	70
Gajah	6	Mg	0.33	0.26	0.788	-
Daun	7	Mg	0.73	0.6	0.822	45
Daun flank 1	7	Mg	0.52	0.37	0.712	-
Daun flank 2	7	Mg	0.55	0.38	0.691	-
Daun flank 3	7	Mg	0.58	0.57	0.829	160
Hulupalik	7	Mg	1.02	0.88	0.863	60

RESULTS AND DISCUSSION

Some of the volcanoes in this study are monogenetic marr-type volcanoes. Mountains such as Kaba Volcano, Daun Volcano, and Hulupalik Volcano are located in the Musi and Ketahun fault zones. Some of these volcanoes play an important role in the Volcanic Arc of Sumatra.

In a similar study by Marliyani (2020) here, we used morphometric trend data of the volcano to infer the orientation of the maximum and minimum horizontal stress at the time of placement. In general, a volcano is defined as a volcano fed by a dike that opens perpendicular to the maximum horizontal compressive stress. Feeder dikes can not only indicate the orientation of regional tectonic stresses at the time of dyke intrusion, but also the orientation of stresses during the formation of previous faults. This is especially likely if the dike intrusion intersects the fault during its ascent. This is especially the case if the dike intrusion intersects a fault during its rise (Gudmundsson, 2006; Valentine & Krogh, 2006). Crater extension is usually aligned with the underlying magma-feeding fractures (Figures 1 & 2). However, the information obtained about the alignment of the volcanic center is uncertain, especially about how the breakout points (holes) in the pyroclastic cone are located. Analysis of pyroclastic cone craters can remove this uncertainty. Crater geometry may reflect the shape of the dikes because the crater region is not typically covered by freshly erupted lava and volcanic products. (Tibaldi, 1995). In addition, the irregularity of the crater rim morphology, indicated by the presence of raised and depressed points along the crater rim, is also considered parallel (Figures 6 & 7) with the feeding-fracture trend (Corazzato & Tibaldi, 2006; Tibaldi, 1995).

At Kaba Mountain, we think the most likely suspect is a strike-slip fault because it is close to the Musi and Ketahun fault segments. It can be seen in the figure (Figure 6) that the azimuth angle of the maximum stress (σ_{Hmaxs}) is oriented straight 62° to the East-Northeast/ENE. The direction of the horizontal main stress (σ_{Hmaxs}) can be seen, that the azimuth line is parallel to some hills around Kaba volcano, so we argue that the direction of plate movement that horizontal stresses Kaba volcano is from the east-northeast/ENE and west-southwest/WSW. In accordance with the explanation of Heidbach (2016), where the stress regime is the relationship of the main stress σ_{Hmax}s/S_{Hmaxs} with the type of fault (stike-slip fault) so that, the horizontal stress line σ_{Hmaxs} will split from the direction of fault movement. The movement of the Indo-Australian Plate infiltrating beneath the Eurasian Plate causes the Sumatra Fault to become 19 sections, which makes it active, one of which is the Musi Bengkulu Segment (Hadi & Brotopuspito, 2016).

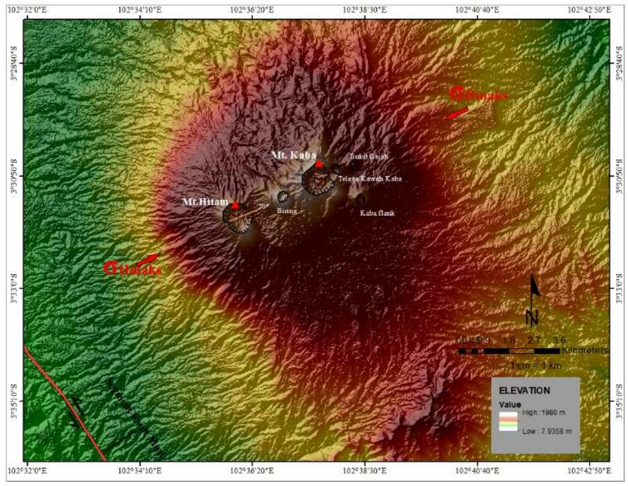

Figure 6. Map of Kaba and Hitam Mountain volcanoes located in Rejang Lebong and Kepahiang regencies, shows an example of tectonic cone alignment. The orientation corresponds to the coincident trend of the cone alignment and is a good indicator of the orientation σ_{Hmaxs} (Red arrow).

The morphometric indicators measured on each cone are presented in table 1. Some volcanoes are very complex and have easily recognisable craters. Crater axes have maximum diameter dimensions of ±330 m to 1.18 km, and minimum dimensions of ±260 m to 980 m (Table 1. Figure 5d). Most of the craters have a near-circular shape or circular craters, originating from monogenetic volcanoes where crater flattening can be an indicator of magma path geometry (Marliyani et al., 2020). Some monogenetic craters are seen on Mount Kaba, Mount Hitam and Mount Daun (Figures 6 & 7). As shown on the regional geological map, these alignments are not associated with lithological data; however, they may be associated with normal faulting (Marliyani et al., 2020).

We also measured the direction of the crater and plotted it on a diagram rose (figure 5) and the results of the measurements are in table 1. It can be seen that the crater of Mount Hulupalik is towards N60°W±30°. On Mount Daun 3 the crater is also orientated towards S160°E±30° and on Mount Daun the sulphur crater is orientated towards NE45° (Figure 8).

