Volcanostratigraphic Approach for Evaluation of Geothermal Potential in Galunggung Volcano

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Abstract. The geothermal systems in Indonesia are primarily associated with volcanoes. There are over 100 volcanoes located on Sumatra, Java, and in the eastern part of Indonesia. Volcanostratigraphy is one of the methods that is used in the early stage for the exploration of volcanic geothermal system to identify the characteristics of the volcano. The stratigraphy of Galunggung Volcano is identified based on 1:100,000 scale topographic map of Tasikmalaya sheet, 1:50,000 scale topographic map and also geological map. The schematic flowchart for evaluation of geothermal exploration is used to interpret and evaluate geothermal potential in volcanic regions. Volcanostratigraphy study has been done on Galunggung Volcano and Talaga Bodas Volcano, West Java, Indonesia. Based on the interpretation of topographic map and analysis of the dimension, rock composition, age and stress regime, we conclude that both Galunggung Volcano and Talaga Bodas Volcano have a geothermal resource potential that deserve further investigation.

1. Introduction
Determination of areas which have potential geothermal energy depends on the presence of geothermal manifestations at the surface. Existing geothermal manifestations are indicative of the geothermal potential of an area. However, a geothermal area may lack of surface manifestation. Lack of surface manifestation could cause difficulties during exploration to determine the potential of geothermal in an area.

Volcanostratigraphic approach is performed at the early stage of geothermal exploration to determine the geothermal potency before further exploration. Volcanostratigraphic mapping is a method used in the early exploration stage. This method is useful to distinguish and classify eruption products based on the eruption centers. This classification is important to delineate the eruptive sources as they indicate the presence of once active or still active magmatic intrusions related to heat source thus to make the study of volcanic rock mapping becoming more effective, focused, systematic and targeted.

Volcanostratigraphy analysis is based on topographic maps with scale of 1:100,000 and 1:50,000. Determination of stratigraphic units consist of determining centers of eruption, ridge lineaments, drainage pattern and the boundary of the volcano stratigraphic unit [1]. Eventually, topographic analysis will be grouped based on volcanostratigraphic classification, namely hummock (gumuk), crown (khuluk), and brigade (bregada) [2]. Interpretation of volcanostratigraphy is based on the relation between the topographic map analysis and regional geological map.

In this paper, we conducted evaluation of geothermal potential by adopting the evaluation of geothermal exploration in volcanic regions [3]. The evaluation consists of size and elevation of the cone
complex, degree of magma evolution, age of the volcano, stress regime or distribution of the vents and other factors such as the occurrence of surface manifestations. The volume of the cone and the distribution of vents can be determined by volcanostratigraphic mapping. The evolution of magma and the maturity of the geothermal system can be analyzed in reference to the regional geological map.

Galunggung Volcano and Talaga Bodas Volcano are active quaternary volcanoes which are located in the southeastern area of Bandung. Galunggung Volcano has a large crater and is interpreted as the upflow zone of the geothermal system. Based on regional geological map, there are only as follows limited surface manifestation at Galunggung crater, such as cold water with bubble near neutral water at crater and Cipanas hotspring. Other manifestations present such as an alteration zone at the seepage location and warm spring located 25 km south of Galunggung Volcano, in Cigunung, and Cibalong while the geothermal potential of Talaga Bodas Volcano has been proven by exploration drilling. This paper will discuss the application of volcanostratigraphic approach in evaluating the potential of proven area such as at Talaga Bodas Volcano and unproven area like Galunggung Volcano.

2. Methodology
The basic volcanic mapping is using volcanostratigraphy [4]. The stratigraphic unit of a formation is equivalent to a crown, while the smaller units are considered as hummocks. Two or more volcanic crowns can be considered a brigade and a volcanostratigraphic unit which consists of many crowns, brigades and super brigades is an arc.

The first step to determine the volcanostratigraphic unit is delineating non-volcanic rock to confine the research area by overlaying the topographic map with regional geological map of the same scale. The next step is volcanostratigraphy mapping by identifying crown and hummock through the interpretation of topographic map scale 1:100,000 and more detailed identification through interpretation of topographic map scale of 1:50,000 so the hummock can be identified. This identification is only carried out on non-sedimentary units. Identifying the units of volcanostratigraphy such as crowns and hummocks was performed by determination of primary and secondary centers of eruptions. This identification can be used as a guide in estimating the distribution of eruption products. Important morphologic features such as circular structures, craters, or calderas are considered primary eruption markers.

The next step is to trace every single river path with blue to mark the drainage pattern. The path of the main river usually bounds two separate crowns. The next step is to trace lineaments which represent ridges with the color brown. The morphology of lineaments traced in brown usually represents one eruption center and will form a radial pattern.

