Structural Geology and Volcanism in Hululais Geothermal Area, Bengkulu, Indonesia

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Abstract. Hululais Prospect in Rejang Lebong, Bengkulu is one of the geothermal fields developed by Pertamina Geothermal Energy. The field is situated within the Bukit Barisan Mountain Range, an NW-SE volcanic arc of Sumatra, and located 8 km western from Musi Segment of Sumatra Fault Zone Zone. Based on field data from geological mapping, remote sensing analyses and borehole data these regional structures influence the occurrence of the NW-SE volcanic axis in Hululais Volcanic Complex (HVC). The Hululais Volcanic Complex (HVC) itself is a Quaternary volcanic complex which comprised of six crown units namely: (Bukit Resam, Suban Agung, Bukit Beriti, Bukit Gedang, Bukit Lumut and Bukit Pabuar) with its associated Hummocks and primary/secondary deposits. These NW-SE distributed of Subang Agung, Bukit Beriti and Bukit Gedang volcanic crowns can be grouped as Hululais Brigade. The manifestations distribution in Hululais also depict the influence of the NW-SE geological structure and its volcanic activity. This is validated by the presence of geothermal manifestation such as fumarole in the central of Hululais Volcanic Complex and hot spring in the medial – distal part of the field.

1. Introduction

The Hululais field in Rejang Lebong, Bengkulu Province, Indonesia is one of the geothermal working areas developed by Pertamina Geothermal Energy (PGE). The Hululais field can be reached by a 5-6 hours’ drive towards the mountainous Barisan Range in the North of Bengkulu City (Figure 1). Due to its location that is close to the Sumatran Fault Zone (SFZ), which is a segmented major NW-SE strike-slip fault along the Sumatra Island, the Hululais’ structural development and volcanism are influenced by the SFZ activity. These two factors play a role in the existence of geothermal system beneath the Hululais field, which is shown by the occurrence of fumarole, solfataras, mud pool, hot springs, and surface rock alteration.

Geoscience studies in Hululais and the surrounding areas have been carried out by Pertamina and other institutions since 1992. The earliest publication focuses on the regional geological mapping of Bengkulu on a scale of 1:100,000 [1]. A more detailed geological mapping of the area was carried out internally [2] which led to the geothermal resource assessment of Hululais. Since then, various several geoscience publications have been made, although the structural and volcanism aspect in Hululais need to be discussed in detail.
This study integrated the outcrops data from geological mapping, interpreted fractures from borehole image logging, and remote sensing analysis to reveal the relationship between the structural geology and volcanism in Hululais. These two topics will be discussed in this paper with its relationship being concluded at the end of the paper.

Figure 1. Location map of the study area World Topographic Map [3].

2. Structural Geology
Sumatra Island is influenced by the convergence of two plates, the northward movement of the Indian Plate beneath the Eurasian Plate. The convergence of these two plates is accommodated by an oblique subduction. The result of the oblique subduction is depicted on the surface by the NW-SE dextral strike-slip of the Sumatra Fault Zone (SFZ). The fault zone forms the NW-SE Barisan Range of Sumatra Island that separates the back-arc basin to the east and forearc basin to the west (Figure 2).

The length of the Sumatra Fault Zone is 1900 km with 20 major segmentations separated mostly by valleys and lakes that form as dilational jogs. The dilational jogs length vary from about 35 km to 200 km [4]. The movement of the SFZ provides pathways for magma that is a result from partial melting of the product of the oblique subduction. Therefore, most major volcanoes on Sumatra Island are located parallel to the SFZ in close proximity to the fault zone.
2.1. Geologic structure of Hululais

According to Figure 2, the Hululais area is bounded by two dextral strike-slip faults of Ketahun Segment to the north and Musi Segment to the south. These two segments are part of the Sumatra Fault Zone. The Musi Segment lies 70 km to the Air Keruh pull-apart basin in the southeast and has slip rate of 11 mm/yr [6]. It is also interpreted to continue beneath the Hululais and Bukit Lumut mountain. Ketahun Segment has 85 km in length and at the southern tip of the segment, it ends at the 6-8 km wide dilatational step over onto the Musi Segment [6]. As a result of the movement of two right stepping dextral strike-slip faults, the overlap area is the extensional overstep that is known as the pull-apart basin. [7] interpreted that these two segments exist within the study area based on the recorded microearthquake data (Figure 3).

**Figure 2.** Tectonic map of Sumatra showing the relative location of Hululais to the clustered volcanoes within the Sumatra Fault Zone (SFZ) modified [5]. Hululais location is at the overlap area of the right-stepping faults, in between Ketahun Segment and Musi Segment of Sumatra Fault Zone [6].