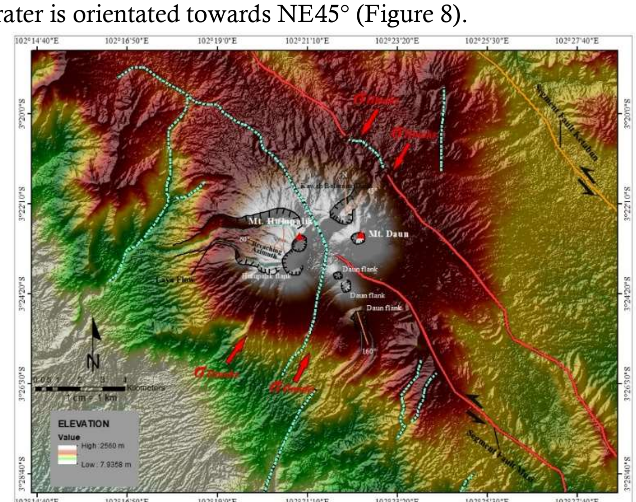

Figure 7. Map of Gunung Daun and Hulupalik in Rejang Lebong, Lebong and North Bengkulu. Where the orientation that can be seen from the monogenetic cone shows the Maximum horizontal stress or σHmaxs (red arrow).

In (Figure 7) we also determine the azimuth angle of the Horizontal stress orientation σ_{Hmax}, where on Mount Hulupalik follows the pattern (Figure 2b left) where the direction of the azimuth angle is NNE29°. Mount Daun follows the pattern (Figure 2a) where the azimuth angle itself is NNE26°. From the azimuth of the horizontal stress (σ_{Hmaxs}) of Daun and Hulupalik volcanoes, we think that the plate stress moves from South Southwest/SSW and North Northeast/NNE. Mount Daun volcanism occurs between the ends of two Sumatra fault segments, the Ketahun and Musi segments. These two segments are strike-slip faults (Ikhwan, 2020). In situations where the volcano is underlain by a horizontal fault structure known as a strike-slip fault, cracks tend to open at an acute angle to the horizontal maximum principal stress σ_{Hmaxs} (Lagmay et al., 2000; Lagmay & Valdivia, 2006).

We also measured the direction of the crater and plotted it on the rose diagram (Figure 5). It can be seen that the crater of Mount Hulupalik is towards N60°W±30°. On Mount Daun 3 the crater is also orientated towards S160°E°30° and on Mount Daun sulfur crater is orientated towards NE45° (Figure 7). Breakthroughs are one of the most obvious morphological features we examined in our study area.

We see Quaternary volcanoes of different ages, which suggests that the stress orientation conditions may have changed over time, but in our study area, we believe that the stress orientation during the Quaternary period did not undergo significant changes (Figure 8).

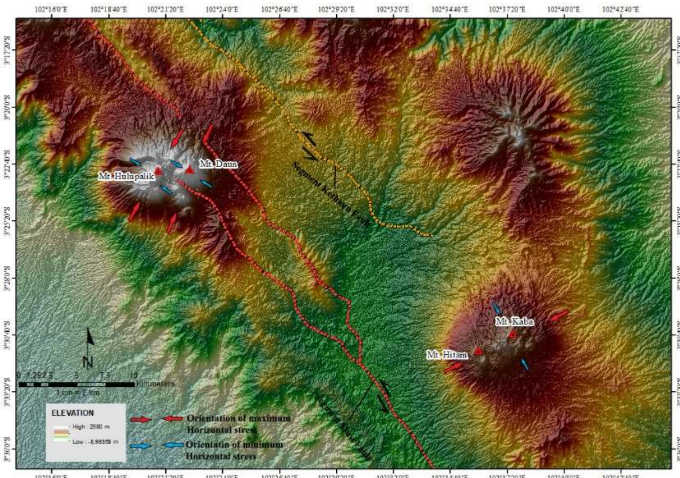

Figure 8. Map of main stress orientation distribution on active volcanoes Kaba, Daun & Hulupalik hills.

We also display the results of the main stress distribution (S_{Hmaxs} and S_{Hmins}) of the study area. It is found that the stress direction of each volcano is slightly different because it is influenced by several factors, including faulting and geomorphology. Faults are most likely to be orientated perpendicularly and obliquely if the underlying fault is a horizontal or normal fault (Tibaldi et al., 2008)

CONCLUSION

We present morphometric analyses of volcanoes in the volcanic region of Sumatra arc and their Its usefulness in indirectly assessing the geometry of subsurface magma flow structures, that may be hidden by recently erupted material. In the study area that we observed, the direction of orientation stress is almost the same towards the Northeast/NE. At Kaba and Bukit Hitam volcanoes which show the direction of the S_{Hmaxs} azimuth 62°ENE / East-Northeast, then on Mount Daun shows the direction of the S_{Hmaxs} azimuth 26° NNE, then on Mount Hulupalik the S_{Hmaxs} azimuth is 29° to the

NE. Regardless of the direction of the horizontal stress/σ_{Hmaxs} of each mountain, there are several factors that can cause the stress direction to be different; for example, faults that may be different in nature and the morphology of the mountains.

We estimate the mountain we observed to be quaternary in age based on its recent activity, published geological maps and Geomorphological features. The analyses from this research can also add to the data set and clarify the data available in the World Stress Map (WSM). Quaternary morphometric analyses of monogenetic and polygenetic volcanoes, as well as volcanic areas, which were investigated in this study, show that the methods used in this study can infer and determine the direction of current stress orientation. This method can also provide insight into the complex inter-relationships between volcanoes and faults, and can provide new data to complement other information using other methods.

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