Surface and Subsurface Fracture Zones Modeling Using Automatic Lineament Analysis and Geostatistical Method, with Case Study of Wayang Windu Geothermal Field, West Java, Indonesia

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Abstract. Geological structures such as faults and fractures in a geothermal prospect area might be an indication of a permeable zone for geothermal fluids through fractures that appear inside the rocks. Such geological structures can be identified by lineaments in satellite images and aerial photographs. In this study, we determine the effect of pixel size on the results of automatic lineament extraction and examine the relationship between lineaments at the Wayang Windu geothermal field (WWGF) and nearby geothermal areas, automated lineament results which were extracted from digital elevation models (DEMs) with pixel sizes of 0.5 m, 1 m, 2 m, 3 m, 4 m, 5 m, 10 m, 15 m, and 20 m based on aerial photographs, DEM Nasional (DEMNAS) images, and Shuttle Radar Topography Mission (SRTM) images. Under similar parameters, larger pixel sizes revealed fewer and longer lineaments than smaller pixel sizes. The type of image (i.e., satellite images or aerial photographs) used for lineament extraction did not affect the results. Based on lineament density maps, the lineaments from images with smaller pixels had a wider distribution area than those with larger pixels. Surface geothermal manifestations, such as hot springs, showed good correlation with lineaments found in images with smaller pixel sizes (≤ 5m), which were found in moderate to high lineament density zones. Based on the lineaments extracted from SRTM images, each geothermal field in southern Bandung (Patuha, WWGF, Darajat, Kamojang) had a local geological structure that greatly correlated with the lineament extraction results. All of the lineaments in the geothermal fields were primarily oriented in the NE–SW direction (i.e., N65°E for Patuha, N51°E for WWGF, N57°E for Darajat, and N24°E for Kamojang). Subsurface fracture zone modeling was conducted at WWGF to estimate the permeability zones based on the fracture density from production well data using the Ordinary Kriging (geostatistical) method. The results revealed the direction of subsurface fracture dips and strikes as well as the relationship between subsurface fracture geometries and surface lineament structures. In general, the subsurface fracture zones featured strikes in a NE–SW...
direction, with dip angles ranging from 74° to 85° and fracture density ranging from 36 to 43 fractures per 10 m. Additionally, the fracture density linearly corresponded to the depth of wellpads. Compared to the surface lineament extraction map, the majority of lineaments were in the NE-SW direction, similar to the major strike of the subsurface fracture zones.

1. Introduction

Indonesia is located in the subduction zone between the Eurasian and Australian plates. Thus, the country features many active volcanoes and high-potential prospect areas for geothermal energy, a renewable source of energy that may replace fossil fuels in the future. Geological structures, such as faults and fractures, may create openings inside rocks to allow geothermal fluids to pass through, creating a permeable zone. Those structures are shown and can be observed as lineaments in satellite images or aerial photographs. In this study, the lineaments extracted at various pixel sizes from Wayang Windu geothermal field (WWGF) and its surroundings were compared and compiled into lineament densities, to determine the relation of WWGF and the surrounding geothermal fields in the southern region of Bandung, West Java, Indonesia. The extracted surface lineaments at WWGF were analyzed to determine their correlations with the subsurface fracture density, which was modeled using a geostatistical method (ordinary kriging) from the geometrical fracture data of geothermal production wells.

The WWGF is located in southern Bandung which is a depression among the mountains mostly filled with young volcanic sediments, the products of surrounding volcanoes [1]. Based on the geological map of the Garut sheet [2], the regional stratigraphy of the study area could be found in the form of Quaternary Malabar-Tilu volcanic rock formations (Qmt) composed of tuffs, lava breccia containing small amounts of pumice and lava. The Qmt Formation is located in the Malabar Volcanic Stone Unit. The geothermal field around WWGF was also discussed in this paper such as Patuha, Darajat, and Kamojang fields. The Patuha field is surrounded by a volcanic centre or vents which are distributed along a west to northwest trending structure. The general structure trends that develop in this field are NE-SW and NW-SE, which are coincided with the Meratus and Sumatera trends [3]. The Darajat field is spatially associated with an eroded andesitic stratovolcano, Gunung Kendang. The volcanics found in the central part of the area consist of hornblende andesite lava, rhyolite obsidian, and related ash tuffs. Structures trend predominantly in NE-SW and NW-SE directions [4]. The Kamojang field could be divided into two formations (from older to younger): Pangkalan Formation and Gandapura Formation. Pangkalan Formation (1.2 Ma), which consists of weathered andesite, lies to the west of Pangkalan Lake, while Gandapura Formation (0.4 Ma) is formed by pyroxene andesite rocks and situated on the east of Kamojang. Two important faults in these volcanic series are Kendang Fault and Citepus Fault, where the orientation both of them are NE-SW. The orientation is in conformity with the tectonic regime in the region where the direction of subduction of Australian Plate under the island in north-south. This opening creates a passage for volcanism [5].

