Volcanostratigraphy Study of Slamet Volcano and the Implication to Its Early Stage of Geothermal Exploration

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Abstract. The application of volcanostratigraphy has been broadly used on many early stages of geothermal exploration. The method is simple yet powerful to give a preliminary suspicion on geothermal potential before a field survey. By combining contour analysis in certain scale (1:50,000 and 1:100,000) such as ridge and river pattern with the stratigraphic analysis of volcanic product the volcanostratigraphy units are determined. In this study, the volcanostratigraphy units were assessed using geothermal potential evaluation scheme for a stratovolcano to determine the potential of a geothermal green field. As the object of the study, a quaternary stratovolcano of Slamet Volcanic Complex in Central Java region was analyzed. Eight volcanostratigraphic units were determined in Slamet Volcanic Complex area and its surrounding, including six crowns and two hummocks. In addition, the hydrothermal fluid from several manifestations within the Slamet Volcanic Complex area (warm springs) were analysed to characterize the potentials of Slamet Volcanic Complex Region. Based on these determined volcanostratigraphy units, the occurrence of hydrothermal manifestation within the defined volcanostratigraphy units, the result of hydrothermal fluid analysis, and the criteria matching to the potential evaluation scheme for stratovolcano, the Slamet Volcanic Complex was categorized as potentially beneficial to be surveyed in detail. In such system, the volcanostratigraphy method is relatively simple and reliable to be applied since the volcanic evolution sequences data are accessible.

1. Introduction
The study area is located at Central Java Province, Indonesia (longitude 109°12’00” to 109°22’00” E and latitude 7°10’00” to 7°17’00” S, included into the Brebes, Tegal, Pemalong, Purwalingga and Banyumas districts. Volcanostratigraphy is a study of stratigraphy (e.g. spatial and temporal arrangement, relationship and origin of strata, or rock/deposit body in an area) related to volcanism and its products [1]. The term stratigraphy (layering system) in this method is determined with respect to volcanic source, deposit type, and sequence of time relative [2]. The analysis of volcanostratigraphy involving correlation between topographic map and the volcanic product distribution based on the geological mapping of a volcano local area. In this study, contour map of A1 sheet (1:100,000 and 1:50,000 scale) and geological map of Purwokerto-Tegal [3] was used. From the previous study from [4, 5], it could be concluded that Slamet Volcano is the youngest volcano in the study area and classified as a quaternary stratovolcano. Hence, it implies that the volcanostratigraphy analysis
approach [1] should be efficient to be applied in this study case. By means of the volcanostratigraphy unit determination and criteria matching to classification of a geothermal potential, the possible heat source of a geothermal system around Slamet Volcanic Complex (e.g. location and size) and its potential is estimated.

2. Aim of the Study
The aim of this study is to conclude the estimation of geothermal potential within the Slamet Volcanic Complex area based on its size and its location with respect to the determination of volcanostratigraphy units including Hummock (Gumuk), Crown (Khuluk), Brigade (Bregada), Super Brigade (Manggala), and Arc (Busur) [6]. Each volcanostratigraphy unit represents different volcanic eruption center. Hence, the determined volcanostratigraphy units in the study area will reveal the estimated size of geothermal potential based on criteria from [7] which involves size and elevation of cone complex, degree of magmatic evolution, age, and stress regime distribution of vents as its parameters (Figure 1).

3. Method
In order to determine volcanostratigraphy units properly, this approach should take account of volcanic geology concepts, genetic volcanism, volcanic landscapes, variation of volcanic rocks, volcanic facies, paleo volcanoes, and super-imposed volcanism [2]. As a start, the analysis of a topography map (including 1:100,000 and 1:50,000 scales) was conducted to generate the circular feature, ridge, and river patterns. These patterns are recognizable to have separated each other. The different pattern might show different episode of genesis, might also be a clue of different volcanism process. Delineating this present pattern gives a guide to the interpretation of the continuous volcanic process from magmatism through volcanism to its transportation processes [1].

