Geothermal prospect areas based on physical characteristics using remote sensing at Cimandiri Fault, West Java

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Abstract. Cimandiri fault is an active fault indicated by the appearance of hot springs that prove the presence of geothermal activity. The hot springs have different temperature due to physical characteristics in each location. The purpose of this research is to find geothermal prospective region based on physical characteristics at Cimandiri fault, West Java. This research uses integrated survey methods between geography, geology, and geochemical aspects with remote sensing technology. Remote sensing used in analyzing Land Surface Temperature in research areas. The Geochemical survey is done by collecting hot spring samples to get concentration of the Na and K elements. The data latter are used in counting reservoir temperature using Geothermometry method. The results concluded that there are three geothermal prospective regions in Cimandiri Fault classified in low and moderate levels. The low geothermal prospective region is represented in Cibubuay region with reservoir temperature of 109°C at high fault density zone, low concentration of Na/K, low reservoir temperature, and the hot springs located far away from the fault. The moderate geothermal prospective regions are represented in Cibadak region (130°C) and Cikundul region (189°C) at low until moderate fault density zone, high concentration of Na/K, moderate reservoir temperature, and the hot springs located close to the fault.

1. Introduction
Geological conditions in Indonesia are affected by the presence of three plates interacting with each other. The collision between the Indo-Australian plate and the Eurasian Plate produces a subduction zone under the Java-Nusatenggara Islands [1]. The occurrence of collisions between the plates affects the formation of many faults in Java, especially in western of Java.

The Cimandiri Fault is one of the oldest faults in West Java that stretches from Pelabuhanratu Bay continuously to the Northeast to Subang. The fault generated from this process is one that affects the process of geothermal energy formation. Based on geological activities in the area, it is estimated that the potential of geothermal resources in West Java is about 5,411 megawatts (MW) or 20% of the total potential possessed in Indonesia [2].

Geothermal energy is an alternative renewable energy that is environmentally friendly and sustainable [3]. In Indonesia, most of the geothermal that has been utilized so far is energy extracted from the hydrothermal convective system [4]. Its existence is marked by the manifestation of geothermal systems which among others are indicated by the presence of hot springs.
There are some differences in geothermal potential in every region. One that affects those differences is the physical characteristics of each region. The characteristics include location of the reservoir source, fluid circulation, and fault lines. The fault and fault system in geothermal fields as a medium for fluid penetration that rises to the surface is usually characterized by mineral deposits.

The mineral deposits are associated with manifestations and symptoms of rock alteration. Data about manifestations can be useful in the prospecting stage to identify where there is a geothermal system in a region [5]. This study aimed to identify the geothermal prospect area in the Cimandiri fault area. The identification is generated by processing physical variables that which were identified by utilizing remote sensing data.

2. Study Area
This research was carried out throughout and around the Cimandiri Fault, Sukabumi, West Java. The research area in question is a catchment area marked by a fault and various manifestations appear on the surface. Cimandiri catchment area is an area located on an active fault line, where active faults are generally associated with the presence of heat sources at depth. The physical characteristics of a region cause the unevenness of interactions between the main components of a region's geothermal system with other regions, leading to differences in the geothermal prospect area.

3. Materials and Method
The variables used in determining the geothermal prospect's manifestation area include the distance between manifestations, the distance between manifestations and faults, and reservoir temperatures. Identifying variables that can explain the physical characteristics of a geothermal prospect area in the Cimandiri Fault include; land surface temperature, vegetation density, rock permeability, lithology and morphology.