2. Material and Methods

2.1. Digital Elevation Model

Digital Elevation Model (DEM) is a digital map that contains elevation data of the earth’s surface based on the coordinate information (X, Y, and Z). DEMs can be used to calculate areas, volumes, slope angles, and contour mapping [6]. DEMs can be made using aerial photographs or satellite image data. DEMs from aerial photographs are acquired using photos from an airborne or unmanned aerial vehicle (drone) and processed by software to create a model. DEMs from satellite images are made by using radar images such as Shuttle Radar Topography Mission (SRTM) produced by National Aeronautics and Space Administration (NASA) and DEM Nasional (DEMNAS) produced by the Indonesian Geospatial Information Agency. SRTM uses radar systems on board of NASA satellites to generate DEM of the earth surface in its orbit. The DEMNAS is constructed from Interferometric Synthetic
Aperture Radar images (IFSAR), TerraSAR-X images and Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar (ALOS PALSAR) images by adding mass-point data from stereo plotting [7].

2.2. Automatic Lineament Extraction

Automatic lineament extraction from DEM images was performed in this study. The LINE module of PCI Geomatica was used in this study to extract and record lineaments as polyline vectors. The LINE module has a similar logic to the segment tracing algorithm (STA), as addressed in [8], but the former uses only one image and the latter uses two types of images (ascending and descending). The algorithm used in the LINE module involves edge detection, thresholding, and curve extraction.

2.3. Subsurface Fracture Density Modeling

The data used in this study concerns the results of drilling at the DHA and DHB production wells, with each well pad having four wells: DHA1, DHA2, DHA3, DHA4, DHB1, DHB2, DHB3, and DHB6. The collar elevation of the DHA well pad is 1946 masl and that of the DHB well pad is 2074 masl. The wells were inclined about 40-50° with varying azimuth (N, NE, E, SE, W, NW). Modeling was performed on an 1800 m × 2600 m area with a well depth of 1500 m in average.

Geostatistics is a method used to analyze data from a population by considering the location of that data spatially. In geostatistics, the spatial distribution function of data is shown through variograms. The variogram model used is generally a Spherical model. The Ordinary Kriging (OK) method is one of the most widely used geostatistical methods for estimating the value of a point or block as a linear combination of the observed values around that point or block.

Drilling data was processed by preparing the fracture density data composites at an interval of 10 m, then performing statistical analysis such as histograms. The compositing data were then plotted; fracture density data at a 10 m interval was estimated and modeled; and fracture continuity orientation was generated using the OK method with SGeMS software. The stage of fracture density and geometrical modeling using geostatistics is depicted in Figure 1.

![Figure 1](image-url) The stage of fracture density modelling using geostatistical method.

3. Results and Discussion

A DEM from aerial photographs with a pixel resolution of 0.5 m was used in this study and resized to obtain the other pixel sizes (i.e., 1 m, 2 m, 3 m, 4 m, 5 m, 10 m, 15 m, and 20 m). These data were compared with DEMs from SRTM and DEMNAS images (Figure 2).

3.1. Automatic Lineament Extraction

The DEMs were converted to shaded relief images using the hill-shade module of ArcMap. The azimuth and altitude of shading were 315° and 45°, respectively. The parameters used in the LINE module are shown in Table 1. The results of automatic lineament extraction for each pixel size are shown in Figure 3, and a rose diagram of the extracted lineaments is shown in Figure 4. All the extracted lineaments show major trends in the NE–SW direction.
Figure 2. (a) DEM of an aerial photograph of WWGF, (b) DEMNAS image of southern Bandung, and (c) DEM SRTM image of southern West Java. Note: the blue rectangle in Figures (b) and (c) indicates WWGF area.