By involving the geological data (e.g. a lithological map and its stratigraphy sequence, Figure 2), a carefully joint interpretations were conducted to reveal the relative ages of all volcanoes in the study area. A center of a volcanic eruption which is characterized by circular feature (or might be just a small volcanic edifice without any eruption) can be divided into a hummock, several hummocks or a single medium size volcanic edifice create a crown, a group crown become a brigade, some brigades and super brigades form an arc. The interpretation results (Figure 3) were used as parameters to estimate the geothermal resource potential from a geothermal area, based on the geothermal potential evaluation of stratovolcano flow chart from [7]. A geothermal field potential can be calculated by knowing the volume of the volcano. By assuming that the geometry of a volcano is a cone shape, this formula is applicable:

\[
V = \frac{1}{3} \pi h (r_1^2 + r_1 r_2 + r_2^2)
\]

Figure 1. Geothermal potential evaluation on stratovolcano [7]
Figure 2. Modification of regional geological map and its stratigraphy of Purwokerto-Tegal Districts [3]
Figure 3. Volcanostratigraphy unit map of Slamet Volcanic Complex.

\[ V_{\text{volcano}} = \frac{1}{3} \pi r^2 t \]  

(1)

where:

- \( V_{\text{volcano}} \): volume of volcano (km\(^3\))
- \( r \): radius of volcanic cone (km)
- \( t \): height of volcano (km)

The other consideration is the magma type of the volcano, especially the most representative one which will be recognized by analyzing the regional tectonism type, the volcano type, and its possible eruption type. The magma type could be basaltic, andesitic, dacitic, or rhyolitic. The determination of volcano age is also essential as it will be considered in the potential estimation, the younger the volcano, the more potential it is. The last parameter is the stress regime and its distribution of vents which are considered to be the constant cause of permeable pathways distribution for the hydrothermal fluid to ascend to the surface. In addition, there are several extra factors to indicate that an area should be surveyed in detail [7].

4. General Geological Condition of Study Area

Based on the distribution of lithologies extent as shown in the geological map (Figure 2), it is clearly seen that the Mount Slamet is a volcanic complex consist of more than one volcanism episodes since the pyroclastic products are categorized as older and younger product. There were two sources of eruption Slamet Volcanic Complex, namely Old. Slamet Volcano and Young Slamet Volcano [4]. The center of eruption of the Old Slamet Volcano is at the west, estimated to be located around the peak of Cowet, 2.5 Km apart from the center of the eruption of Young Slamet Volcano. In contrast, the Young Slamet Volcano eruption center which has a lava dome in it is located at the east, at the peak of Slamet Volcano. Based on the chronology of the product and its eruption center, from old to young, Slamet
Volcanic Complex is divided into two phases of volcanism, namely old slamet volcanism and young slamet volcanism. Regionally, Slamet Volcano is included in the stratigraphic section of the Purwokerto-Tegal area which was compiled by [3]. In the regional map there are four formations which are stated to be the products of Slamet Volcanic Complex, namely, from old to young, the Linggopodo Formation contains volcanic breccias, tuffs and lava that are thought to be the results of the Old Slamet volcanism activities; Undefined Slamet Volcanic Rock consisting of volcanic breccias, lava and tuff; Slamet Volcano Lava which contains hollow andesite lava; and Slamet Volcanic Complex lahar sediment containing lahar with lumps of volcanic rock andesite-basal composition with 10-50 cm in diameter was produced by the Old Slamet volcanism. Lava flows from Young Slamet Volcano associated with cinder cones were commonly produced by Young Slamet Volcano’s vent and flank eruptions during the Quaternary Period [5]. This is considered as a cinder cone field by [5], which indicate the presence of a huge basaltic magma supply, accommodated by surface fractures (fracture zone) as its ascending pathway. Based on [5], the area of Young Slamet Volcano is occupied by radial strike slip faults with two main trend, NE-SW and SE-NW (both sets of faults are strike slip left-lateral oblique slip faults). In the eastern part of the area, the relationship between tectonic stress and cinder cone lineaments is more obvious, the cinder cones appear in a radial alignment [5]. On the other hand, the rocks that form the basement of Slamet Volcanic Complex are Tertiary sedimentary rocks [8]. Most of the Tertiary deposits are concealed beneath the Quaternary volcanic products of Young Slamet volcanism, which ranges from a thin layer to a cover more than 2000 m thick.

