Geological Controls on Thermal Manifestation Occurrences in Batu Gede and Batu Kapur, Subang Regency: A Preliminary Result

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Abstract. Batu Gede and Batu Kapur are administratively located in Subang Regency, West Java, precisely in the northern part of Tangkuban Perahu Geothermal Working Area. Characteristics of the manifestations in Batu Gede and Batu Kapur are generally bicarbonate neutral pH warm springs and their location exposed in the foot of Tangkuban Perahu Volcano. Despite the similar chemical characteristic of those two manifestations, there is a significant characteristic difference between them. Spring with low pH with the pungent smell emerges in the Batu Gede not far from neutral pH bicarbonate warm spring. The aim of this research is to determine control of the occurrence and relationship of manifestation in both areas by conducting geological mapping. Surface manifestations are controlled by a geological process associated with primary and secondary permeability. Both manifestations emerge dominantly in the control of fault as a secondary permeability. Primary permeability also controls the occurrence of manifestations but not significant. Batu Gede manifestations are dominantly controlled by overstepping structure, while Batu Kapur are dominantly controlled by intersections between structures. Based on high content of SO$_4^{2-}$, acid pH, and the presence of sulfur, the acid manifestation might be correlated with magmatic activity beneath Batu Gede’s manifestation.

1. Introduction

Batu Gede and Batu Kapur are two regions located in Subang Regency, West Java Province. These two regions are located about 13 – 15 km in the northern part of Tangkuban Perahu volcano (Figure 1). The distance between these two regions is about 5 km away. The geothermal manifestations in the Batu Gede and Batu Kapur areas are located at the distal facies of Tangkuban Perahu Volcano. Characteristics of the manifestations in Batu Gede and Batu Kapur are generally bicarbonate neutral pH warm [1, 2].

Despite the similar chemical characteristic of those two manifestations, there is a significant difference between them. A preliminary geological study was therefore carried out to determine the control of
thermal manifestation occurrences in both areas. Surface manifestations of these areas might be controlled by primary permeability, secondary permeability, or both of them. According to [3], primary permeability is permeability that formed when rocks are formed, such as porosity, autobrecciated lava, lithological contact, and diatreme. Meanwhile, secondary permeability is formed due to several processes such as tectonic activity, intrusion, rock dissolution, and hydrothermal breccia. All processes that result in the formation of permeability are controlled by geological activities that occur either by tectonic or volcanic processes.

2. Data and Method
To understand the occurrences of Batu Gede and Batu Kapur geothermal manifestations, a lot of literature and maps have been collected and studied to build initial assumptions and narrow down the scope of the research. The basic framework is to comprehend the correlation of the occurrence of manifestations with lithology, geological structure, alteration, spreading pattern of the manifestations, and water. Starting with geomorphological study, Digital Elevation Maps downloaded from DEMNAS was used to analyze the drainage pattern, slope analysis and determine the catchment area. Geomorphological study is expected to explain relationship of water geochemistry and hydrology in this area. Field work then was conducted including geological mapping and geochemistry (water) sampling. Geological mapping has been done with scale 1:5000. Rock sample representing the rock unit was analyzed using petrography analysis. Petrography analysis shows the characteristic of lithology, alteration, and microstructure. At the same time, water sample was collected to analyze cation, anion, and neutral species. The thermal water sample was analyzed in PT. Geoservice. These data and analyses will provide a simple understanding of Batu Gede and Batu Kapur's manifestation. The result of this study could be helpful for a better understanding of the geothermal systems in the mutual geologic environment.

3. Geological Setting
Java is located at the southern part of the Sunda Land of Eurasian Plate, where the Indian-Australian plate is subducted beneath Eurasian Plate (Figure 2). The present subduction beneath Java began at about 45 Ma and has been almost perpendicular to the Java Trench. Active plate convergence has produced arc volcanism and intrusion since the early Oligocene along the Sunda Arc. West Java is
considered to be located in the transitional zone between oblique subduction in Sumatra and orthogonal subduction in the eastern part of West Java [4].