Lineaments and river flow are identified using SRTM image which are aimed to determine the boundaries between hummock and crown. The boundaries are marked by black dashed line. The assumption that is used for determining volcanostratigraphic limit is when distribution of ridges and rivers form a more or less radial pattern, it is considered the same source [5].

The volcanostratigraphic unit, of a crown, is generally characterized by contour pattern of large volcanic cone or groups which may be linked genetically. While a hummock is generally characterized by contour pattern of small volcanic cone located near to a crown. Each crown and hummock that has been identified can be named according to the geography.

The next step is identification on a more detailed topographic map with scale of 1:50,000. The specific identification on a detailed scale is performed due to the possibility that one crown identified on a topographic map of 1:100,000 scale could turn out to be two crowns in 1:50,000 scale. On detailed topographic map of 1:50,000 scale, radial flow patterns of rivers and lineaments of ridges become detailed and clear.

After stratigraphic identification on topographic map, the next step is evaluation of geothermal exploration in volcanic regions using evaluation scheme. The scheme uses a flowchart with a series of parameters. These parameters including volume of volcanic complex, degree of magmatic evolution, age of volcano, stress regime, and other factors such as the presence of manifestations at the surface (figure 1). In the case of Galunggung Volcano, a simplifying assumption is used in that the edifice is cone-shaped such that its volume can be roughly approximated in equation (1).
Where, $V_{\text{volcano}}$ is volume of volcano (m$^3$)
$r$ is radius of volcano (m)
$t$ is elevation difference between the highest marked peak and the surrounding average
lowest elevation respectively (m)

![Figure 1. The evaluation guideline for geothermal potential in stratovolcano - modified from [3]](image)

Evaluation of volcano’s size is used to estimate the depth of a magma intrusion beneath the surface. The shallower magma intrusion, the greater potential into heat source of the geothermal system. The size of the volcano will help delineate the area of magma chamber that lies beneath the surface. Such area may be associated with an area of reservoir.

Degree of volcano’s maturity was estimated by comparing the volcanic parameters which is listed in figure 2. After understanding composition of magma, we can estimate the heat which is contained in volcano. Composition of magma changes from mafic to silicic along with rising magma to the surface. Shallow magma confined close to the subsurface causes assimilation with the surrounding rocks which increase silica content. Besides, a number of intrusions cause mixing between shallow magma and deep magma which can move upward to the surface.

The composition of magma can also be expected from the type of volcanic eruption. Strombolian and Vulcanian are types of eruption that can produce monogenetic cones of mafic magma. Central vent and fissure vent can produce complex cone of mafic-intermediate magma from Vulcanian eruption type.
While the central vent can produce complex parasitic cone, dome and caldera of intermediate-silicic magma which type of eruption is plinian or pelean. When basaltic magma from crust flows up to the surface caused by fracture or fissure its composition will get changed through differentiation, mixing or assimilation. If fractures or fissures that act as magma discharge path are small, it will prevent magma to emanate to the surface so that its composition will get changed into intermediate or maybe silicic while prevented in subsurface. The more the process of mixing or differentiation that occurs the composition of magma will increasingly intermediates or silicic when emanates to the surface. Figure 2 shows that maturity degree of volcanoes can be characterized by its products that are pyroclastic flows and ash falls.

![Figure 2. Geothermal potential based on maturity degree in volcanoes [3]](image)

3. Result and discussion
Based on the volcanostratigraphic interpretation, there are five crown units that we have identified from the Tasikmalaya topographic map on 1:100,000 scale. These units are Galunggung, Talaga Bodas, Sawal, Cakrabuana and Sadakeling (figure 3).
Figure 3. Topographic map of Galunggung Volcano 1:100,000 on scale [6]

Figure 4. Overlay topographic - geological map [7] of Galunggung Volcano and its surrounding area
The interpretation results were then compared with published geological map of Tasikmalaya (figure 4) and there is relatively good correlation between the interpreted volcanostratigraphy unit boundaries and the distribution of volcanic lithological units. It also implies that there is a correlation between the distributions of eruption products and the morphology of volcano.

A more detailed topographic map on scale of 1:50,000 and satellite images was also analyzed for Galunggung Crown and Talaga Bodas Crown region on the northwest flank of Tasikmalaya. There are additional hummock units on Galunggung Crown and Talaga Bodas Crown which were previously unidentifiable. The additional hummock units on Galunggung Crown; are Beuticanar, Walirang and Guntur, while Talaga Bodas Crown has nine additional hummock units; there are Ciherang, Cupu, Tegalsari, Canar, Lebakrejo, Bungbuan, Malang, Candramata and Pasir Sadahurip. Guntur crater is an old summit crater of Galunggung composite volcano before collapsed producing horse shoe-shaped crater and Tasikmalaya debris avalanches deposits [9]. These hummock units and crown units are grouped as the Gandewa Brigade (figure 5). The analysis of geothermal resource and potential for development of Galunggung Crown and Talaga Bodas Crown was done by adopting the evaluation scheme in geothermal exploration [3]. The scheme uses a flowchart with a series of geological and physical parameters.

