Integration of the Lineament Study in the Karaha-Bodas Geothermal Field, West Java

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Abstract. The Karaha-Bodas geothermal field is classified as a hydrothermal volcanic system. This field is characterized by the emergence of manifestations in the form of hot springs, solfatara, steamy soil, and mud pools. The manifestations are spread in the northern part of Karaha and south of Telaga Bodas. Based on the characteristics of the manifestations that appear in Karaha and Telaga Bodas, there are allegations that the Karaha Bodas geothermal system is divided into two systems. The distribution of the Karaha Bodas geothermal system can be estimated through geological studies. In this case, the method used is the integration of the lineament study. A lineament study was carried out applying hillshade from four angles, namely 0°, 45°, 90°, and 135°. The results of the lineament will be mapped into structural lineament density anomalies or Fault Fracture Density (FFD). FFD analysis is then integrated with volcano stratigraphy, gravity anomalies, and MT resistivity. Based on the results of the integration, the Karaha-Bodas geothermal system is estimated to be two systems that are different from the high lineament structure density zone in Karaha.

1. Introduction
The Karaha-Bodas geothermal field is one of the geothermal fields in the province of West Java. This geothermal field is categorized as a partial vapor dominated geothermal system [1]. In this field, 9 wells have been drilled, but only five of them are categorized as productive wells. The five wells can produce a total generating capacity of 30 MW which is classified as Unit I and has been operational by the end of February 2018. Wells in this field have temperatures ranging from 250 – 350°C [2].

Geologically, the Karaha-Bodas geothermal field is below the trend north of the andesitic ridge which is approximately 15 km east of Garut district, West Java. This geothermal field is located near the historic environment of active volcanoes, namely the Guntur, Papandayan, Cikuray and Galunggung volcanoes (Figure 1) which indicate intensive heat input to the top of the crust. Galunggung volcanic crater located in the southeastern part of the Karaha-Bodas ridge which has an indication of the influence of volcanic activity on the geothermal system above it [1]. According to [3], geothermal fields in volcanic environments will show thermal manifestations with characteristics that tend to be acidic, such as acid hot springs, mud pools, steaming ground, and fumaroles or solfatara.
The thermal manifestation activities possessed by the Karaha-Bodas geothermal system are divided into 2 (two) separate areas with a distance of about 10 km (Figure 2). In the southern part (Talaga Bodas) or the boundary of the system which has an area of about 2 km² and an altitude of 1750 m above sea level, there is an area of fumarole (Saat Crater), an acidic lake (Telaga Bodas) and hot springs. At lower elevations about 1 km from the southeast of Telaga Bodas lake, there are springs of sulfide-bicarbonate type with moderate to low pH (pH 2 and flow rate of 7 L/s). The Karaha Crater is located in the southeastern part of the volcanic flanks of the Putri-Erewanda complex (altitude 1060 m above sea level) which has manifestations such as solfatara, steaming ground, mud pools, and hot springs (flow rate of 1.6 L/s and maximum temperature of 91°C). In addition, there are also several low-temperature bicarbonate springs that appear in the valley close to the Karaha-Bodas ridge [1].

The survey results of resistivity in the Karaha-Bodas geothermal system indicate that the Karaha-Bodas geothermal system is a single system with resistivity values ranging from 5 – 20 Ω.m, where the resistivity value in the range of 10 – 20 Ω.m is in the northern part of the Karaha-Bodas ridge. While the resistivity values in the range of 5 – 10 Ω.m are in the south with indications of argillic alteration. In addition, based on the gravity method, positive anomalous values are in the middle of the area close to Talaga Bodas and Saat Crater which cover an area of 10 km². The positive gravity anomaly is an indication of volcanic intrusion which acts as a subsurface heat source between Talaga Bodas and Saat Crater [1].

The determination of the geothermal system boundary is generally carried out using geophysical data, namely through resistivity data from the magnetotelluric (MT) or geoelectric survey. Resistivity values <10 or 20 Ω.m which indicate the caprock zone is often considered as a reference for limiting the reservoir of a geothermal system [4].

In this study, the determination of the boundary of the Karaha-Bodas geothermal system will discuss based on the lineament study integration method. The determination of the boundary of the Karaha-Bodas geothermal system will be adjusted according to the delineation of the permeable zone of lineament density or Fault Fracture Density (FFD). FFD is a simple method used to determine areas with high structural density. High structural density is formed by interconnecting faults and fractures.
both tectonically and volcanically [5]. The FFD anomaly map will be correlated with the volcano stratigraphy, gravity, and resistivity of the Karaha-Bodas region.