Table 1. Automatic lineament parameters.

| Parameters                          |   |
|-------------------------------------|---|
| Filter Radius (pixels)              | 12|
| Edge Gradient Threshold             | 40|
| Curve Length Threshold (pixels)     | 25|
| Line Fitting Error Threshold (pixels)| 3 |
| Angular Difference Threshold (degrees) | 20 |
| Linking Distance Threshold (pixels) | 1 |
Figure 3. Results of extracted lineaments for each pixel size: (a) 0.5 m, (b) 1 m, (c) 2 m, (d) 3 m, (e) 4 m, (f) 5 m, (g) 10 m, (h) 15 m, (i) 20 m, and (j) DEMNAS at WWGF.

Figure 4. Rose diagrams of extracted lineaments for each pixel size: (a) 0.5 m, (b) 1 m, (c) 2 m, (d) 3 m, (e) 4 m, (f) 5 m, (g) 10 m, (h) 15 m, (i) 20 m, and (j) DEMNAS at WWGF.

As shown in Figure 3, smaller pixel sizes give smaller lineaments and wider lineament distribution areas, while larger pixel sizes give fewer and longer lineaments. As seen in Table 2, the pixel size 0.5 m produced 68,400 lineaments with average length 19 m, pixel size 10 m produced 360 lineaments with average length 333 m, and pixel size 20 m produced 90 lineaments with average length 675 m. The
different types of images (aerial photograph and DEMNAS) had little impact on the results, following
the same trend of smaller pixel sizes giving more and shorter lineaments than larger pixel sizes. The
results also show that extracted lineaments are concentrated in the rivers and mountain areas.

Table 2. Summary of the result of lineament extraction as the function of pixel size.

| Pixel size (m) | Number of lineaments | Minimum length (m) | Maximum length (m) | Average length (m) |
|----------------|----------------------|--------------------|--------------------|--------------------|
| 0.5 × 0.5      | 68,400               | 2.30               | 116                | 19                 |
| 1 × 1          | 21,260               | 5.00               | 259                | 34                 |
| 2 × 2          | 6,540                | 8.20               | 258                | 67                 |
| 3 × 3          | 3,310                | 19.20              | 432                | 101                |
| 4 × 4          | 2,010                | 21.50              | 444                | 136                |
| 5 × 5          | 1,340                | 28.30              | 479                | 171                |
| 8 × 8          | 590                  | 71.40              | 978                | 282                |
| 10 × 10        | 360                  | 78.80              | 959                | 333                |
| 15 × 15        | 170                  | 100                | 1,315              | 496                |
| 20 × 20        | 90                   | 113                | 1,423              | 675                |

Figure 5. Local geological structures and their respected major directions in the: (a) Patuha, (b) WWGF, (c) Darajat, and (d) Kamojang fields (modified from [2]).

The major directions of the results based on pixel sizes shown in the rose diagrams are N49°E for 0.5 m, N47°E for 1 m, N50°E for 2 m, N51°E for 4 m, N51°E for 5 m, N49°E for 10 m, N47°E for 15 m, and N45°E for 20 m. The rose diagram shows little difference in major direction, so the pixel sizes of an image have little relationship to the major directions of the extracted lineaments.
Each geothermal field near WWGF, i.e., Patuha, Darajat, and Kamojang also had lineaments extracted based on the SRTM images. The results in Figure 5 show that some of the lineaments correspond to the local geological structures and some do not. The major structures at Patuha and Kamojang fields show significant differences, although, in general, they still show a NE-SW direction. The major directions of structures at the Patuha, WWGF, Darajat, and Kamojang fields are N65°E, N51°E, N57°E, and N24°E respectively. The Darajat field is the closest to WWGF and some of the geological structures might, therefore, be correlated.
3.2. Fracture Density Maps

Fracture density maps were made from the extracted lineaments. These maps were made using a searching radius of 250 m and a grid size of 250 m × 250 m. The fracture density was divided into nine categories using the Natural Breaks classification system. This system was based on Jenks Natural Breaks algorithm, which uses the best similar group values and splits the group if there are relatively significant differences in the data. Cubic convolution, which uses the 16 nearest values in a grid to determine the value of a point, was used for resampling. The fracture density maps for each pixel size are shown in Figure 6.

