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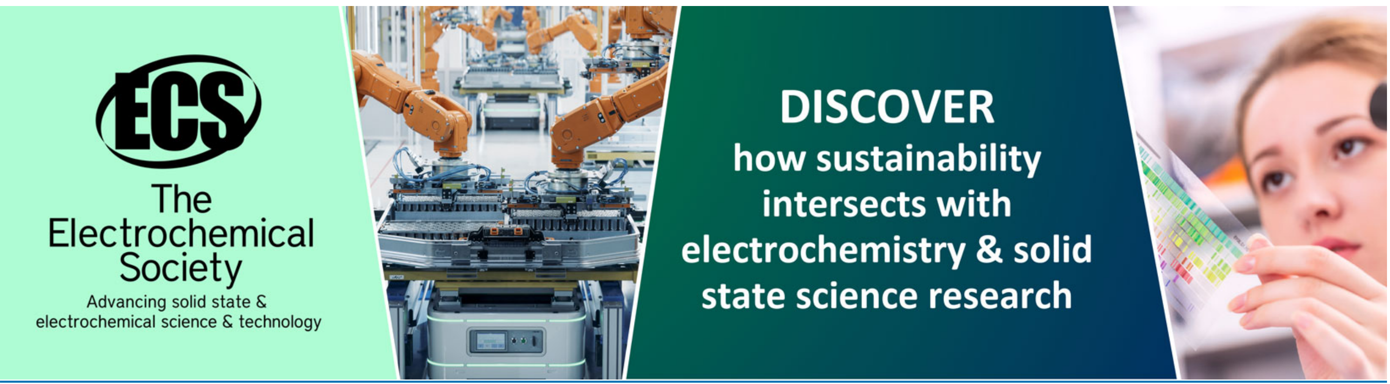


Volcanostratigraphic Study in Constructing Volcano Chronology and Its Implication for Geothermal Resource Estimation; Case Study Mount Sawal, West Java

F A Dermawan, H Hamka, R T A Malik, J Y Sianipar and Q S Ramadhan

Magister Program of Geothermal Engineering, Faculty of Mining and Petroleum Engineering, Bandung Institute of Technology (ITB), Jl. Ganesha no. 10, Indonesia 40132

Email: fikri.adam.derma@gmail.com

Abstract. One of the researches that should be done before carrying out a preliminary survey on the geothermal exploration with a volcanic system or volcanic-hydrothermal is by studying the volcanic stratigraphy. Determining the center of the volcanic eruption and its distribution based on the volcanostratigraphic study will be very helpful in a direct mapping that will be implemented, given that the type and characteristics of volcanic rocks are nearly the same between one source of the eruption and the other. On this case, volcanostratigraphic study had been done on Mount Sawal, where a topographic map with a scale of 1: 100,000 is used to determine the center of eruption of each crowns, while another map with a scale of 1: 50,000 is used to identify the distribution of the monogenetic (Hummock) eruption products and crowns border in detail. It is found approximately three crowns, which are Langlayang, Sawal big crown, Pamokolan, and the Cikucang Hummock that is located on the southern edge of the Langlayang crater. These Hummock and Crowns collection will be grouped into Tasik Bregade. Based on the volcanostratigraphic analysis, DEM, and geology, the chronology of how Tasik Bregade is formed is originally from the Langlayang, Sawal big Crowns, and Pamokolan. Tasik Bregade is classified into sub-mature potential geothermal system, from the analysis results, the potential magnitude of the electrical capacity contained in the system is around 0.74 to 1.24 MWe for 30 years, but further research needs to be done because of the detailed geological and other support data that are still lacking.

1. Introduction

Almost all geothermal system in Indonesia is associated with volcanic heat source which are distributed along subduction zone from Sumatera, Java, Bali, Flores, North Sulawesi, and Maluku archipelago. Generally these systems have high temperature (~250°C) and high enthalpy also large potential (> 50 MW) [3].

Surface geological mapping is a method to investigate and examine the geological condition of this area in particular to determine the volcanic center which often associates with intrusive body inferred as heat source[4]. However, mapping in volcanic area is a tricky task because it is difficult to distinguish the origin of various volcanic product due to their similarity. The problem will become worse when ones encounter volcanic complex in an intensive erosion stage [5]. Therefore volcanostratigraphic study is really helpful to classify and group the eruption product to interpret its eruption center.

This research was conducted in northern Tasikmalaya area, Mount Sawal and its surrounding, using 1:100.000 topographic map for regional analysis and 1:50.000 topographic map for detail analysis. This volcanic complex is classified into type “B” that is a volcano where its eruption activity hasn’t been recorded or never shows any activities since 1600, A.D. but it still has forming a volcanic cone [6]. The topographic analysis will be grouped based on volcanostratigraphic classification, namely Hummock (Gumuk), Crown (Khuluk), and Bregade (Bregada) [7,8]. These groups are based on ridge lineament analysis, drainage pattern, eruption source with converge contour, circular feature that indicate an eruption crater.

2. Methodology

The first step of volcanostratigraphic method according [5] and Bronto, S (Personal communication) begins with determining the peaks of volcano marked by geodetic elevation. This determination is followed by digital elevation model (DEM) analysis because not all peaks from the highest topography represent the mountain peak, may be it is a crater rim or the remnants of past volcanic eruption (Bronto, S., Personal communication). The next step is identifying some circular features which mark by more or less concentric depressions. These circular features could be a guidance for distribution of respective eruption products. The next step is tracing every drainage pattern by using blue color as the mark of river flow. In general, the common drainage system encountered in volcanic setting is more or less a radial pattern, this pattern also shows the volcanic center/peak and may last well after the volcano has been eroded [9]. Tracing the ridge patterns can be done at the same time as drainage pattern or after. The ridge lineament is particularly flanked by rivers on each side, indicating volcanic product flow direction. The boundary among units were determined by the previous steps and usually cut by the river. The boundaries of individual units were then marked with black dashed lines.