Data collection and processing in this study consists of:
1) Map of geothermal prospect area
The data that required in generating a map of the prospect of geothermal are consist of hot springs, faults, and concentrations of Na and K. Here are the steps:
a. Buffer analysis on hot spring data with a distance of km to determine the region of hot springs.
b. Multiple ring buffer analysis of fault data by distance classification (Table 1) of known manifestation or hot springs.

c. Calculate reservoir temperatures with following equation [7]:
   \[ T = \left[ \frac{1390}{(1.75 + \log(\text{Na} / \text{K}))} \right] - 273.15 \]  
   \( (1) \)
Where T is the temperature of the reservoir and Na / K is the ratio of the elemental content of Na and K to hot springs. Reservoir temperature results are classified into three classes (Table 2.)

| Table 1. Classification of the Distance between Manifestation and the Faults [6] |
|-----------------------------------|-----------------|----------------|
| No. | Distance of Manifestation to Fault (m) | Potention |
|-----|------------------------------------|-----------|
| 1   | >600                               | Low       |
| 2   | 300-600                            | Moderate  |
| 3   | <300                               | High      |

| Table 2. Classification of Reservoir in Estimating in Geothermal Energy [8] |
|-----------------------------------|-----------------|
| No. | Temperature (°C) | Potential |
|-----|------------------|-----------|
| 1   | <125             | Low       |
| 2   | 125-225          | Moderate  |
| 3   | <225             | High      |
2) Land Surface Temperature (LST) and Vegetation Density Index (NDVI)

Land surface temperature maps and vegetation density maps in 1994, 2004 and 2014 were made by processing raster data with the results shown are anomalous temperature changes that occurred in the geothermal prospect area in that year [9] [10]. The images used are Landsat Image 5 and Landsat Image 8. The steps are as follows:

a. DN to Spectral Radians, performs radiometric calibrations on thermal sensors.

The formula of Landsat 5:
\[ CV = ((L_{max} - L_{min})/(Q_{cal_{max}} - Q_{cal_{min}})) \times (Q_{cal_{min}} + \ln) \]  

The formula of Landsat 8:
\[ L = ML \times Q_{cal} + AL \]

where ML = scale factor, AL = enhancer factor, Qcal = digital number (DN).

b. Radian Spectral to Kelvin Spectral, calculates the temperature value in units of kelvin

\[ T = \frac{K_2}{\ln \left( \frac{K_1}{CV_{R2}} + 1 \right)} \]

where \( T \) = temperature (kelvin), \( CV_{R2} \) = radiance value in the thermal band, \( K_1 \) and \( K_2 \) = constant in metadata.

c. Emissivity, correction of the temperature value in units of kelvin. The formula
\[ \varepsilon_{TM6} = 0.004P_v + 0.986 \]

where \( P_v \) is the NDVI value that has been obtained.

d. Kelvin to Celsius, convert the Kelvin temperature value into units of Celsius. The formula:
\[ \text{Celsius} = \text{Kelvin} - 272.15 \]

e. Vegetation density (NDVI) is a method used in calculating vegetation density. The formula:
\[ \text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \]

where \( \text{NIR} \) = band that has near infrared wavelengths (on landsat 5 band 4 and on landsat 8 band 5). \( \text{Red} \) = band that has a red wavelength (on landsat 5 band 3 and on landsat 8 band 4). NDVI values are classified into three classes (Table 3).

| No. | NDVI       | Density |
|-----|------------|---------|
| 1   | -1.0 - 0.32| Low     |
| 2   | 0.32 - 0.42| Moderate|
| 3   | 0.42 - 1.0 | High    |

3) Permeability map of rock (fault density), the data needed is the data broken then the data is analyzed overlay line density in units of km/km^2. The results of this process are classified into three classes (Table 4.).

| No. | Fault Density (km/km^2) | Density |
|-----|-------------------------|---------|
| 1   | -1.0 - 0.32             | Low     |
| 2   | 0.32 - 0.42             | Moderate|
| 3   | 0.42 - 1.0              | High    |

4) Making maps of rock types is done by digitizing Geological maps of Bogor Sheet and Jampang Sheet and Balekambang Scale 1: 100,000. Rock types found in the study area will be analyzed to see the relationship between rocks and rock permeability.
Making terrain shape maps. The morphology in the study area is represented by the shape of the terrain which is then classified into a landscape of faulty mountains. It takes data on altitude and slope area in making this map. The height region is divided into four classes (<100 m, 100-500 m, 500-1000 m, and> 1000 m) [12] and the slope area is divided into five classes (<2%, 2-8%, 8-16%, 16-30%, and> 30%) [10]. After that, the altitude region with the slope area overlapped (overlay) to get the terrain shape region with classification based on the modification of terrain shape into five classes qualitatively namely Low Flat, Mid-Wavy, Mid-Slope, Medium Steep Mountains, and High Steep Mountains [13]. The analysis used in determining the geothermal prospect area is to classify each variable with using a matrix which is then carried out a query of data that has been classified (Table 5.).