The maps in Figure 6 were compared with the local structure and fracture density maps overlaid with manifestations (hot springs, craters) and monitoring holes for radon measurement (see Figures 7a and 7b). The fractures density maps for smaller pixel sizes are well aligned with the locations of hot springs and monitoring holes, which are mostly located in the yellow (medium) and red (high) zones of the map. This indicates that hot springs may correspond to the surface structures that generated channels through which fluids could reach the surface. However, when it is compared to the local fracture density map (Figure 7b), the results show a slight similarity. The results show more similar and noticeable peaks for larger pixels than for smaller pixels. The result from the SRTM image shows less similarity with the larger pixels rather than with the smaller pixel. This indicates that fracture density maps have an optimum pixel size that gives the best result and utmost similarity to the local fracture density. In this study, the fracture density map from DEMNAS (Figure 6j) with a pixel size of 8 m × 8 m presents the most similarity feature with the local fracture density map (Figure 7b).
Figure 7. (a) Local geological structures at WWGF and (b) fracture density map of local structures within the blue rectangle area shown in Figure (a). Note: K and NSD are points at which the concentration of radon gas is monitored. The value unit of fracture density is number of fractures per meter square.

Figure 8. Distribution of fracture geometrics: (a) fracture density, (b) dip angle, (c) strike direction from DHA and DHB well pads, and (d) strike direction from surface lineaments.
3.3. Distribution of Subsurface Fractures
The composites of fractures number in each 10 m interval into fracture density were analyzed descriptively using a histogram. The fracture density distribution from DHA and DHB well pads is shown in Figure 8a. There are at most 77 fractures per 10 m interval and at least one fracture in each 10 m, with an average of 13 fractures in each 10 m.

The dip angle distribution for the DHA and DHB well pads is shown in Figure 8b. The average dip angle is 61°NW, and most ranged from 60°NW to 75°NW. Additionally, the strike fracture distribution is shown in Figure 8c. The frequency of each range is almost the same, meaning that the distribution is quite normal. The most frequent range was N210°E to N250°E, with an average strike of N163°E. Figure 8d shows the distribution of the strikes of surface lineaments extracted from DEMs. The histogram shows that the average strike is N229°E, and the range with the highest frequency is N225°E to N250°E.

3.4. Major Direction of Subsurface Fractures
The dip directions and strikes of all fractures were extracted from the drilling data of the DHA and DHB well pads, and this information was plotted in a rose diagram using GeoRose software. Rose diagrams of the dip direction and strike direction of subsurface fractures are shown in Figures 9a and 9b. The major dip direction and strike direction of the subsurface lineaments are N315°E and N225°E, respectively. In addition, the direction of each surface lineament was determined based on the surface lineament map. A rose diagram of surface lineament directions is shown in Figure 9c. The major direction of surface lineaments is N245°E, which is similar to the major strike direction of subsurface fractures.

3.5. Geometry of Permeable Zones
A 3D diagram of the estimated fracture density of the DHA and DHB well pads allowed us to analyze the directions of high-frequency fractures and the presence of permeable zones, as shown in Figure 10. Figures 11a to 11d show that, in general, the fractures are oriented in a NE–SW direction and lower elevations (i.e., the DHB1 and DHB3 wells) have higher fracture density. According to the OK method, the estimated fracture density is 1–50 fractures per 10 m interval, with the highest fracture density (36–43 fractures per 10 m interval) occurring in the permeable zones, which are circled in the Figures. Fracture density starts to have high values at an elevation of 1000 masl or depth of 1000 m below the surface. In the conceptual model of the WWGF shown in Figure 12, the reservoir is located on the northern side at an elevation of 1000–500 masl. This is consistent with the results of the fracture density estimation.

Areas of high fracture density and the dip angle in fracture continuity (74–85°) can be observed in the fracture geometric estimation model in Figures 13a and 13b. However, the estimated strike direction in Figure 11c has less continuity, with the major strike direction estimated to range from N115°E to N261°E. The major strike direction of the raw data shown in Figure 9b, N225°E or SW–NE, is consistent with the results of fracture geometric estimation and within the range of most fracture densities.
Figure 9. Rose diagrams of the: (a) dip direction of fractures, (b) strike direction of fractures from DHA and DHB well pads, and (c) direction of surface lineaments.

Figure 10. Results of fracture density estimation. The orange line and circle indicate the strike direction and area with a high density of fractures, respectively.
Figure 11. Estimation of fracture densities at elevations of (a) 1250 masl, (b) 1000 masl, (c) 750 masl, and (d) 500 masl. The orange lines and circles indicate strike directions and areas with a high density of fractures, respectively.
Figure 12. The conceptual model of WWGF is dominated by two-phase steam [9].