Eventually, the result of topographic map analysis will be correlated with digital elevation model to assure the peak of volcano. This is because in old volcanic systems which have undergone advance erosional state, conical shapes are remnant of hardest rock or resistant part from erosional process, so it is necessary to correlate with digital elevation model (Bronto, S., Personal communication). Digital elevation model can also assist in analyzing the age of volcano through morphological shape. Volcanoes with smooth morphological texture are classified into young age whereas old age with rough texture.

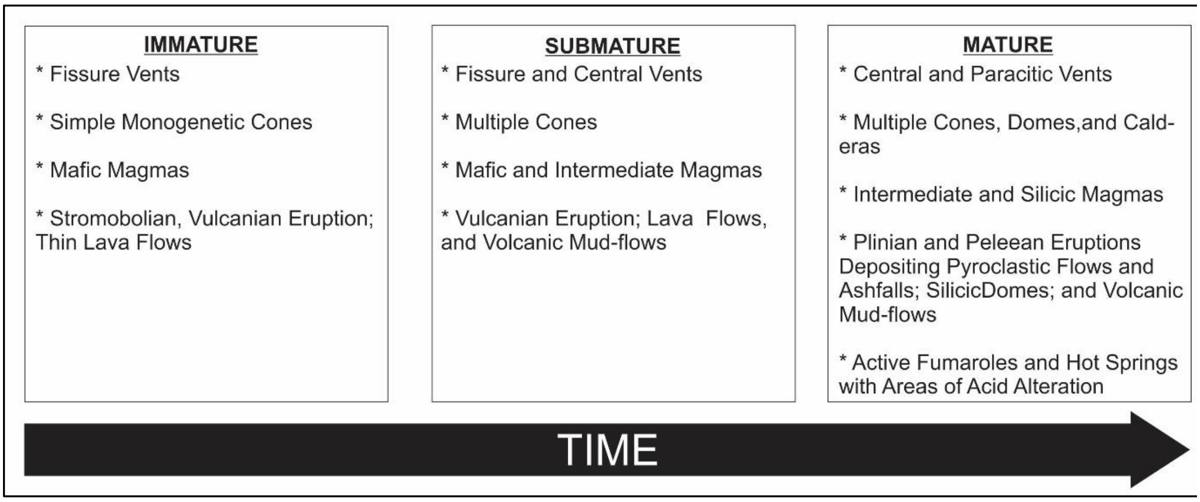


Figure 1. Geothermal Potential based on maturity degree modified from [10].

Geothermal resource potential assessment of Mount Sawal adopts several methods which were published by [10]. The first method is to classify the maturity of stratovolcano based on age (£Figure 1). Every replenishment number of eruption will enhance the silicate content of magma, shallow the magma chamber, and enlarge the energy content.

The greater the potential of the volcano, stratovolcano will be more mature. This potential is supported by long-lasting heat source, which is sustained by multiple intrusions and broad volume of magma chamber (the magma's diameter is equal or bigger than caldera ring faults (Smith and Shaw (1975) in [10]).

Another method is by using flow chart guideline for geothermal potential which was proposed by [10,11]. There are five main factors to evaluate the geothermal potential in stratovolcano complex, namely (1) size and elevation of stratovolcano complex, (2) degree of magma evolution, (3) age of volcano, (4) stress regime or vents distribution, and (5) the presence of surface manifestation (Figure 2).

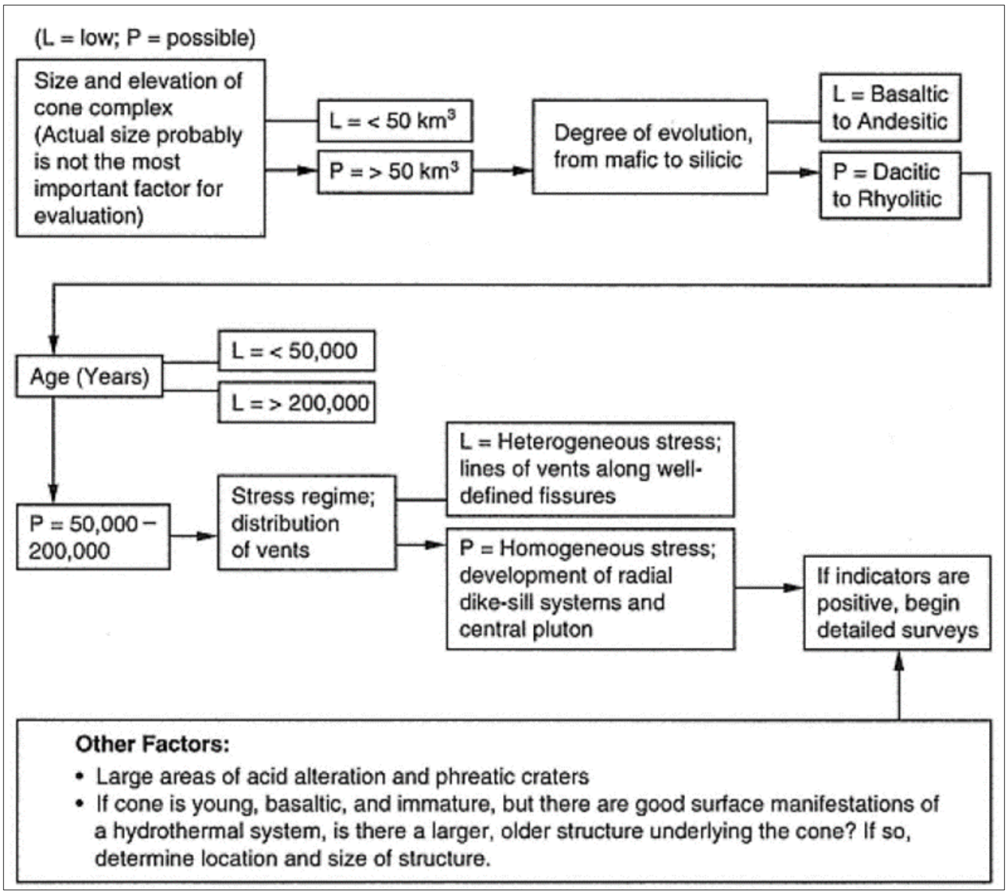


Figure 2. The evaluation guideline for geothermal potential in stratovolcano [10].