| Table 5. Classification Matrix of Geothermal Prospects Area | Classification of Geothermal Prospect Area | Low | Moderate | High |
|-----------------------------------------------------------|-------------------------------------------|-----|----------|------|
| The Distance Between Manifestations (km)                   | ≤ 3                                       | ≤ 3 | ≤ 3      |      |
| The Distance of Manifestation to Faults (m)                | >600                                      | 300 - 600 | < 300   |      |
| Temperature of Reservoir (°C)                             | < 125                                     | 125 – 225 | >225    |      |

The formula / query used to obtain the geothermal prospect area (WPP) are as follows:

a. Low Level. “Distance between manifestations” = ‘≤3’ AND "Distance between manifestations with faults / fault" = ‘> 600’ AND "Reservoir temperature" = ‘<125’
b. Medium Level. "Distance between manifestations" = "≤3" AND "Distance between manifestations with faults / fault" = ‘300-600” AND "Reservoir temperature" = ‘125-225’
c. High Level. "Distance between manifestations" = "≤3" AND "Distance between manifestations with faults / fault" = ‘<300” AND "Reservoir temperature" = ‘> 225

4. Result and Discussion

4.1 Manifestation (Hot Springs) at the Cimandiri Fault

Based on field survey, there are eight hot springs around Cimandiri Fault where hot springs vary between 39 °C-61 °C.

4.2 Geochemical Hot Springs at the Cimandiri Fault

The Cimandiri Fault is a geothermal prospect area which is shown by manifestations that appear on the surface in the form of hot springs. Manifestations in the study area can be analysis using fluid geochemical analysis. Based on this analysis, it can be estimated the type of water, the position of manifestations in the geothermal system, as well as the reservoir temperature in the study area.

4.2.1 Results of Fluid Chemical Analysis. Based on the results of fluid chemical analysis the highest Mg and Ca content is found in the Santa hot springs with values of 32.01 ppm and 128.62 ppm. This shows that the abundance of Mg and Ca dissolved ions is quite high, if development efforts are made to generate electricity, it can trigger the deposition or scaling of drilling pipes. So that the hot springs of Santa do not have the prospect of being a geothermal development area.

Cikundul hot springs have the highest content of the elements Fe, Na, and the compound HCO3 (bicarbonate) with values of 0.0111 (Fe), 145.15 (Na), and 0.222 (HCO3), respectively. The Fe element at this hot spring location indicates that rocks are associated with subaerial volcanic deposits with extrusive intermediate lava constituents indicated by the Jampang Formation. So that this hot spring prospect to be a geothermal development area is indicated by a high reservoir temperature value. The iron and bicarbonate content in hot springs is of high value as a result of local rock reactions (either in shallow reservoirs or during flow to the surface). During the reaction, many protons disappear and...
produce water with bicarbonate as the main parameter and chloride has a low concentration. Based on this explanation, this type of water tends to react easily and is highly corrosive so that it can accelerate damage to the drilling pipes.

4.2.2 Types of Hot Springs in the Cimandiri Fault. The type of hot water in the Cimandiri Fault is included in the sulphate water type of hot water. In this type of hot water the fluid is formed at shallow depths and is formed as a result of the condensation of geothermal gases that come to the surface. The fluid contained in the hot springs in the Cimandiri fault is a bicarbonate water fluid with bicarbonate concentrations between 0.0267 ppm - 0.2222 ppm. This means that water in this type of fluid contains a lot of CO2.

Bicarbonate water from the hot springs around the Cimandiri Fault is included in the zone of steam heated water. The process that occurs in this zone is the heating of surface water by a heat source beneath, the water evaporates and undergoes condensation which then emerges to the surface with the dominant HCO$_3$ element content.