**Figure 4.** Distribution of thermal springs in the Slamet Volcanic Complex geothermal working area, and several thermal spring manifestations outside the area [8]

5. Geothermal Manifestation and Its Implication

The manifestations within the Slamet Volcanic Complex area divided into two clusters based on its location of occurrence (Figure 4), namely Guci and Baturaden [8]. Only those manifestations were analysed in this research because the other manifestations from previous research are not located within the area of determined volcanostratigraphy units. By combining the location of manifestations with the defined area of volcanostratigraphy units, it could reveal the correlation between them. Baturaden cluster occurs within the Baturaden Crown, while Guci cluster within the Guci Crown).
The analysis of major cation and anion ratio (Figure 5), the pH, and temperature of each manifestation indicate that the location of those manifestations is the outflow zone of Slamet Volcanic Complex geothermal system, since all the water are plotted in the immature water zone, has neutral pH, and warm water temperature. Further analysis (Figure 5) of Cl, Li, B shows distinct characteristics between water from Gucci and Baturraden cluster, which indicate those two clusters of manifestation are representing two different geothermal systems.

![Image](5x5.png)

**Figure 5.** Cl-Li-B (left) and Na-K-Mg (right) trilinear plot of thermal water in Slamet Geothermal Area.

### 6. Result and Discussion

From the contour map analysis with 1:100,000 scale, it was identified that there are six crowns and two hummocks namely Slamet Crown, Guci Crown, Baturraden Crown, Pandansari Crown, Batursari Crown, Karangtengah Crown, Pesanggrahan Hummock, and Malang Hummock (Figure 3). Due to a relatively close distance between those six crowns, together they could be regarded as a Slamet Brigade. The Slamet Brigade includes the area of Old Slamet Volcano and Young Slamet Volcano product since the similar characteristic of Old Slamet Volcano and Young Slamet Volcano products were identified which leads to a concept that those two volcanisms were possibly fed by a single magma chamber. On the other hand, the 1:50,000 scale contour map analysis gives a clearer interpretation to determine the hummock within Young Slamet Volcano area. Malang Hummock and Pesanggrahan Hummock are located within the Slamet Crown area which strongly means that those small units were resulted from the same volcanism as Young Slamet volcanism. To support this concept in further, the rock geochemistry analysis such as isotop analysis should be conducted to review the characteristic of Old and Young Slamet volcanic product if they were fed by a single magma chamber or not. Proofing this concept would be crucial to determine is the size of the possible geothermal resource in this area.

Based on the determination of volcanostratigraphic units, the possibility of how beneficial a geothermal system would be after a detailed survey were estimated. Due to the hummocks are located within the Slamet Crown area, those two units were not included to the criteria matching using flow from [4]. The only stratigraphic unit which was involved in the criteria matching process is Slamet Crown, Guci Crown, Baturraden Crown, Pandansari Crown, Batursari Crown, and Karangtengah Crown. The result shows that Mt. Slamet is possibly beneficial to be surveyed in detail since the summation size of those crowns is approximately 291 km$^3$, with basaltic magma, five years old of last eruption, and has a central volcanism structure creating radial alignment of cinder cones, and possibly a radial dyke-sill system.
7. Conclusion

Volcano-stratigraphy units in Slamet Volcanic Complex divided into six crowns and two hummocks namely Slamet Crown, Guci Crown, Baturraden Crown, Pandansari Crown, Batusari Crown, Karangtengah Crown, Pesanggrahan Hummock, and Malang Hummock. Based on the criteria matching to the flow chart from Wohletz and Heiken, and regarding the occurrence of geothermal manifestation within defined the volcanostratigraphic units, Slamet Volcanic Complex has a good possibility to be well developed by doing further exploration. Since Slamet Volcanic Complex consists of two stratovolcanoes, i.e. Old Slamet and Young Slamet, the geothermal potential evaluation is being used appropriately and the result of this method is reliable.

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