The last method of estimating geothermal potential is by evaluating the magmatic thermal energy contained within Mount Sawal's magma chamber. Based on Smith (1979) cited by [10] in their research, the volume of volcanic eruption product is only 10% from the volume of magma chamber. It is assumed that the product of volcanic eruption comprises with equal proportions of lava and pyroclastic (nearly 50% each). Based on all these assumptions, the resource estimation of thermal energy within Mount Sawal could be calculated by the following formulas:

$$V_{DRE}\ Pyroclastics = 0{,}6 \times 0{,}5 \times V\_Volcano \quad (1)$$

$$V_{DRE} Lava = 0{,}5 \times V_{Volcano} \quad (2)$$

$$Q = \rho \times (V_{DRE} Pyroclastic + V_{DRE} Lava) \times 10 \times H \quad (3)$$

Where V_{DRE} is volume of dense rock equivalent, means volume of igneous rock after all the pore space caused by vesiculation, fracturing, and intergranular porosity has been subtracted, ρ is rock density (kg/m3), H is magmatic heat content (kJ/kg), and Q is thermal energy (J) [5,10]. $V_{Volcano}$ in this equation is the volume of per-eruption and in this case the $V_{volcano}$ is from monogenetic eruption product (Cikurai Hummock).

3. Geological Setting

Regionally, the volcanic arc in Java Island was formed by subduction process between Indo-Australia oceanic plates with Eurasia continental plate (convergent plate boundaries) with nearly vertical orientation. This subduction process produce magma as partial melting with asthenosphere in depth and this magma will penetrate through the weak zone such as fracture and fault zone with basaltic to andesitic composition.

The interaction between Indo-Australia plate and Eurasia plate has been active since Late Cretaceous [12]. Eventually, this process leads to the regional structure evolution in Java Island. Based on Pulunggono and Martodjojo (1994) cited by [12], there are three dominant Java structure patterns, namely (1) Meratus direction (SW-NE) with Late Cretaceous epoch, (2) Sumatra direction (NW-SE) with Late Cretaceous to Paleocene epoch, (3) Sunda direction (N-S) with Eocene to Late Oligocene epoch and (4) Java direction (W-E) with Early Miocene epoch. West Java itself has been controlled by Sumatra, Sunda, and Java patterns (Figure 3).

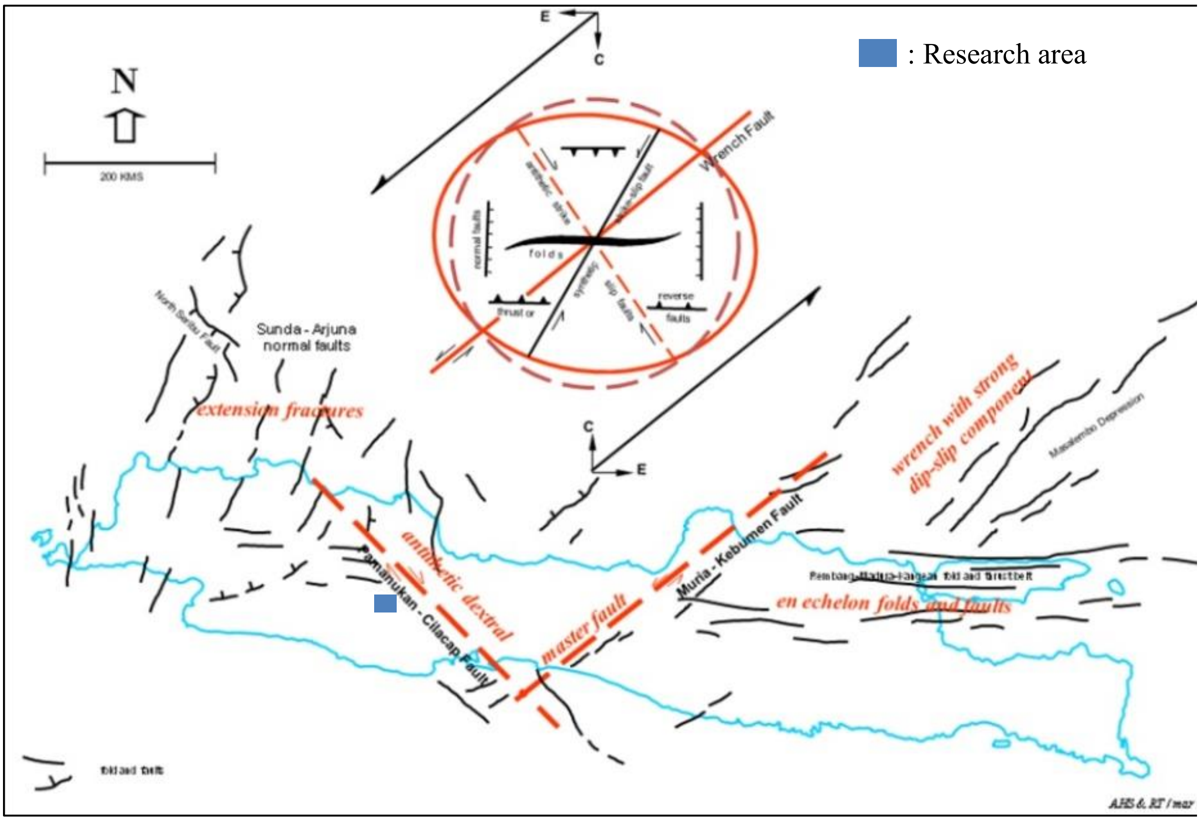
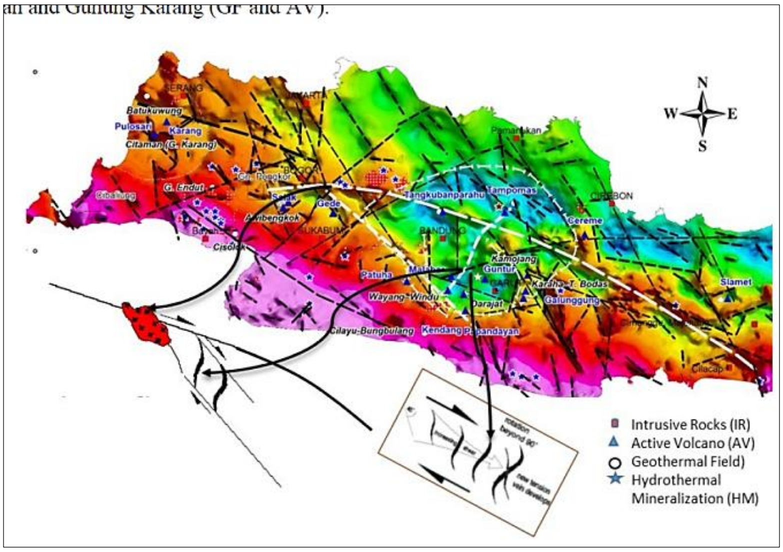