4.3 Geothermal prospect area in Cimandiri Fault

Geothermal prospect area (WPP) is an area that can be utilized as a source of geothermal energy where the signs of geothermal resources are seen from their appearance on the surface (manifestations) and get a picture of the regional geology in the region.

4.3.1 Source of Reservoir at Cimandiri Fault. Eight hot springs in the study area are assumed to be divided into three reservoir sources with the state of one reservoir consisting of more than one hot spring. The distance between hot springs is around ≤3 km (Figure 1). The three reservoir sources are Cibubuay, Cibadak, and Cikundul.

![Figure 1. Distance between Manifestations (Hot Springs) in the Cimandiri Fault](image)

4.3.2 Reservoir Temperature Hot Springs Area in the Cimandiri Fault. The geothermal system in the Cimandiri Fault is included in the low and medium entalphi geothermal system [5]. The low entalphi system is represented by the Cibubuay reservoir source at 190 °C and the entalphi system is being represented by the Cibadak reservoir source at 130 °C and the Cikundul reservoir source at 189 °C. All hot springs are located below the immature water line, it shows that the temperature of manifestations that appear to surface tends to be low and influenced by interactions between hydrothermal fluid with elements in rocks that are passed through such as silica. Conditions where high temperatures and pressures before reaching the surface have also experienced mixing with surface water (meteoric water).
4.4 Physical characteristics of geothermal prospect areas in the Cimandiri Fault

Land Surface temperature, vegetation density, fault density, rock type, and morphology are physical characteristics that influence the geothermal prospect area in the Cimandiri Fault.

4.4.1 Surface Temperature and Vegetation Density at Cimandiri Fault. Temperature anomalies that occur in the hot springs area indicate the potential for geothermal in the Cimandiri Fault area. This is indicated by the similarity of rock types that exist in the study area but have different temperatures based on thermal sensors from the Landsat image (Figure 2).

![Figure 2. Surface Surface Anomaly of Cimandiri Watershed in 1994-2014](image)

Significant changes in surface temperature occur in the Cibadak hot springs where the trend of change tends to rise. In 1994 the surface temperature of 13.28°C rose 9.32°C in 2004 to 22.60°C and rose 2.21°C in 2014. Whereas in the Cibubuay hot springs in 1994 to 2014 during the span of 10 years the temperature tends not to change around 19°C, namely 19.16°C (1994) and 19.37°C (2004).

4.4.2 Fault Density (Rock Permeability) at Cimandiri Fault. The results of the fault density in the study area show the density value in the range 0.147-2.096 km / km2. It is assumed that the area > 1 km/km2 is the intensive fault zone (Figure 3). Faults are generally indicated by the presence of a continuous straight-line contour pattern, river and hill straightness, or shifting, and bending of hills or rivers, and parallel and rectangular river flow patterns. In this zone there are horizontal faults and normal faults. A horizontal slip (strike slip fault) marked by the appearance of a river flow pattern that turns suddenly and there is a shift in the contour pattern (offset).

![Figure 3. Fault Density of Ci Mandiri Watershed](image)

Based on the fault map of the Cimandiri watershed, high rock permeability is found in the southwest of the study area (Cibubuay reservoir source) with a value of 1.216-2.096 km/km2, as well as in the north
of the study area (Cibadak reservoir source) with a value of 0.427-0.772 km/km², and in the northeast of the study area (Cikundul reservoir source) with a value of 0.772-1.216 km/km². The relationship between fault density and the appearance of manifestations is that the greater the fault density value, the more manifestations (hot springs) that appear. This is associated with the movement center of geothermal fluid or permeable zones. Therefore, hot springs are an indicator of the geothermal system located in the fault zone.

