Topographic map analysis to determine Arjuno-Welirang volcanostratigraphy and implication for geothermal exploration

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Abstract. Volcanostratigraphy study is used for supporting geothermal exploration on preliminary survey. This study is important to identify volcanic eruption center which shows potential area of geothermal heat source. The purpose of volcanostratigraphy study in research area is going to distinguish the characteristics of volcanic eruption product that construct the volcanic body. The analysis of Arjuno-Welirang volcanostratigraphy identification are based on topographic maps of Malang sheet with 1:100.000 scale, 1:50.000 scale, and a geological map. Regarding to the delineation of ridge and river, we determine five crowns, three hummocks, one brigade and one super brigade. The crowns consist of Ringgit, Welirang, Arjuno, Kawi, and Penanggungan, the hummocks comprise of Kembar III, Kembar II, and Kembar I, the brigade is Arjuno-Welirang, and the super brigade is Tengger. Based on topographic map interpretation and geothermal prospect evaluation method analysis, shows that Arjuno-Welirang prospect area have good geothermal resource potential.

1. Introduction
Geographic position of the research area is in longitude 112°29'12”–112°37'39” and latitude 7°37’56”–7°49’51” or UTM coordinates is in 665500 – 679250 mE and 9139000 – 9158200 mN, and under the Malang district, Mojokerto district, and Pasuruan district, East Java Province. Volcanostratigraphy is stratigraphy related to volcanism and its products. The volcano-stratigraphy layering system are based on volcanic source, deposit type, and sequence of time relative. The volcanostratigraphy interpretation consist in relation among topographic map, geologic regional and the Arjuno-Welirang volcano-stratigraphy analysis are using the topographic map of Malang sheet, scale 1:100.000 and scale 1:50.000. The name of extinct volcano in the west of Arjuno-Welirang is Anjasmor. Malang Plain is considered as maar volcano[1].
2. Study Objective
This study objective is to identify eruption center of volcano in order to delineate volcanostratigraphy units such as Hummock (Gumuk), Crown (Khuluk), Brigade (Bregada), Super Brigade (Manggala), and Arc (Busur) [2]. After delineating, it is integrated with geological data, DEM data, and manifestation occurrence in the research area. By doing all of the steps, it can predict geothermal potential area for further exploration survey.

3. Method
Before applying volcanostratigraphy, geologists need to understand basic volcanology, e.g. volcanic geology concepts, genetic volcanism, volcanic landscapes, variation of volcanic rocks, volcanic facies, paleovolcanoes, and super-imposed volcanism. On the basis of a principal in geology, i.e. the present is the key to the past, a volcanic geology concept emphasizes that there is a continuous processes from magmatism through volcanism to sedimentation [3]. The research started with identify the top of mountain in a topographic map, then marking the rivers flow system, and the mountain ridges alignment. The Interpretation process is based on the topographic map and the geologic data of the research area by determining the relative ages of all volcanoes in the area. To determine the relative ages of the volcanoes, we interpreted the texture of the volcano itself and looked at the geology data. All these information will lead us to the geothermal resource potential of this research area. Other interpretation methods is divided by each volcanic eruption center into some smaller volcano stratigraphy units. A volcanic eruption center can be devided into a hummock, several of hummock create a crown, a group crown become a brigade, some brigades and super brigades form an arc. The interpretation result is used as a reference to estimate the geothermal resource potential from a geothermal area, based on to the Geothermal Exploration of Volcano Composition flow chart [4].

Figure 1. Location Map of Research Area.
A geothermal field potential can be calculated by knowing the volume of the volcano using this formula:

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

(1)

Which:

- \( V_{\text{volcano}} \) : Volume of volcano (km³)
- \( r \) : Radius of volcanic cone (km)
- \( h \) : Height of volcano (km)

Furthermore, it is critical to know the volcano’s magma characteristic, such as the degree of partial melting for determining the magma types is produced, whether it is basaltic magma, andesitic magma, or rhyolitic magma. Knowing the volcano age, its structure, and the tectonic features are also important. If the measurement of all factors result are a valuable potential, it can be continued with a detail survey.

**Figure 2. Geothermal Potential Evaluation on Stratovolcano [4].**

4. **General Geology**

Based on the geological region data and East Java tectonic system, the research area is part of the Kendeng zone which is an anticlinorium formed by igneous rocks and sedimentary rocks [5]. In general stratigraphy of the research area from the oldest to the youngest are Linting followed by Arjuno and finally Welirang [6].
There are 5 (five) eruption centers i.e. Mt.Welirang, Mt. Arjuno, Mt. Kembar I, Mt. Kembar II, Mt. Kembar III, Mt. Bakal and side vent eruption in Mt. Balak. Each of the volcano products are classified as magmatic eruption that produced lava and pyroclastic material. A strong tectonic deformation affected the Arjuno-Welirang volcanic activity and caused a difficulty to find the main crater of Linting. Then, there was a big eruption ejected the old Arjuno-Welirang volcanic material and created an abyss in the old Arjuno-Welirang products, which is shown by the present of ring fracture and an collapse zone. Furthermore the abyss would facilitate the coming of new volcanic material, the young Welirang-Arjuno, after it was formed. The volcanic process continued with the forming of Mt.Kembar I, followed by Mt.Kembar II and Mt.Bakal, Southeast trending. The last eruption that produced magmatic material was came from Mt. Kembar II located between Mt. Welirang and Mt. Arjuno.