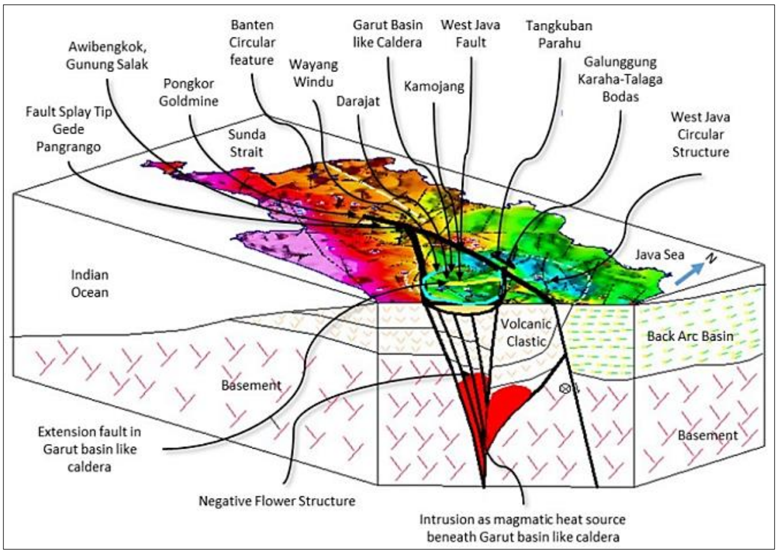
Figure 3. Geologic structure map of Java Island purposed by [12] based on strain ellipsoid kinematic. The main structure is Muria-Kebumen strike-slip in the eastern side of Island on the other side Pamanukan-Cilacap strike-slip as the antithetic.

[13] and [14] mention in their research that the extensional condition, which is produced by the regional structure, will (1) provide conduit for magma to ascend into the upper crust that may act as a

heat source for geothermal and (2) control the secondary permeability of the system. The regional structure that control volcanism and geothermal process in West Java is the West Java Fault system which major trend is N 300ºE or NW-SE [13]. This regional structure has two main splay faults that are Salak-Gede-Patuha-Papandayan fault and Tangkuban Parahu-Karaha-Galunggung fault, where in the middle of them pull apart basin occurs as extensional conduit for magma intrusion (Figure 4). Extensional zone is formed by N-S orientation in West Java.



(a)



(b)

Figure 4. (a) Overlay map of volcanic product and geologic structure from anomaly bouger analysis. (b) 3D block diagram shows the negative flower structure which control West Java. This structure has two main splays, namely Salak-Gede-Patuha-Papandayan splay fault and Tangkuban Parahu-Karaha-Galunggung splay fault [13].

Jampang Formation, the oldest formation, lies in the southern area, also known as Old Andesitic Formation, was formed at Late Oligocene to Early Miocene and unconformity deposited with Halang Formation (Early Miocene) and Tapak Formation (Early Pliocene). Physiographically, Mount Sawal is categorized as Quarternary Volcanic that is composed of volcanic breccia, flow breccia, tuff, and andesitic to basaltic lava [15]. It is interpreted that Mount Sawal overlies Tapak and Halang Formation. The volcanic product of Mount Sawal is distributed in the E-NE map and inferred as Old and Young Sawal Crown eruption products (~~f~~Figure 5).