Regional lithological units that present in the study area from older to younger, respectively are [5]:

1. Kaliwangu Formation (Pk) is a ± 600 m thick bed, tuffaceous sandstone, conglomerate, and claystone, rarely calcareous sandstone, limestone, and thin layers of peat and lignite. Sandstone and conglomerate contain abundant Mollusca.
2. Citalang Formation (Pt) tuffaceous marl intercalated by tuffaceous sandstone, breccia, and conglomerate, with thickness 500 – 600 m.
3. Older Volcanic Products (Qob), with 600 m thick, consist of breccia, lahar, and sandy tuff. Bedding with low angle initial dip is observed in this formation.
4. Undifferentiated Young Volcanic Products consist of tuffaceous sand, lapilli, lava, agglomerate mostly from Mount Tangkuban Perahu, and Mount Tampomas. Between Bandung and Sumedang, this unit expressed as a flat or low hill area covered by yellowish gray to reddish gray soil.
5. Old Volcanic Products Lava (Qyl), lava, showing columnar joints and sheeting, it is basaltic in composition and partly propylitized.
6. Alluvium (Qa), mainly deposits of Holocene streams, consists of clay, silt, sand, and gravel.

Figure 2. Present-day tectonic setting of Indonesia [4].

In the southern part of the study area lies Old Volcanic Products Lava (Qyl), Pumiceous Tuff (Qyt), and Older Volcanic Products (Qob). Undifferentiated Young Volcanic Products found in the middle area. These are eruption products of Mount Tangkuban Perahu located in the south of the study area. The total thickness of these products is more than 600m, known from the thickness of Qob alone is 600m, and the others are not clear. The northward area is dominated by Citalang and Kaliwangu Formation. Kaliwangu formation is indicated as marine sediment, corresponding with the presence of calcareous sandstone and limestone.

As shown at regional map Figures 3, Kaliwangu Formation has regional dipping direction southward approximately 10-29°. It can be interpreted as proof that Kaliwangu Formation can be found below the study area. Kaliwangu formation's bed is relatively thick on the east, thinner on the middle area, and getting thicker westward. These conditions caused the occurrence of travertine on Batu Kapur is more intense than Batu Gede.
4. Detailed Geology

4.1. Remote Sensing Geomorphology

Geomorphology is the study of the earth's physical features and the processes in which those features are formed [6]. Geomorphological studies carried out include the identification of drainage patterns, slope analysis, and catchments area delineation. All analyses above were carried out by observing remote sensing images. The data used in this research are topographic maps (scale 1:25000) and Digital Elevation Model (DEM), which are also processed further using QGIS software to generate drainage patterns and slope maps. This study is pre-field activity that very helpful to interpret geological condition.

![Figure 3](image_url)

**Figure 3.** (a) Geology Regional of the study area redrawn after [5], (b) Interpretation of geology regional of the study area redrawn after [5].

4.1.1. Drainage Pattern. The identification of drainage is carried out to determine the general characteristics of lithology, slope, and indications of the presence of geological structures. Drainage patterns in the research area consist of four patterns, according to [7], namely dendritic, sub-dendritic, sub-parallel, and rectangular (Figure 4). The dendritic pattern is associated with homogeneous lithologies, horizontal or very gently dipping strata, flat topographic surface with low reliefs. This pattern is found in the northwestern part of the research area precisely around Cinangka Village. Sub-dendritic pattern is found at the eastern parts of the research area precisely around Cicariu and Tambakan Village. The rectangular pattern is characterized by regularly spaced right-angle bends in the tributaries and mainstream. River with this flow pattern has a sharp turn direction attain to 90°. This drainage pattern implies the control of tectonic structures, typically joints and faults, at or near right angles. These structures may result from one deformation event or, most likely, are structures from multiple deformation events overprinting one another. This drainage pattern is found in the center part of the research area around the Batu Gede and Batu Kapur area.
4.1.2. **Slope Analysis.** Slope analysis is carried out to show the characteristics of each geomorphological unit. The data used to create the slope map is a Digital Elevation Model (DEM) satellite image. The image is processed using QGIS software by classifying the angle of slope based on the classification, according to [8]. The difference in slope inclination indicates different types of lithology and erosional stages. On steeper slopes, the lithology is resistant to the weathering process. Otherwise, the gentler slopes (flat) could indicate that the lithology relatively consists of softer rocks.