5. Geological Structure
The geology structures in study area not only influence by tectonic but also volcanic activity. The SE-NW trend of volcanic centers (Arjuno, Kembar I, Kembar II & Welirang) and hot spring of Padusan at Pacet Mojokerto District (SW slope of Welirang) may be controlled by subsurface fault.

a. North-South Trending Fault
The north-south trending fault was represented by The Cangar Fault, The Puncung Fault, and The Claket Fault, which was an alignment manifestation, with the present of fault scarp, waterfall, and the topography difference, that is moderately steep.

b. North-West Trending Fault
This fault was predicted as the antithetic of the major fault, trending southwest-northeast, parallel with the Meratus fault system. This fault was represented by The Kemiri Fault, and The Bakal Fault. The Kemiri Fault and The Claket Fault was assumed to form a graben, where the downward area was filled by the pyroclastic flow from Welirang. This faults became the trigger of thermal manifestation around Padusan area.

c. Southwest-Northeast Trending Fault
This fault was the major fault that causing the forming of Arjuno-Welirang volcano area. And it was associated to the forming of Mt.Penanggungan, trending towards the Sidoarjo Mud. This fault was represented by The Welirang Fault, The Kembar Fault and The Balak Fault.

d. West-East Trending Fault
This fault was represented by The Ledug Fault and The Ringit Fault.

e. The ring fault of Anjasmoro Caldera
This fault type is a normal fault, that formed a steep and circular scarp. This fault appearance can be seen clearly on the way to reach Cangar. This fault was thought to be formed from the remaining of an old caldera that appeared by volcano tectonic activity in Anjasmoro area.

Figure 4. Geological Map of Arjuno-Welirang Volcanoes [6].
6. Result and Discussion

The topographic map analysis scale 1:100,000, identified that there are five crowns i.e. Welirang, Arjuno, and Kawi crowns, three hummocks, one brigade and one super brigade (Figure 6). The Tengger Super Brigade that is located in the Southeast is identified as the oldest unit, and followed by Kawi Crown, Arjuno Crown, Welirang Crown, and Penanggungan Crown as the youngest located in the north of Arjuno-Welirang Brigade. Based on the topographic map of Malang sheet with scale 1:50,000, focus on Arjuno-Welirang Brigade, identified there are five crowns, they are Ringgit, Arjuno, and Welirang Crown and several hummocks (Figure 7). In Arjuno-Welirang Brigade, there are three hummocks i.e. Kembar III, Kembar II, and Kembar I. Based on integrated geological data, volcano-stratigraphy and manifestation occurrence, it is predicted that Welirang Crown has geothermal potential resources.

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Figure 6. Topographic Map of Arjuno-Welirang and Its Surrounding Area (map scale 1:100,000).
5.1 Welirang Geothermal System

Welirang has a central vent eruption that indicated the present of heat resource below the eruption center. There are several geothermal surface manifestations on the top of Mt.Welirang such as solfatara and fumarole (94-137°C) which acts as the upflow zone, and Padusan hot spring at
Kecamatan Pacet, Mojokerto District and another hot spring is called Cangar hot spring, located in the west slope of Kembar I (55°C) with neutral pH acts as the outflow zone in the northwest side of Mt. Welirang [7]. The volcano stratigraphy analysis on a scale map 1:50,000 identified on Welirang crown. This crown data is used to calculate the geothermal potential using the geothermal potential evaluation on stratovolcano method [4].

The volume measurement of Welirang crown shows the diameter value is approximately 10.4 kilometers with the highest elevation is 3339 meters, and the volcano volume is estimated about 102 km³. This volume indicates that Welirang has a big geothermal resources potential. The Welirang volcanic rocks consist of volcanic breccia, lava, and tuf, which age is Middle Quaternary, around 200,000 years old [4].

6. Conclusion
Volcano-stratigraphy units in Arjuno-Welirang Brigade has three hummocks (Kembar III, Kembar II, and Kembar I), five crowns (Ringgit, Welirang, Arjuno, Kawi, and Penanggungan), one brigade (Arjuno-Welirang), and one super brigade (Tengger). Welirang is a stratovolcano that classified into a high terrain geothermal system. The geothermal potential evaluation on stratovolcano method on Mt. Arjuno-Welirang indicate that the volcano has geothermal prospect to be developed by doing further exploration.

7. Recommendation
A geothermal exploration takes a complex information also some sufficient and qualified data for doing further exploration like geological survey for the purpose of creating a detailed geological map and the geothermal manifestations mapping, thus the interpretation process will be more accurate.

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