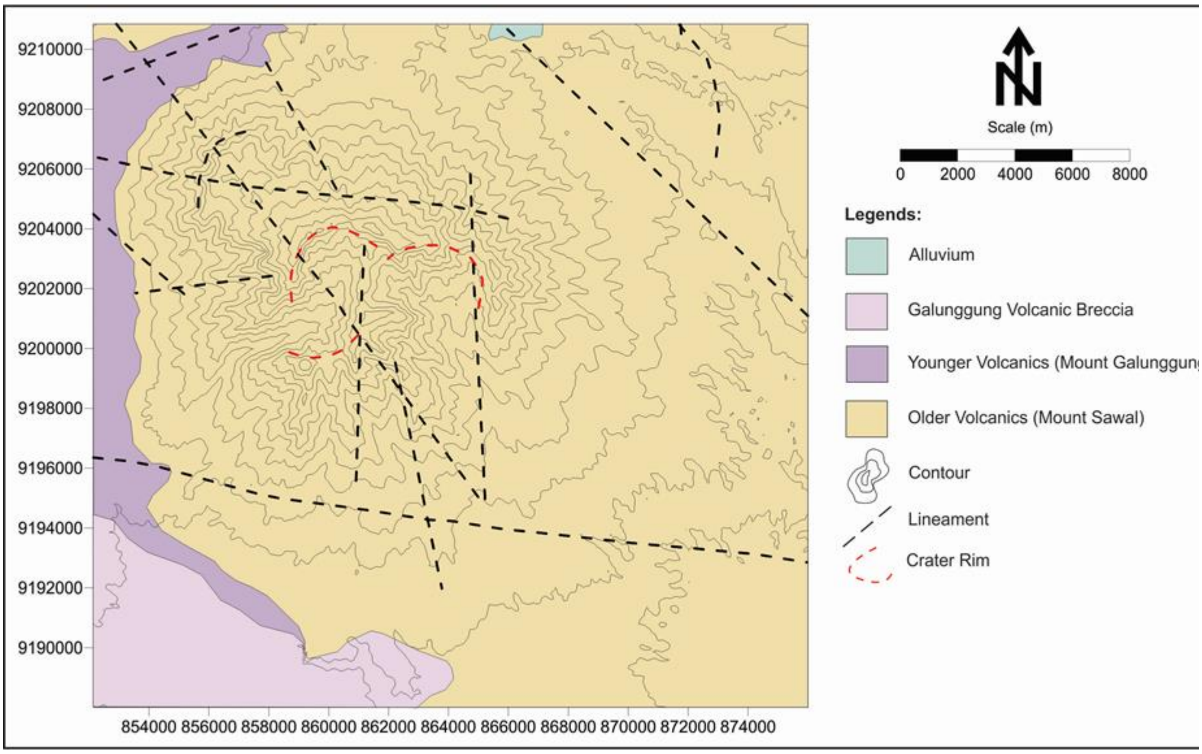


Figure 5. Geological map of Mount Sawal and its vicinity (Modified from [15].

The dominant orientations of geologic structures in Mount Sawal complex are NW-SE, N-S and W-E which resemble Java's regional structure (Sumatra, Sunda and Java directions). This orientation is interpreted as the result of Salak-Gede-Patuha-Papandayan splay fault and triggering the volcanism in this area.

4. Result and Discussion

There are at least three crowns which could be identified using 1:100.000 scale topographic map, namely Langlayang, Sawal and Pamokolan. Later on, Sawal Crown is divided into two sub-crowns based on rims and morphology roughness from DEM data. These sub-crowns are Old Sawal sub-Crown on east side of main Sawal Crown and Young Sawal sub-Crown on the west side. The smallest unit such as hummock (Cikuray Hummock) is also identified on this map where it's located in the southern rim of Langlayang crater (figure 6). The Hummock identification was also supported by DEM for validation. Consequently, this Mount Sawal complex is classified into Tasik Brigade [7,8].

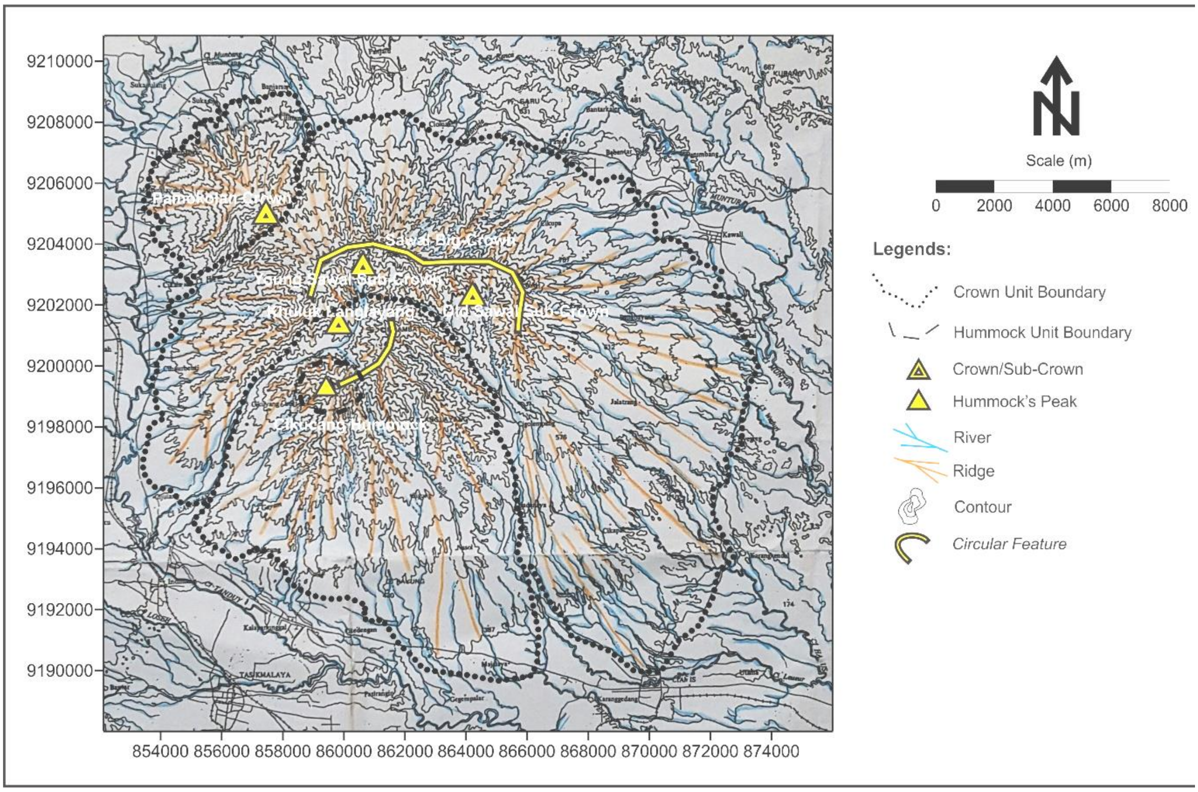


Figure 6. Volcanic stratigraphy distribution map based on topographic map (1:100,000 scale) analysis which consist of three crowns and one hummock. This Mount Sawal complex is classified into Tasik Brigade.