![Map of Karaha-Bodas](image)

**Figure 2.** Map of Karaha-Bodas along with the wells and thermal manifestations [6]

2. Geology

The Karaha-Bodas geothermal field is associated with quarterly volcanic deposits, which consist of andesitic-dacitic lava and pyroclastic (tuff) rocks, and clastic lava. This sequence is locally intruded by the diorite intrusion bodies and covers the sedimentary complex from the landscape formation. Volcanic activity continues until the recent date and is expressed in the Karaha region in the form of NW-SE volcanic cones with an age of around 0.5 million years ago. In the southern part of Talaga Bodas, volcanic activity is expressed by the presence of an andesitic-dacitic N-S dome, there is a crater, and is 0.3 million years old. The presence of Galunggung in the south reflects that volcanic migration moves from north to south.

The structural patterns in the Karaha-Bodas area are northwest-southeast, northeast-southwest, passing through the Karaha crater (Figure 3). The structure that is estimated to be directed by the WNW-ESE located between the Karaha ridge and Talaga Bodas.

The stratigraphy of the Karaha-Bodas region, respectively, from the oldest to the youngest are breccia pyroclastic II (Mt. Cakrabuana), breccia pyroclastic III (Mt. Cakrabuana), breccia pyroclastic I (Mt. Sadakeling), tuff (Mt. Talaga Bodas), andesite and breccia (Mt. Talaga Bodas), breccia pyroclastic (Mt. Talaga Bodas), andesite (Mt. Sadakeling), breccia pyroclastic (Mt. Putri-Eweranda), breccia pyroclastic IV (Mt. Talaga Bodas), andesite (Mt. Eweranda), tuff (Mt. Putri), and alluvial (Figure 4) [7].
3. Geophysics

3.1. Gravity

The Bouguer gravity data which depicted in Figure 5 is the original data taken from the GENZL survey. The data is reduced using a density value of 2.3 g/cc. The Figure shows the existence of a high-density unit extending from Talaga Bodas to Karaha Crater. Anomalies of high-density units appear to peak

![Geological Map of Karaha-Bodas](image)

**Figure 3.** Geological map of Karaha-Bodas [8]

| Dates (m. y.) | Symbol | Lithology |
|---------------|--------|-----------|
| 0.507         |        | Alluvial   |
| 0.554         |        | Tuff (Mt. Putri) |
| 0.586         |        | Andesite (Mt. Everanda) |
| 0.649         |        | Breccia Pyroclastic IV (Mt. Telaga Bodas) |
| 1.3           |        | Breccia Pyroclastic (Mt. Putri-Everanda) |
| 1.74          |        | Andesite (Mt. Sadakeling) |
|               |        | Breccia Pyroclastic (Mt. Telaga Bodas) |
|               |        | Andesite and Breccia (Mt. Telaga Bodas) |
|               |        | Tuff (Mt. Telaga Bodas) |
|               |        | Breccia Pyroclastic III (Mt. Cakrabuana) |
|               |        | Breccia Pyroclastic II (Mt. Cakrabuana) |

**Figure 4.** Stratigraphy of Karaha-Bodas
radially symmetric at Talaga Bodas. The cause of this widespread anomaly is caused by the presence of quartz diorite at a certain depth. This interpretation is consistent with the high temperatures found at relatively shallow depths, high fluid inclusion temperatures, and the presence of secondary minerals (such as fluorite, sulfur, tourmaline) that show episodic magmatic degassing. This interpretation illustrates the existence of a heat source based on the delineation of the source of gravity. The Karaha-Bodas data gravity analysis produces a consistent model of mushroom-shaped intrusion that reaches a relatively shallow depth under the thermal area of the Talaga Bodas system. The intrusion extends around 10 km to the north with a relatively thin form underlying most of the geothermal prospects.

Figure 5. Bouguer gravity Karaha-Bodas anomaly map [9]

3.2. Resistivity MT
MT Karaha-Bodas resistivity data comes from measurements carried out by Geosystems in 1996 and 1997. The low resistivity zone at shallow depths (<10 Ω.m) is observed in the Talaga Bodas area (Figure 6). This shallow conductive area is likely to be correlated with argillic type alteration in the upflow and surrounding zones. In this conductive area, there are two resistive points which are considered as a sign of steam emitting in the Bodas area.
At deeper depths, the conductive zone (<10 Ω.m) becomes wider and covers almost two thirds of the area (Figure 7). The extent of this layer is likely to be controlled by the hydrothermal fluid which is deeper circulating in accordance with the topography, or the presence of deeper argillic alteration. At the top of the Talaga Bodas area, most of it consists of argillic alterations with low conductivity 1-10 Ω.m. This layer then extends from the upflow zone around 7 km to the north and thinning (up to 700 m) toward 7 to 12 km to the north in the Karaha region. The layer resistivity range also slightly increases to 5 – 14 Ω.m [10].