**Figure 3.** Microearthquake epicenter distribution on surface (left) and its hypocenter distribution on vertical section. Microearthquake data cluster depict a fault zone of Ketahun and Musi Segment [8].
The geologic structure of Hululais was analysed from various surface and subsurface data which included remote sensing, surface measurements (extension fracture, shear fracture, sheeting joint, and possible fault surfaces), gravity, fracture orientation from borehole log data and feed zone depth were integrated with the lineament analysis.

Hundreds of fracture orientation in each well and about 329 surface structures data were obtained and shows in (Figure 4). Those structures are plotted on the stereonet and indicates that there are at least three structure orientations in Hululais:

1. NNW-SSE or relative N-S
2. NE-SW
3. NW-SE

The location where the data is obtained is influenced by nearby structures. It is observed that the orientation of the fracture from the borehole log data is mostly parallel to the nearby proven faults. The proven faults itself are responsible for lineaments and fracture orientations and alignment viewed from the borehole image log and also coincides with the occurrence of the feed zone in the well. The NNW-SSE to N-S structure and NW-SE structure are also responsible for the occurrence of surface manifestations in Hululais. The two permeable structure trends observed in Hululais has resulted from the movement of two major NW-SE dextral strike-slip faults that have N-S compressional stress creating a N-S extensional structure and NW-SE major faults.

**Figure 4.** Geologic structure map of Hululais showing three main structure orientations based on open fracture orientation from borehole image log (blue stereonet, left and bottom section) and field measurements (Sheeting joint, fault, extensional fracture and shear fracture). A contoured plot of 329 structures from field measurements with its dominant structure direction are shown on the right (bottom). A transparent rainbow color in the background are the residual gravity that is used to delineate lineaments besides the remote sensing data. Nevertheless, nearby geologic structures influence the recorded data in specific location in wells and also on surface.
As the surface measurements are mostly located near and within the pull-apart basin (red dots on Figure 4), the structures in that area are controlled by the formation of the pull-apart basin. The plot of all surface fractures shows that the NE-SW shear fracture with its conjugate and the NE-SW extension fracture follows the structural model of a pull-apart basin (Figure 5, lower right). On the other hand, the NE-SW extension fractures are the product from E-W faults. These structures are very localized as the data was obtained from the outcrop in Sungai Air Kotok.

Based on the shape and the orientation of the structures, the pull-apart basin has rhomboidal to stretched geometry with a length-to-width ratio of 3:1 depicted in Figure 5. This is in agreement with the average geometry of pull-apart basins that are described by their length-to-width ratio of 3:1 [9] assume that the geometry of the pull-apart basin is related to its geometrical stages due to fault growth. It is interpreted that the pull-apart basin stages in the study area are more mature than the other lazy S-Z shaped (spindle) pull-apart basins in other areas of Sumatra.

![Figure 5. Simplified pull apart basin geometry in overlap area of both dextral right stepping faults of Musi Segment and Ketahun Segment (left) shows length-to-width ratio of 3:1. The pull apart basin on the map has the rhomboidal to stretched shape that reflects the geometry stages (upper right). Structures from field measurement in the study area is influenced by forces acted on pull apart basin (bottom right) as its data mainly located near and within the basin.](image)

3. Volcanism of Hululais
Volcanostatigraphy of Hululais follows the guidelines on [10, 11] where each unit is divided based on the volcanic source, description and the genesis (Figure 6). The sequence of each unit is determined directly from observation in the field and indirectly from remote sensing analysis and also from previous researches [11, 12, 13, 14, 15].

Crown is the basic unit of volcano stratigraphy which comprised of rocks/deposits from one eruption point or more, in other words, the crown unit is a terminology used for a single composite volcanic body that is constructed from various volcanic activities or stages [16]. In Hululais, there are 6 Crown units varying from old to young, Bukit Resam, Suban Agung, Bukit Beriti, Bukit Gedang, Bukit Lumut and Bukit Pabuar.
Hummock is the eruptive material of a particular Crown on its main crater or the flank and mostly composed by homogeneous volcanic rock/deposit (eg. Parasitic cone, lava cone, lava dome, etc). Hummock acts as the subdivision of the Crown unit but a Crown does not always have a Hummock [15]. For instance, the Bukit Gedang Crown unit has two distinct hummocks that can be differentiated based on the morphology and its deposits, the Bukit Gedang Muda Hummock, and Bukit Gedang Tua hummock.

Each volcanostratigraphy unit is divided into primary rocks/deposits and secondary rocks/deposits. The primary product is related to volcanism, which is either an explosive or effusive product, while the secondary product is the deposit from the reworked primary product. In Hululais, the primary deposits are comprised of non- epiclastic/pyroclastic deposit, debris avalanche and alluvial. Debris avalanche deposits are characterized by semi-consolidated to an unconsolidated deposit of boulder size from various lithology within the finer altered matrix. These recent debris-avalanche deposits are considered as the secondary deposit from the crater of Bukit Suban Agung, while the ancient debris-avalanche deposits are related to the primary process of Bukit Suban Agung volcanism.