A more detailed topographic map, 1:50.000 scale, was analyzed to discover Cikucang Hummock boundary. This boundary will be used for $V_{volcano}$ calculation where the hummock is interpreted as the latest or a single body of monogenetic eruption product (Figure 7). Once obtained, $V_{volcano}$ value can be applied to estimate thermal energy of magma and geothermal potency for 30 years. Further analysis on DEM data indicates that in the southeastern part of Sawal Crown lies an eruption product or avalanche product (may be pyroclastic flow, or lahar or debris avalanche) from Sawal Crown eruption (Figure 8). It is important to conduct detailed geological mapping of Mount Sawal in the future to comprehend the geological condition and unit boundaries utterly.

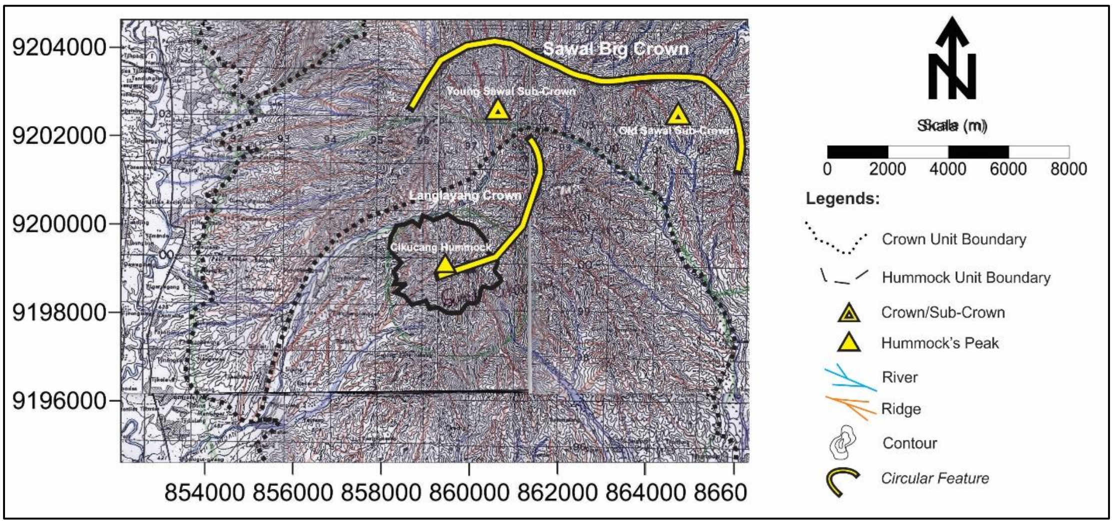


Figure 7. 1:50,000 topographic map was used for tracing unit boundaries of Cikucang Hummock.

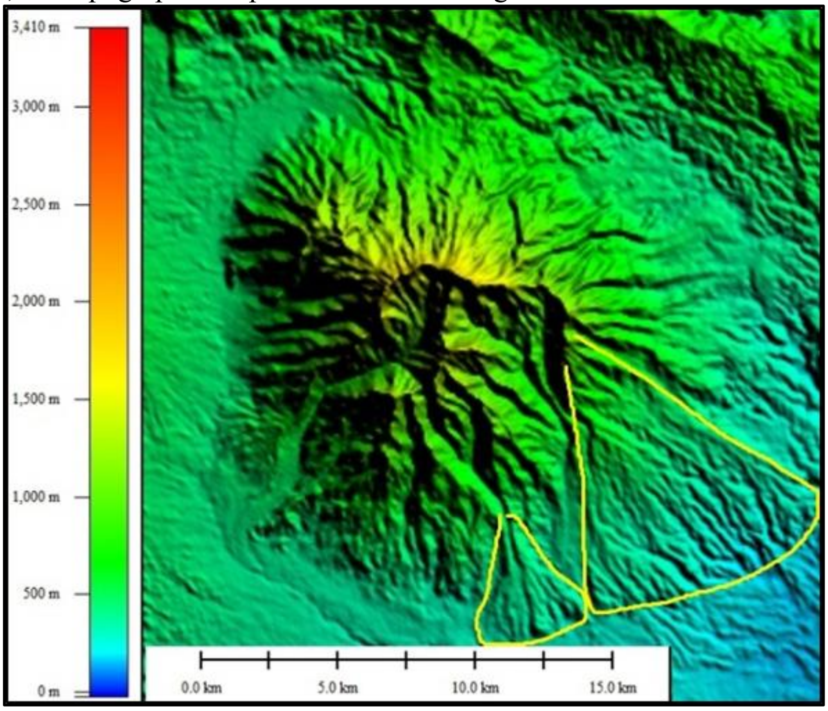


Figure 8. The distribution of Tasik Brigade volcanic product. Based on DEM analysis is interpreted into debris avalance from Sawal Crown eruption.

Hereafter, the volcanostratigrapy distribution result is overlaid with Mount Sawal geological map (Figure 9). The deployment of Mount Sawal product shows similarity with geological map, which are distributed in the center and eastern area map, but with the interpretation result from volcanic stratigraphy and DEM help to divide in detail each eruption product from eruption source.

The chronology of Tasik Brigade formation begins with Langlayang Crown formation and Old Sawal Hummock formation on the northeastern part of crown. N-S and NW-SE structure orientation allegedly played as the weak zone for magma to intrude (Bronto, S., Personal communication). As time goes by, Langlayang Crown erupted and extruded its material on the west flank while the Old Sawal Hummock evolves into sub-Crown. This evolution of Old Sawal was followed by Young Sawal Hummock on the west flank volcano. It is still questionable whether both of them erupted at the same time or the Old

Sawal first. Supposedly, Young Sawal sub-Crown eruption product was covered by Galunggung volcanic product. Subsequently, Pamokolan Hummock grew and arises on the northwestern flank of Sawal Crown, where today the Pamokolan Hummock has evolved into crown. The last eruption product is interpreted to occur at the southern rim of Langlayang Crown, Cikucang Hummcok. This interpretation is based on smooth morphology and clear radial drainage pattern. The eruption trend of Tasik Brigade is northeastern to northwestern direction (Figure 10).