![Figure 6. The Karaha-Bodas MT resistivity map for (a) the period 0.25 s (depth of 800 m); (b) the period 1.0 s (depth of 1600 m) [10]](image-url)
4. Material and Method

The materials used in this study are the lineaments from topographic maps. The topographic map is obtained from the Digital Elevation Model (DEM), which was built from several data sources including IFSAR data (resolution 5 m), RARED-X (resolution 5 m) and ALOS PALSAR (resolution 11.25 m) (Figure 7). The lineament withdrawal is done by applying the hillshade from four angles, namely 0°, 45°, 90°, and 135°. The results of the lineament drawing from each angle are combined into one which is then formed a lineament density anomaly map known as the Fault Fracture Density (FFD). The FFD map is made using grid dimensions measuring 1 km × 1 km. Furthermore, the FFD map is used to be correlated with a volcano-stratigraphic map which is the basis of volcanic mapping. The stratigraphic unit of the formation is the same as a crown and a unit smaller than that is considered a hummock. Two or more crowns can be considered as brigades. Meanwhile, the volcano-stratigraphic units which consisting of several crown, brigades, and super brigades are referred to as arc [11].

In addition to being correlated with volcano-stratigraphic maps, the FFD map is correlated with a map of the gravity anomaly and resistivity of the Karaha-Bodas area. The values of positive gravity anomaly and low resistivity are considered as in delineating the boundary of the Karaha-Bodas geothermal system. Through this method, recommendations regarding productive zones for further exploration in the Karaha-Bodas area can also be estimated.

![Figure 7. Digital elevation model of Karaha-Bodas](image-url)
5. Results and Discussion

5.1. Lineament Study and Fault Fracture Density (FFD)

A lineament study carried out on hillshade DEM maps (0°, 45°, 90°, and 135°) indicates the dominant line in the middle of the Karaha-Bodas area. The line trend tends to be the NW-SE direction (Figure 8). This seems clear when the lineament pattern is changed to the FFD anomaly contour shown in Figure 9.

In Figure 8, the line density value ranges from 0 to 5283. The high lineament density value is a representation of the alignment in a one-dimension grid measuring 1 km × 1 km. The high-density values are scattered in several locations and tend to be dominant in the middle of the Karaha-Bodas area. High lineament density can reflect the existence of permeable structures that act as a path of thermal fluid flow from a reservoir at a certain depth to a shallower part [5]. This can be seen through the appearance of manifestations of hot springs in the southern part of the crater of Talaga Bodas and north of the Karaha Crater. The emergence of manifestations of hot springs in the Talaga Bodas Crater coincides with fair to high lineament ranges from 1321 to 3962. The same applies to the emergence of manifestations of hot springs in the Karaha Crater which have lineament density ranging from 2641 to 3962.

Figure 8. Lineament map of Karaha-Bodas from four angles (0°, 45°, 90°, and 135°)
5.2. Volcano-stratigraphy

Based on the volcano-stratigraphic interpretation, there are four crown units and nine hummocks in the Karaha-Bodas area and its surroundings (Figure 10). The four crowns units are Cakrabuana, Sedakeling, Talaga Bodas, and Galunggung. While the nine hummocks are Cakrabuana, Sedakeling I, Sedakeling II, Sedakeling III, Talaga Bodas I, Talaga Bodas II, Talaga Bodas III, Talaga Bodas IV, and Galunggung. The withdrawal and determination of the crown boundary are based on the topography of the Karaha-Bodas region which then compared to the geological map (Figure 11). The delineation of the crown boundary corresponds to the stratigraphic boundary of the Karaha-Bodas region and its surroundings. Cakrabuana Crown has a stratigraphic unit of pyroclastic breccia (Mt. Cakrabuana). Sedakeling Crown has andesite stratigraphic units (Mt. Eweranda), pyroclastic breccia (Mt. Putri-Eweranda) and andesite (Mt. Sadakeling). Talaga Bodas Crown has a stratigraphic unit of pyroclastic breccia IV (Mt. Telagabodas), pyroclastic breccia (Mt. Telagabodas), andesite and breccia (Mt. Telagabodas), and tuff (Mt. Telagabodas). Galunggung Crown has a stratigraphic unit of IV pyroclastic breccia (Mt. Telagabodas). Determination of the Galunggung crown with a stratigraphic unit of breccia pyroclastic IV (Mt. Telagabodas) was based on the contour and topographic patterns which tend to reflect the vent in southeast.
Figure 10. Volcano-stratigraphy map of Karaha-Bodas