3.1. Galunggung Volcano

For the analysis of Galunggung Volcano dimension, the diameter is taken as the average distances between pairs of slopes with lowest inclination, while the elevation difference is taken from the Digital Elevation Model (DEM). The diameter of Galunggung Volcano is 32 km with elevation difference is 1,591 m; therefore the volume of Galunggung Volcano is 430 km$^3$. The large volume of the volcano indicates that Galunggung Volcano has a large potential for geothermal energy. Volcanic rocks of Galunggung Volcano consist of Old Galunggung Formation, Tasikmalaya Formation and Cibanjaran Formation. The first rock formation is volcanic rock that formed Galunggung Stratovolcano (age 10.000 - 50.000 years?) while the second formation overlies the rock which formed caldera (150 ± 4.200 years?) and the third formation were the erupted products from 1822, 1894, 1918 and 1982 - 1983 [9].

Figure 5. Topographic map of Galunggung Volcano 1:50.000 on scale and its surrounding area [8]
Old Galunggung Formation consists of intercalation of lava flows, pyroclastic and dyke. By using $^{14}$C method, the age of this formation is 20,000 - 25,000 years, implying the entire activity of Galunggung Volcano took place 50,000 - 100,000 years ago. Tasikmalaya Formation consists of debris avalanche and pyroclastic flow. Debris avalanche is rocks in volcano that show contact between lava flows and pyroclastic deposit. Pyroclastic flows of Tasikmalaya Formation are grey-brown in color and unconsolidated. Cibanjaran Formation or Post Caldera consists of eruption products from Galunggung Volcano in 1822 as pyroclastic flow, in 1894 as pyroclastic fall, in 1982-1983 as pyroclastic flow that are rich in ash and bomb fragments with $5.6 \times 10^6$ m$^3$ in volume [9].

![Conceptual model geothermal system of Karaha – Talaga Bodas](image)

**Figure 6.** Conceptual model geothermal system of Karaha – Talaga Bodas [12]

Galunggung Volcano has homogeny stress regime, it can be seen since the spread of vent centralizes at peak of Galunggung Volcano. This means the plutonic rocks as heat source are located inside it. There are only as follows limited surface manifestation at Galunggung crater, such as cold water with bubble near neutral water at crater and Cipanas hot spring. Other manifestations present such as an alteration zone at the seepage location and warm spring located 25 km south of Galunggung Volcano, in Cigunung, and Cibalong. The temperature is 60°C. These manifestations are expected as outflow from Galunggung Volcano geothermal system [10]. Based on the evaluation for geothermal potential of stratovolcano [3], Galunggung Volcano has large potential for geothermal energy that can be developed and needs further detailed exploration.

### 3.2. Talaga Bodas Volcano

The second crown is Talaga Bodas. Talaga Bodas is a volcano located at northern of Galunggung Volcano. The difference between highest elevation and lowest elevation is 1.623 m with total area 126 km$^2$, thus its volume is 65 km$^3$. This large volume indicates there is a large heat source. The dominant volcanic rocks in Talaga Bodas are pyroclastic deposit, epiclastic, and the distribution of andesitic-basaltic lava flow. Based on age dating using $^{14}$C methods, the age of the rocks of that area is from 41.500 ± 1.200 to 5.910 ± 96 years ago [11]. There are also some manifestations such as hot springs, fumarole and acid crater (Saat Crater).

Talaga Bodas crown also has homogeny stress regime where the dominant trend of geological structure is northwest-southeast and centralized vent. This phenomenon indicates that the maturity level of Talaga Bodas is mature and has good potential for geothermal energy. The potential of Talaga Bodas geothermal area has been proven by drilling results. The drilling was conducted by Karaha Bodas Co.
LLC by the end of 1990. There are 29 exploration wells with 3 km in depth. Figure 6 shows the geothermal system in Talaga Bodas. It is a high temperature system with the temperature at the bottom of well TLG 2-1 is 353°C.

4. Conclusion
Based on the criteria evaluation geothermal exploration [3], the degree of magma evolution, age, stress regime and the distribution of the crater, it can be concluded that Galunggung Volcano and Talaga Bodas Volcano are possible candidates for geothermal exploration and are to be investigated further. Based on the results of the study, show that volcanological approach can be applied in early stage of geothermal exploration activity in volcanic regions.

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