4.4.3 Rock types of geothermal prospect areas in the fault Cimandiri. The types of rocks that make up the Cimandiri flow area are sedimentary rocks and volcanic rocks. Table 6 shows the lithology of hot springs in Cimandiri flow area.

| Hot Springs Area | Code | Formation                  | Lithology                  | Sedimentation  | Age          |
|------------------|------|----------------------------|----------------------------|----------------|--------------|
| Cibadak          | Qypo & Tomr | Sedimentation of Volcanic Rock, Formation of Rajamandala | Extrusive : intermediate : polymict, Sedimen : clastic : fine : marl | Volcanism : subaerial, Sedimentation: netric | Holosen, Oligosen-Miosen |
| Santa            | Tmjv | Formation of Jampang       | Extrusive : intermediate : lava | Volcanism : subaerial | Miosen       |
| Cikundul         | Tmjv | Formation of Jampang       | Extrusive : intermediate : lava | Volcanism : subaerial | Miosen       |
| Cibuguay         | Tmjc | Cikarang                   | Sedimen : clastic : claystone | Sedimentation : transitional | Miosen       |

Geothermal field which is usually associated with volcanic landscapes is one area that usually has constituent rocks in the form of volcanic rocks as cover its (cap rock). But in reality, the rock cover in this area is formed by sedimentary rocks. The relationship between faults and manifestations of geothermal can be seen in the field in the form of an alignment pattern between a geothermal manifestation location with other locations in a fault system. With regard to rock types, most of the study area is covered by lava and lava and extrusive igneous rocks.

4.4.4 Morphology of Geothermal Prospects Area in Cimandiri Fault.

Morphology is the earth's surface that has undergone a change in landform, whether caused by volcanism symptoms, tectonism, or a combination of both [13]. Morphology in this area is divided into five namely the Low Flat region, the Mid Flat region, the Mid-Wavy region, the Mid-Ramps area, the Medium-Steep Mountains region, and the High-Steep Mountains Region (Figure 4).

Figure 4. The Terrain of Cimandiri
The characteristics of the fault span are as follows; there are ridges of fault blocks (with fault faults or fault lines), hills or horst ridges, fault zones, Bancuh hills (Melange), and graben valleys. Fault block mountains are mountains composed of clastic rock, marked by various forms of faults, such as graben, horst, triangle facet, and so on. Melange hills complexes are complexes (hills/mountains) that consist of rocks resulting from tectonic mixing and melt-mixing which take place under gravity so that they are deformed of varying sizes. Horst hills are fields higher than the surrounding area due to faults resulting in uplift while valley graben is fields that descend on a surface so that the fields are lower than the surrounding area due to faults so there is a decrease.

4.5 Geothermal Prospect Areas Based on Physical Characteristics in the Cimandiri Fault

Based on these variables characterizes the prospect geothermal, after analysis of the overlay area, there are two classifications of geothermal prospects that the geothermal prospects with low-level and intermediate level. Where the prospect of lower energy level is represented by the hot springs and the prospect Cibubuay geothermal levels are represented by the hot springs at Cibadak or Cikundul (Figure 5). Overall, the types of rocks in the geothermal prospect area lie in sedimentary rocks and a little in volcanic rocks. Morphology is in fault mountains with terrain ranging from mid-choppy to steep mountains with surface temperatures between 20.22°C-20.84°C and reservoir temperatures of 109°C-189°C.

![Figure 5. Geothermal Prospect Areas in Cimandiri Fault](image)

4.5.1 Geothermal Prospect Area in Low Classification. The low classification geothermal prospect area is represented by the Cibubuay hot spring (reservoir source) area of 56,495 ha. The surface temperature in this region is 20.48°C with a vegetation density index of 0.48. The fault density in this region is 0.772 km/km2 - 1.216 km/km2. In this region with the fault density values there are three hot springs with each hot spring temperature of 39°C (Cibubuay 1 and Cipicung hot springs) and 41°C (Cibubuay 2 hot springs) with alkaline pH (ranging between 8.20-8.40). Rock type is dominated by sedimentary rocks with miocene age and is in the form of steep step mountainous terrain. The reservoir temperature in the Cibubuay region is 109°C with the highest content of Fe (0.003 ppm), Ca (23.90 ppm), Na (84.15 ppm), K (1.49 ppm), Mg (4.07 ppm), and HCO3 (0.2000 ppm).