Figure 11. Volcano-stratigraphy map of Karaha-Bodas
5.3. FFD and Volcano-stratigraphy
The results of volcano-stratigraphic interpretation are combined with the Karaha-Bodas FFD anomaly map (Figure 12). Based on these images, the Sadakeling crown tends to have a denser lineament density structure compared to the Talaga Bodas crown. The denser lineament density in the Sadakeling crown area is considered to be a more permeable area with an average lineament density of around 5283. While in the Talaga Bodas crown area, the density is not as dense as in the Sadakeling crown area. This is indicated by the average lineament density which is only less than 5283. Nonetheless, the number of manifestations in the Talaga Bodas crown area are more than in the Sadakeling crown area. The manifestations that appear in the Talaga Bodas crown area are in the Talaga Bodas Crater area. There are relative advantages and disadvantages between the two types of well pumps as outlined in Table 2 (adapted from [1]), and these aspects can be the basis in selecting which pump type is preferred for a particular system.

![Figure 12: Overlay of the FFD anomaly and volcanostratigraphy map of Karaha-Bodas](image)

5.4. FFD and Gravity
The gravity anomaly map is combined with the Karaha-Bodas FFD anomaly map (Figure 13). High gravity anomalies in the Talaga Bodas area show a high anomaly of lineament density in the surrounding area. This is probably related to the presence of intrusion which acts as a sub-surface heat source. Formation of fractures or lineament structures can form around the intrusive body which developed during the intrusion of igneous rocks to surrounding rocks [10]. The densely lineament density zone in the middle is related to the expansion of the high-density gravity zone from Talaga Bodas towards Karaha. The possibility of small intrusions in the north-western part of Karaha is supported by the
density of the compact structure around it. The intrusion in the north-western part of Karaha appears through the contour pattern of gravity anomalies which slightly increases to the northwest of Karaha.

5.5. FFD and Resistivity MT

The resistivity maps of MT at depths of 800 and 1600 m are combined with the FFD anomaly map. The resistivity at depth of 800 m (Figure 14), a low resistivity zone (<10 Ω.m) was observed in the Talaga Bodas area with a less dense lineament density around 1321. The lineament density in this area may be related to the presence of the Talaga Bodas Crater which correlates with the argillic alteration. At the top of the Talaga Bodas area was dominated by the argillic alterations with low conductivity 1-10 Ω.m. The existence of these argillic alteration may affect the lineament to be less visible on the surface.

The resistivity at depth of 1600 m (Figure 15) shows the conductive zone (<10 Ω.m) becoming wider and covering almost two thirds of the area with a denser lineament density in the north. The lineament density that is denser in this area probably acts as a permeable zone that controls the hydrothermal fluid to deeper circulate according to topography. The presence of hydrothermal fluid also affects the conductivity to be wider.

![Figure 13](image)

**Figure 13.** The overlay between Bouguer gravity and FFD anomaly map of Karaha-Bodas
Figure 14. The overlay between resistivity (at 800 m depth) and FFD anomaly map of Karaha-Bodas

Figure 15. The overlay between resistivity (at 1600 m depth) and FFD anomaly map of Karaha-Bodas
6. Conclusion
The results of the integration study of the lineament on several data which shown from Figure 12 up to Figure 15 indicate that the Karaha-Bodas geothermal system is estimated to be two different systems, i.e. the Karaha system and Talaga Bodas system. The Karaha system is associated with the Karaha ridge which according to the volcano-stratigraphy map referred to Sedakeling crown. The Talaga Bodas system is associated with the Talaga Bodas ridge which referred to the Talaga Bodas crown. The presence of intrusion that acts as a heat source in the Karaha system can be estimated through the gravity anomaly contour which increases to the northwest of the Karaha with dense lineament density structures around it. A high permeable zone was estimated in the middle of the Karaha-Bodas area with a dense lineament density. This was supported by some expansion of the conductive zone to the north at a depth of around 1600 m which is probably related to thermal fluid circulation. The recommendation area for further exploration tends to point in the north to northwest of the Karaha area.

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