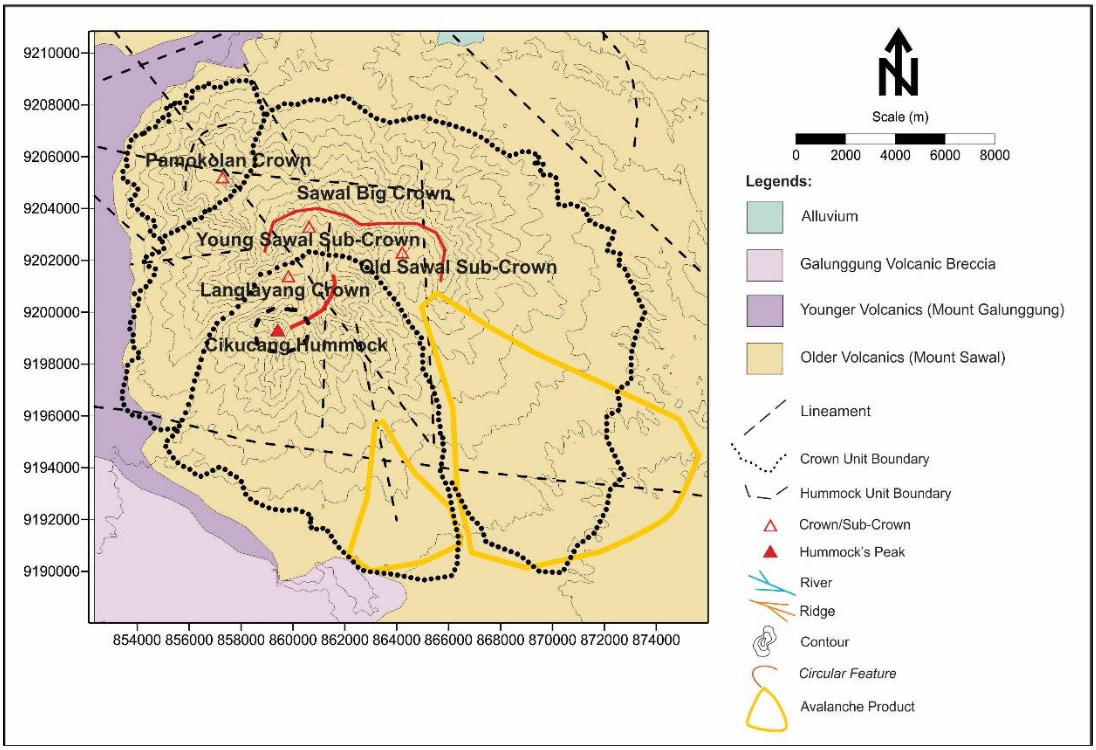
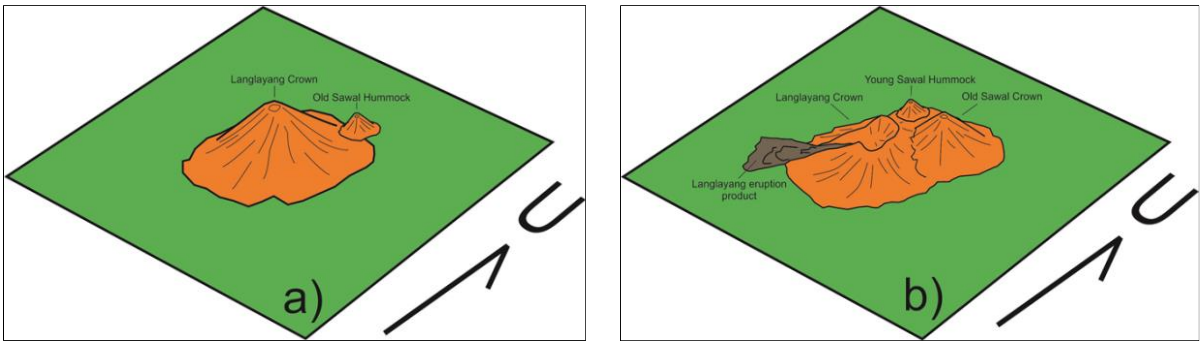


Figure 9. Overlay map between volcanic stratigraphy units, DEM analysis, and geological map of Mount Sawal and vicinity.



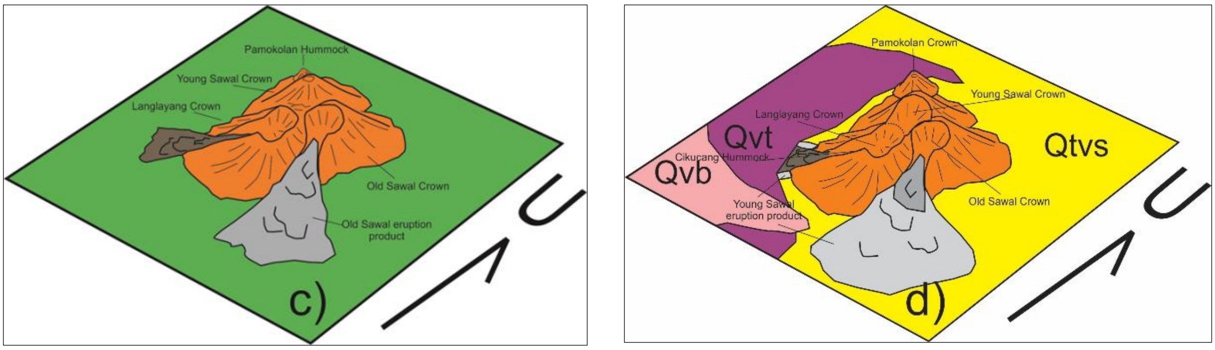


Figure 10. The chronology of Tasik Brigade formation begins with Langlayang Crown as the oldest formation, the Old sub-Crown Sawal, the Young sub-Crown Sawal, Pamokolan Crown and ends with Cikucang Hummock. The eruption trend of Tasik Brigade is NE and NW which is controlled by N-S and NW-SE orientation. Figure (d) is current Tasik Brigade.