Based on the slope analysis of the research area, the slope map shows that the slope ranges from 8 – 40° are associated with volcanic rocks. This unit is the most widely distributed in the center of the study area. The slope between 8 – 16° is associated with sedimentary rocks, which are spread in the northern part of the study area. Meanwhile, relatively gentle slopes (less than 8°) are found as plain. This unit is located in the south-eastern parts of the research area (Figure 5). At Batu Gede, particularly around manifestations, there is a significant change of the slope from gentle in the south area to steep in the northern part. It might indicate the presence of fault or lithology contact. Manifestations emerged on a gentle slope. Therefore, it might be associated with fine-grained size rock. Meanwhile, Batu Kapur is included in the relatively steep hills. The result of this analysis suggests that Batu Kapur area seems to be associated with fault structures that were inferred from topographical offsets, river alignments, and steep slope alignments.
4.1.3. Catchment Area. Delineation of the catchment area helps to understand the concept of hydrogeology or the origin of streamflow from a manifestation. The catchment area delineation is done by determining the outlet point, mainstream, and stream order. A catchment area is confined by tracing the ridgeline over the lowest streams that drain into it. This delineation was carried out on a topographic map scale of 1:25,000. The research area consists of 5 catchment areas (red line) (Figure 6). Each catchment area consists of several sub-catchments (black dashed line). The manifestations of Batu Gede and Batu Kapur are located at the same catchment area, but different sub-catchment areas. The catchment area is originated from the slope of Tangkuban Perahu in the northern part of the research area. It indicates that regional flow is still getting effect from Tangkuban Perahu. However, from detailed observation, Batu Gede's manifestation, in reality, is not directly affected by Tangkuban Perahu. The flow direction of Tangkuban Perahu's product obstructed by a ridge that becomes the boundary of Batu Gede's sub-catchment. The manifestation is concentrated in the main valley of the sub-catchment. Flow direction is originated from a narrow ridge. These facts indicated that Batu Gede is a structural controlled- manifestation. Meanwhile, Batu Kapur manifestation flow clearly originates from ridge lineament with trend NW-SE and WNW-SSE. This shows that Batu Kapur is correlated with heat flow with a source from a certain depth.
Figure 6. Catchment Area Map of Batu Gede and Batu Kapur Area. The red line is represented the catchment area, while the black dashed line is the sub-catchment area.

4.2. Stratigraphy

Detail field mapping was conducted to determine the control of manifestation occurrence. Based on field mapping, lithology in the research area mostly consist of volcanic rocks like andesite, basalt, crystal tuff, pumice rich pyroclastic breccia, vitric tuff, lapilli tuff, volcanoclastic and sedimentary rock such as claystone, sandstone, and limestone (Figure 7).