Figure 13. Estimations of the (a) dip angle, (b) dip value at an elevation of 500 masl (blue circle indicates the area with a high density of fractures), and (c) fracture strike (green circle indicates the area with a high density of fractures).
The histogram of the strike directions of subsurface fractures (Figure 8c) indicated the presence of three populations: one with strikes less than N150°E, one with strikes between N150°E and N300°E, and one with strikes greater than N300°E. In Figure 13c, the first population is represented by blue, the second is represented by green to yellow, and the third is represented by orange to red. The first and second populations occur at almost the same frequency and coexist close to one another, but the third population appears in only a small portion. In addition, the first and second populations share a fairly large range of strike directions (N115°E to N261°E).

3.6. Relationship between Subsurface Fractures and Surface Lineaments

The lineament direction of surface fractures might be connected to the subsurface fracture zones in the WWGF. A map of the lineaments extracted from DEM data is shown in Figure 14. The majority of surface lineaments are oriented in a SW–NE direction, similar to the strike direction of subsurface fractures. As shown in the rose diagrams in Figures 9b and 9c, the strike direction of the subsurface fractures is N225°E and the direction of the surface lineament is N245°E, a difference of 20°, and both are oriented in the SW–NE direction. This similarity means that the continuity of subsurface fractures’ strike directions at the WWGF can be estimated based on the extracted surface lineament map obtained from DEM data.

![Figure 14. Surface lineaments map by automatic extraction based on DEM data at WWGF.](image)

4. Conclusion

In the DEMs, each pixel size was associated with a specific range of parameters that produced the best results for lineament extraction. The fracture density maps produced from DEMs with smaller pixel sizes were strongly correlated with the location of hot springs; almost all were located in medium- and high-density zones. However, larger pixel sizes revealed more clear structures than smaller pixel sizes. DEMNAS images led to the best lineament extraction results and the fracture density map.

It was found that each geothermal field in the study area has local structures that control the location of surface manifestations. The WWGF and its surrounding areas showed major structures in NE–SW
direction (N65°E for Patuha, N51°E for WWGF, N57°E for Darajat, and N24°E for Kamojang). The major direction of the overall strike at the DHA and DHB wellpads is N225°E. The estimated subsurface fracture density, which was determined using the OK method, showed a major strike in the SW–NE direction, with dip angles ranging from 74–85°. Areas with an elevation of 1000–500 masl (or depth of approximately 1000–1500 m) with a density of 36–43 fractures per 10 m are assumed to be permeable zones. The continuity of the surface lineaments from DEM data coincided with the continuity of estimated subsurface fracture geometrics.

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References
[1] van Bemmelen R W 1949 The Geology of Indonesia Vol. IB Government Printing Office, The Hague
[2] Alzwar M, Akbar N and Bachri S 1992 Geological map of Garut and Pemeungpeuk sheet, Java Directorate of Geology, Bandung
[3] Elfina 2017 Updated conceptual model of the Patuha Geothermal Field, Indonesia UNU-GTP Geothermal Training Programme
[4] Rejeki S, Rohrs D, Nordquist G and Fitriyanto A 2010 Geologic conceptual model update of the Darajat Geothermal Field, Indonesia Proceedings World Geothermal Congress
[5] Kamah M Y, Armando A, Rahmani D L, Paramitha S 2017 Enhancement of subsurface geologic structure model based on gravity, magnetotelluric, and well log data in Kamojang Geothermal Field Proceedings of 6th ITB International Geothermal Workshop
[6] Hengl T, Gruber S and Shrestha D P 2003 Digital terrain analysis in ILWIS Lecture Notes and User Guide
[7] Geospatial Information Agency DEMNAS Info taken back from the DEMNAS Seamless Digital Elevation Model (DEM) and National Bathymetry: http://tides.big.go.id/DENMAS/, accessed 18 August 2018
[8] Muhammad I A A 2017 Lineament extraction using remote sensing data mid Iraq Journal of Babylon University/Pure and Applied Sciences 25 582-597
[9] Mulyadi 2010 Case study: Hydraulic fracturing experience in the Wayang Windu Geothermal Field Proceedings World Geothermal Congress 2010