The accumulation of heat below the surface is indicated by the appearance of three hot springs. In this region clay cap (rock cap) is represented by transitional sediments with constituent clastic sediments in the form of clay rock. Conductive rocks are Miocene-aged rocks that have silicified, where heat propagation is conducted through these rocks while heat convection is transmitted through fluids along
the rock permeability zone (fault density). The rocks are in the morphology of the fault mountains in the form of steep mountain terrain.

The hot fluid in this prospect area is included in the hot water phase system with alkaline pH. In this region the geothermal system is included in the low entalphi geothermal system. All hot springs in this region are below the immature water line, indicating that the temperature/temperature that appears on the surface tends to be low before it reaches the surface it is mixed with surface water.

4.5.2 Geothermal prospect area in medium classification. The classification geothermal prospect area is being represented by the Cibadak hot springs area (reservoir source) with an area of 231,552 ha and Cikundul hot springs area (reservoir source) with an area of 4,188.09 ha. The surface temperature in the Cibadak geyser area is 20.22 °C with a vegetation density index of 0.48. The fault density in this region is 0.147 km/km² - 0.427 km/km². In this region with the value of the level of fault density there are two hot springs with each hot spring temperature of 40°C and 41°C with alkaline pH (ranging between 8.35 and 8.57). Rock types are dominated by sedimentary rocks (Raja Mandala formations) and volcanic rocks (old volcanic deposits) with miocene age (sedimentary rocks) and holocene (volcanic rocks) and are in the form of mid fields. Reservoir temperature of 130°C in the Cibadak region.

The surface temperature in the Cikundul hot spring region is 22.70°C with a vegetation density index of 0.45. The fault density in this region is 0.147 km/km² - 2.096 km/km². In this region with the value of the level of fault density there are three hot springs with each hot spring temperature of 39°C (Santa's hot springs), 59°C (Cikundul 2 hot springs) and 61°C (springs hot Cikundul 1) with alkaline and acidic pH (Cikundul 1 and Cikundul 2 hot springs with values of 8.14 and 8.16) Acidic pH is found in Santa hot springs with a value of 6.79). Rock type is dominated by sedimentary rocks (Jampang formations) with myocene age and is in the form of a mid-choppy terrain to steep mountains. Reservoir temperature of 189°C in the Cikundul region.

These two clay cap regions are represented by subaerial volcanic deposits with extrusive intermediate lava constituents dominated by sedimentary rocks. The conductive rocks are in the form of Miocene-aged rocks that have undergone silicification. Where heat propagation is conducted through this rock, whereas heat convection is transmitted through the fluid along the rock permeability zone (fault density).

The reservoir zones in these two regions are located in the groundwater accumulation area and are in the form of hot water systems trapped in rock faults. Heated ground water at a further depth will rise to the surface through the access of the fault zone/rock fault due to the convection force and appears as a hot spring. The rocks are in the morphology of the fault mountain range precisely in the form of a mid-choppy terrain and steep mountains.

The hot fluid in both regions is included in the hot water phase system with a pH close to neutral to alkaline. can also be said that these two regions are included in the medium enthalpy geothermal system. All hot springs in all of these regions are also below the immature water line, which indicates that the temperature/surface temperature has been mixed with surface water (meteoric water) so that the temperature of the hot springs that appear on the surface is not so high.

5. Conclusion
The geothermal prospect area in the Cimandiri Fault is divided into two regions, namely the low and medium level classification. The low level classification area is the area which is in the zone of high fault density, low concentration of Na-K content, low reservoir temperature, and manifestations (hot springs) located far from the fault. While the medium level classification area is in the zone of moderate to low fault density, high concentration of Na-K content, medium reservoir temperature, and manifestations (hot springs) located close to the fault.
Rock type, chemical content, and morphology influence the nature of hot springs in the geothermal prospect area. The lower the topography of an area, the rock type is increasingly dominated by sedimentary rocks so that the chemical content in the prospect area has been mixed with rain water or river water which causes the temperature of hot springs on the surface to be low.

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