Outcrops of volcanoclastic and sedimentary rocks are also founded. Some of them contact with pyroclastic rock, where the sediment rock is placed below the pyroclastic rock. The geological map, therefore, is built based on the lithological unit from those lithologies (Figure 8). Following are lithological unit from younger to older respectively, Tangkuban Basalt Lava Flow, Manglayang Pyroclastic Flow Breccia 4, Manglayang Crystal Tuff 1, Manglayang Pumice Pyroclastic Flow Breccia 3, Manglayang Pumice Pyroclastic Flow Breccia 2, Manglayang Pyroclastic Flow Breccia 2, Manglayang Pumice Pyroclastic Fall Breccia, Manglayang Pyroclastic Flow Breccia 1, Manglayang Pumice Lapilli, Manglayang Pumice Pyroclastic Flow Breccia 1, Manglayang Vitric Tuff, Sunda Basalt Lava Flow, Sunda Andesite Lava Flow, Interbedding of Breccia and Sandstone, and Sedimentary Breccia.

Pumice rich pyroclastic breccias were found in several areas. At KTK02-08, Batu Gede area, this outcrop is about 120 meters to the southeast from cold acid springs and mud pool and about 110 m to the south of bicarbonate warm springs. Pumice rich breccia was found had contact with lapilli tuff in the upper part. However, this pumice rich breccia is thinning to the north-western part, while Lapilli Tuff is thickening (Figure 9). Mud pool and low pH cold spring might be controlled by lithology contact. Mud is easier to form, especially in fine-grained size rocks.

Pumice rich breccia contact with volcanoclastic was observed at JS08-05, where volcanoclastic exposed in the lower part. There is a charcoal layer between the contact (Figure 10a). Outcrop of volcanoclastic has similar characteristics with the outcrop at KTK 04-09 (Figure 10b). From these figures can be observed that colour change between lithological contact represented by alteration in the form of clay alteration abundance and iron oxide. This fact shows that the lithological contact also
estimated to be permeable zone. The appearance of alteration also interpreted to be controlled by paleo-water table.

Volcanoclastic was also observed at KTK 05-02, accompanied by the presence of pisoids (Figure 11a and b). In general, the structure of pisoids consists of a central nucleus and concentric cortical laminations, composed of calcium carbonate (aragonite or calcite) and organic matter. The presence of this texture indicated that the sedimentary process has occurred. Furthermore, limestone is also found in KTK04-07 (Figure 11c-d) in Batu Kapur area and interpreted conformably with Kaliwangu Formation in the regional geology map by [5]. However, limestone is only exposed in Batu Kapur area. Thus, geothermal manifestation occurred in Batu Kapur is interpreted as associated with the limestone.

Figure 7. Observation point map of the research area showing the location of lithology and manifestations.
Figure 8. Geological map of research area.

Figure 9. Contact between Pumice Rich Breccia and Lapilli Tuff at KTK02-08 with charcoal layer in between.
4.3. Geological Structures

Secondary structure evidence found in the study area are slickenside, fault plane, offset, and intense fracture. Moreover, the non-tectonic structure is also found, caused by loading (Figure 12). There is overstepping in Batu Gede Area, controlled by the occurrence of sinistral strike-slip fault with trend ENE-SSW, overlapping among themself, forming an overstepping with trend relatively N-S. This overstepping is an extension and could be used as a permeable zone. The overstepping evidence is found on some of the basalt lava outcrops. This overstepping structure is correlated with antithetic fault from the main fault because it shows different orientation with the main structure. The evidence is also found
in the microscopic observation of the pyroclastic rock (Figure 13). The overstepping structure is also depicted from the morphology of Batu Gede (Figure 14) that shows the ridge wedge valley. Meanwhile, in Batu Kapur, lies offset and slicken line that indicating fault movement with trend WNW-SSE. These faults are interpreted to intersect with NNW-SSE fault, producing permeable zone (Figure 15).

![Figure 12](image1.jpg)

**Figure 12.** Thrust fault caused by the loading of the younger pyroclastic product.

![Figure 13](image2.jpg)

(a) **Figure 13.** Overstepping evidence found in the study area, antithetic of the main fault. This evidence is also observed in the pyroclastic thin section.