The Suban Agung volcanism followed by Bukit Beriti and Bukit Gedang volcanism are three main volcanisms that directly affect the geothermal system of Hululais that covers 70-75% of the surface within the area. Based on remote sensing and aerial photography, the rim of Bukit Suban Agung has an amphitheater shape that opens to the NE with a size of 2.5 kilometers in diameter. The rim with a diameter of more than 2 km can be categorized as a caldera [15]. Based on that definition, the rim of Suban Agung can be named as Suban Agung Caldera. It is interpreted that Suban Agung Caldera is the product of Suban Agung Volcanoes that collapsed and produced debris avalanches during the Pleistocene Period. The morphologic signatures of collapse are characterized by a collapsed amphitheater and Hummock topography on the avalanche deposit. The Hummock topography of the ancient debris avalanche product is located on the northern part of Hululais, approximately 8-10 km
from the rim of Suban Agung (Sadp 1, Sadp 2, Amap and Cmap?). In several outcrops, the Hummock topography is comprised of cataclastic andesite. Rounded pumice fragments and rounded andesite fragments are found in the northern part of the area that is probably from the reworked ignimbrite. This reworked ignimbrite deposit may reflect there was a huge caldera explosion.

Based on the outcrops, the morphology of the amphitheater rim and the Hummock topography on the surface, the collapse of old Suban Agung could be referred to the 1980’s Mt. Saint Helens eruption (Figure 7). Although the deposit distribution either the directed blast or the debris avalanche of St. Helens could reach > 20 km [16]. Suban Agung product was found <10 km from the eruption centre.

Bukit Beriti volcanism and Bukit Gedang volcanism occurred after the Suban Agung volcanism. It is shown on the surface that Bukit Beriti and Bukit Gedang grows on the body of Suban Agung. These two latter volcanisms deposited their product covering the previous Suban Agung Lava and Pyroclastic deposit (Sadp). Based on the texture on its surface, it is interpreted that Bukit Beriti volcanism and its associated product are relatively younger than the Bukit Gedang deposits. These three Crowns can be grouped as Hululais Brigade as it is comprised of two or more volcanic crowns and related to a caldera formation.

Figure 7. Mount. St. Helens topography [17] the deposit from the eruption of Mount. St. Helens [18] and the deposit distribution area from Bezymianny eruption in 1956 and Mount St. Helens eruption in 1980 [16].

Figure 8 shows the volcanism history of Hululais and Surrounding area could be illustrated as follows:

1. During the construction phase of Suban Agung, the volcanoes comprised of andesite lava and pyroclastic with an elevation of approximately 3,000 above msl. The Musi Segment Fault as a part of Great Sumatran Fault (GSF) provides the conduit for magma to emerge from magma chamber.
2. As the GSF is active, it may trigger a potential slope failure due to frequent earthquakes.
3. The destruction phase of Suban Agung might be triggered by a lava dome that is plugged at the top of the crater. The eruption along with a potential slope failure on the volcano body is favourable to have a debris avalanche and a collapsed crater. The ejected material could reach to more than 8 km.
4. The area has active geologic structures that provides pathways for the magma to emerge, the paracitic cone of Bukit Beriti and Bukit Gedang Tua was formed on both flanks. The Bukit Beriti and Bukit Gedang products cover to the NE and N from its eruption centre.
5. The volcanism continues to form later Bukit Beriti hummock units and Bukit Gedang Muda lava dome on top of the eruption centre.
6. Recently, the heat below Suban Agung has become the heat source for the Hululais geothermal system. The active geologic structures from the Musi Segment Fault and volcanic structures provide the permeability for the hydrothermal fluids to circulate.

![Figure 8. Volcanism of Suban Agung, Bukit Beriti and Bukit Gedang](image)

4. Conclusions
The relationship between the structural geology and volcanism in Hululais is related to the movement of the Great Sumatran Fault (GSF) in Sumatra. From the results explained above, Hululais is one of the areas where its volcanoes are influenced by the NW-SE structure and bounded by two segments from the GSF, namely Ketahun Segment and Musi Segment. The faults from Musi Segment provide the pathways for magma to emerge from magma chamber to form NW-SE clustered volcanoes in the area forming the Hululais Brigade.

Therefore, the volcanism in Hululais must be preceded by the activity of the NW-SE dextral major strike-slip fault. The N-S compressional forces, based on the Riedel shear model for two right stepping faults such as Musi Segment and Ketahun Segment, formed the secondary N-S to NNW-SSE structural trend that also acts as the permeable structure in the area beside the main NW-SE structural trend. The permeability of these two structural trends are evidenced from feed zones in the wells and also the appearance of manifestations on the surface. Moreover, in the area where is it close to the pull-apart basin, the geologic structures recorded from the field measurement is influenced by the forces that act to form the basin.

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