According to eruption product composition (basalt and andesitic lava), eruption center, multiple cone (Langlayang, Sawal, Pamokolan Crown) with lava dome (Cikucang Hummock) and vulcanian to pelean eruption type (eruption product was distributed on western side and southeastern side of Brigade), the geothermal potential of Tasik Brigade is categorized into submature type [10]. Detail research is still needed to evaluate the geothermal work flow potential as proposed by [10] in Tasik Brigade. Lack of data in Mount Sawal complex, such as the age of the last eruption product and the occurrence of geothermal manifestation, are affecting the certainty of this Brigade potential.

The last method uses thermal energy calculation which is contained in Brigade's magma chamber. The calculation was using Cikucang Hummock data as the last eruption product of Tasik Brigade. Cikucang Hummock is categorized into homogenetic product, which product consist of one type (Lava or pyroclastic only).

Cikucang Hummock's volume was obtained from the average diameter against its marked peak where the height is from the highest altitude in cross section profile. The hummock volume from calculation is 0,613 km3. Since Hummock is a homogenic eruption product, therefore the V_{DRE} is V_{Volume} of itself (In this case, there are two possibilities of lithology which construct the Hummock, lava or pyroclastic). The thermal energy calculation result is using formula (1) to (3), where the composition is considered as lava, yields the energy contained in Tasik Brigade magma chamber about 11,77 x 1015J or equal to 12.4 MWthermal with 30 years life time production. If the Hummock composition is pyroclastic then the thermal energy contains about 7.06 x 1015J or 7.4 MWthermal/ 30 years life time. Both of these calculation results will be multiplied 0.1 as electrical conversion factor [16] and yield electric capacity ranged from 0.74 MWe up to 1.24 MWe, yet this conversion factor can be range from 0.08 to 0.2 [17]. However, the result was still *an underestimation* since the calculation was only based on morphology without heat loss calculation from geothermal manifestation.

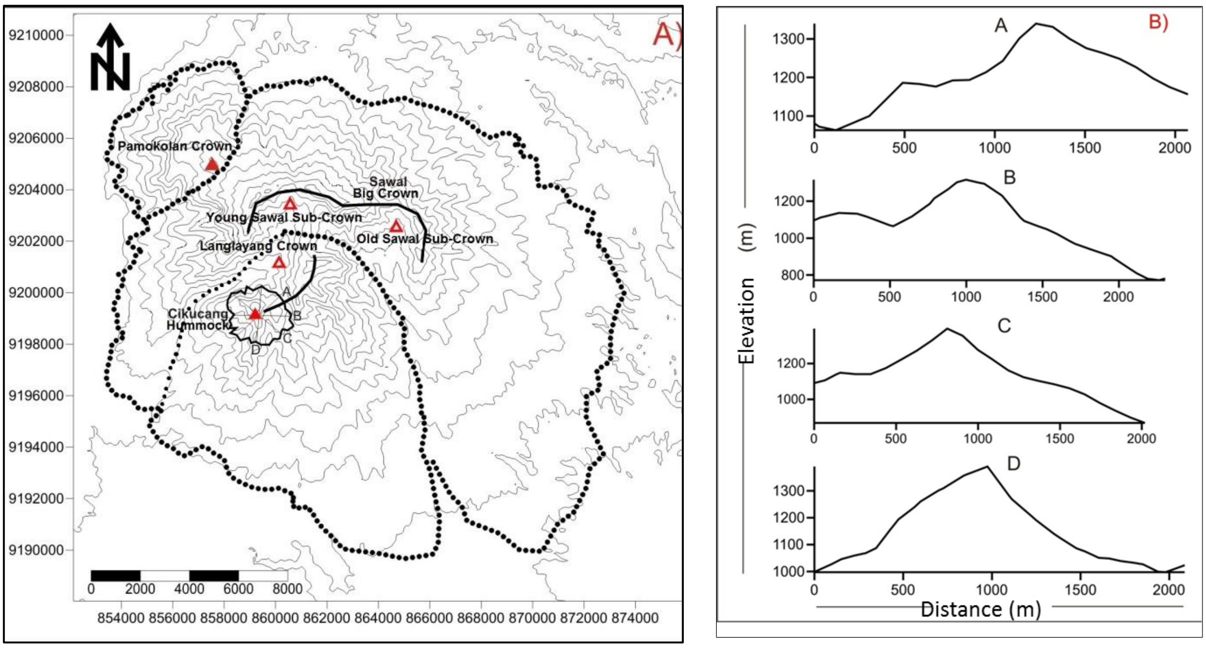


Figure 11. (A) Topographic map with cross section line in Cikucang Hummock. (B) Distance vs elevation profile of Cikucang Hummock which shows a relatively conical shape.

5. Conclusion

Mount Sawal complex has three eruption center (Crown) and one eruption side/monogenetic eruption (Hummock) based on 1:100,000 and 1:50,000 scale topographic map which classified into Tasik Brigade. The distribution of volcanic stratigraphy also correlates with geological map, but the volcanic stratigraphy interpretation has more detailed distribution and boundaries from each eruption product. Digital elevation model analysis shows a debris avalanche/pyroclastic flow on the southeastern flank of Mount Sawal.

Regional structure with N-S and NW-SE orientation presumably control the magma movement in depth or categorized as extensional zone. These structures are also affecting the distribution of volcano eruption pattern (NE and NW pattern). Amalgamating all of the analysis, the chronology of Tasik Brigade formation starts from Langlayang Crown as the oldest, followed by Sawal Crown, Pamokolan Crown and Cikucang Hummock.

Following the evaluation guideline for geothermal potential in stratovolcano, Tasik Brigade is categorized into submature type which possesses electric capacity range from 0.74 MWe up to 1.24 MWe with 30 years life time of production.

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