![Figure 14](image3.jpg)

**Figure 14.** Morphology of overstepping structure in Batu Gede manifestation.
Figure 15. Field evidence including slickenside, fault plane, and offset showing strike-slip movement.
5. Result and Discussion
Batu Gede and Batu Kapur are two locations that have surface manifestations. Both locations are in the Subang Regency, precisely in the northern part of Tangkuban Perahu Volcano. Batu Gede is located at an elevation of 432 m a.s.l., approximately 13 km northeast of Tangkuban Perahu. Meanwhile, Batu Kapur is located at an elevation of 370 m a.s.l. The distribution of Batu Gede and Batu Kapur manifestations shows in (Figure 16 and Figure 17).

Field survey results in the Batu Gede area show that warm springs are around paddy fields with the flat morphology relatively (~432 m a.s.l.). The appearances of these warm springs are thought to be due to the influence of the overstepping faults. In Figure 5, the locations of Batu Gede warm springs are marked by the code KTK02-01 and KTK02-06. The characteristics of KTK02-01 warm spring (Figure 18) are bubbling with the iron oxide deposits around it. In addition, the paddy that surrounds the warm spring appears to experience stress anomalies. This is based on the appearance of paddy fields contaminated with iron oxide and CO₂ gas. Based on the measurement results, KTK02-01 warm spring has dimensions of 2 x 2.5 m with a temperature of around 44.7°C, pH of 7.79, and high flow rates (~0.5 – 1 L/s). Meanwhile, the KTK 02-06 warm spring (Figure 18) is across the Gede river with a plain
morphology. This warm spring has the same characteristics, namely bubbling and iron oxide deposits around it. The measurement results show that this warm spring has a temperature of 47.4°C with a pH of around 6.9 and low flow rates (<0.5 L/s). High discharge on manifestation shows the possibility of fault control. The fault that controlled the occurrence of Batu Gede manifestation related to overstepping structure. It is produced by a sinistral strike-slip fault with trend W-E.

Figure 17. Detailed manifestation map of Batu Kapur Area.

In the Batu Kapur area, numbers of hot and warm springs were found along the river with an elevation of around 370 m a.s.l. Their appearances are expected due to intersections between structures that are relatively north-south and west-east. The locations of hot and warm springs in this area are shown in Figure 17. Batu Kapur hot springs (Figure 19) have colorless, odorless characteristics, and the average flow rates are quite high (~0.5 L/s). Around the hot springs, especially KTK04-02, KTK04-06, and KTK06-01, there are intensive travertine deposits. Based on the observation in the field, Batu Kapur’s manifestations are physically clear and bubbles are present. Direct measurement results in the field using Thermo-couple Hanna showed that Batu Kapur hot springs have temperatures ranging from 50.2 – 57.4°C with a pH of 6.73 – 7.7. The lithology around these warm springs is pyroclastic rocks. The measurement results show that the temperature of Batu Kapur warm springs ranges from 33.9 – 48.9, pH of 6.34 – 6.7, and low flow rates (~ 0.5 L/s). High manifestation’s debit along the river, whether on the left or right side, indicated that manifestation dominantly controlled by fault. Geological data shows the manifestation appears on the intersection of NNW-SSE and WNW-ESE strike-slip fault. However, lithological contact also contributes a little to control the appearance of manifestations. The abundance of bubbles on manifestation indicated the possibility of interaction between subsurface hot water with carbonate-rich rock such as marine sediment. This matter needs to be confirmed with the chemical composition of manifestation.
Figure 18. Batu Gede manifestations and their locations sketch (not-to-scale).

Figure 19. Batu Kapur manifestations and their locations sketch (not-to-scale).
The water geochemical data in Table 1 shows that Batu Gede and Batu Kapur warm springs tend to be bicarbonate water [9]. Based on these data, Batu Gede's warm spring shows an increase in the content of the element chloride (Cl) to reach more than 1500 mg/kg. The high content of chloride (Cl) is also followed by the content of sodium (Na) and bicarbonate (HCO$_3^-$). This is thought to be related to the formation of marine sediments beneath the surface from Kaliwangu Formation.

The type of water content owned by Batu Gede and Batu Kapur warm springs is considered an outflow zone of the Tangkuban Perahu geothermal system [7]. However, the results of the field survey in the Batu Gede area showed anomalies of manifestation that appeared on the surface. This anomaly is characterized by the appearance of KTK02-05 cold springs (Figure 18), which has a dimension of about 70 x 40 cm. These cold springs appear at several points in the paddy fields. Directly measurement results in the field using Thermocouple Hanna show that cold spring has temperatures ranging from 27.2 – 29.1°C with pH around 3.05 – 4.17. The characteristics of the cold spring are bubbling, pungent smell, and high flow rates (~0.5 – 1 L/s). In the vicinity, there are very intensive sulfur deposits and clay alterations. Based on the results of the water geochemical analysis shown in Table 1, KTK02-05 cold spring tends to be dominated by sulfate (SO$_4^{2-}$) content, which reaches 178 mg/kg.

Meanwhile, bicarbonate (HCO$_3^-$) and magnesium (Mg$^{2+}$) contents, which are generally contained in groundwater, tend to be small. Based on this, KTK02-05 cold spring is strongly suspected to be related to the activity of thermal fluid resulting from the condensation of H$_2$S gas beneath the surface. This also affects the surrounding rock so that it undergoes alteration. However, the thermal fluid is likely to have cooled down due to its intersection with water level (potentially related to local groundwater system). The physical appearance of the bubbling cold spring, as well as the warm springs in the Batu Gede area, is thought to be due to the influence of geothermal gas activity that breaks through the rock gaps. The emergence of the Batu Gede area's lowest elevation is very closely related to lithological contact between pumice breccia and lapilli tuff. The presence of sulfur and acidic pH indicated that the heat source of this system potentially from magmatic activity. However, an additional survey, such as gravity and radon analysis are needed to be conducted to confirm the permeability. Besides, gas chemistry analysis is also required to confirm this system's heat source.

Table 1. Water geochemical data of Batu Gede and Batu Kapur springs.

| Elements | Manifestation Types | *Batu Gede | *Batu Kapur | Batu Gede (KTK02-05) |
|----------|--------------------|------------|-------------|---------------------|
|          | Warm Springs |             |             | Cold Spring |
| Na$^+$   | 1340 mg/kg    | 310 mg/kg   |             | 4.2 mg/kg     |
| K$^+$    | 91.4 mg/kg    | 65 mg/kg    |             | 1.9 mg/kg    |
| Ca$^{2+}$| 131 mg/kg     | 50.2 mg/kg  |             | 9.1 mg/kg    |
| Mg$^{2+}$| 63.1 mg/kg    | 43.4 mg/kg  |             | 3.3 mg/kg   |
| Cl$^-$   | 1560 mg/kg    | 229 mg/kg   |             | 2 mg/kg     |
| SO$_4^{2-}$| 0.2 mg/kg  | 82.9 mg/kg  |             | 178 mg/kg   |
| HCO$_3^-$| 1730 mg/kg   | 791 mg/kg   |             | 1 mg/kg   |
| SiO$_2$  | 149 mg/kg     | 198 mg/kg   |             | 6 mg/kg    |

*) Water geochemical data from [2]
6. Conclusions
Based on this study, it can be concluded that:
1. Both of Batu Gede and Batu Kapur area are dominantly controlled by secondary permeability.
2. Batu Gede manifestation is controlled by overstepping structure. Meanwhile, Batu Kapur manifestation is by intersection fault.
3. Based on high sulfate (SO\(_4^{2-}\)) content, the appearance of acid alteration and sulfur, acidic cold spring in Batu Gede might be associated with magmatic activity beneath the surface.
4. Further research such as gravity and gas geochemistry analysis need to be done to confirm the subsurface magmatic activity.

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