The Application of Geologic Lineament Extracted From Dual-Orbit SAR Images for Fluid Flow Path Detection and Characterization in Geothermal System

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Abstract. The limited nature of subsurface imaging data in geothermal field makes surface data important to infer subsurface geologic conditions. One of the main geologic features that can be extracted from surface data is lineament which can be attributed to rock fractures, including joints and deep-seated faults. Fractures play a dominant role in the creation of porosity and permeability that allows the storage and flow of thermal fluid in geothermal reservoirs. Therefore, it is important to characterize rock fractures and model the flow of thermal fluid through them to better understand the geothermal reservoir. This study evaluates the application of lineaments extracted from dual-orbit Synthetic Aperture Radar (SAR) images acquired by the Phased-L Synthetic Aperture Radar (PALSAR) sensor on the Advanced Land Observing Satellite (ALOS) as input for fracture modeling to reservoir simulation in geothermal field. The SAR images were acquired from the Geureudong area in Aceh. Lineaments were extracted automatically from SAR images using modified Segment Tracing Algorithm (mSTA). Noise filtering and edge enhancement algorithms were applied to the SAR images prior to mSTA to optimize the extraction of geologically significant lineaments. The extracted lineaments were spatially analyzed, including lineament frequency density, lineament length density, lineament intersection density, and lineament direction rose diagram. Representative fracture model with a vertical dip angle was created from the extracted lineaments and was assigned with reservoir properties, including permeability and porosity. Thermal fluid flow was simulated through it to detect flow path and to characterize fluid flow in a geothermal system. Spatial analysis of the extracted lineaments showed a good correlation with the trend of geological structures observed in the field. The simulated fluid flow path showed good agreement with the spatial distribution of geothermal manifestations. Simulation results showed a strong correlation between fluid flow characteristics to the orientation, density, and connectivity of the fracture model.

1. Introduction
Fractures play a significant role in the creation of porosity and permeability which allow the storage and flow of thermal fluid in a geothermal system [1] [2] [3]. Therefore, it is paramount to characterize these fractures to better understand the behavior of fluids in geothermal reservoir.
Subsurface imaging data from a geothermal field necessary to characterize the fracture system tend to be sparse and limited which made surface data valuable to infer subsurface geologic conditions. Remote sensing data, especially SAR images are one of the most readily available surface data for geothermal applications. Due to its effective vegetation penetration capabilities and its sensitivity to surface roughness, it becomes suitable for geologic studies [4] [3] [5]. Geologic lineaments can be extracted from SAR images and have been attributed to rock fractures, including joints and deep-seated faults [6] [7] [8] [9] [3].

This study evaluates the application of lineaments extracted from dual-orbit SAR images of ALOS-PALSAR satellite mission as a novel approach for fracture detection, characterization, and modeling. Fluid flow is simulated through the fracture model to predict its path and characteristics in correlation to fracture directions, density, and connectivity.

Geureudong Geothermal Prospect is located at Aceh Province, Indonesia (Figure 1). It consists of Quaternary volcanic complexes, including the active Geureudong Volcanic Complex to the north and the denuded Silih Nara Volcanic Complex (VC) to the south. Right-lateral strike-slip faults consistent with the trend of Sumatran Great Fault (SGF) and NE-SW trending normal faults developed in the study area [10] [11]. It is covered by extensive Quaternary volcanic sediments from the Geureudong VC and Silih Nara VC eruptions, including basaltic, dacitic, and andesitic lava flows, pyroclastic deposits, and tephra [12].

![Figure 1](image-url)

**Figure 1.** (Left) Geologic map of the study area shows the geologic structures and Quaternary volcanic deposits on top of Mesozoic and Paleozoic basement (modified from [11]) and (Right) the inset map shows the footprints of the dual-orbit SAR images covering the study area.

Probable geothermal resource within the study area is estimated at 160 MW [11]. Geothermal manifestations, including hot springs and solfatara, can be found at Wih Pesam, Uning Bertih, Mt. Pepanji, and Wih Porak. Manifestation at Wih Pesam was characterized as neutral, high chloride, and high total dissolved solid (TDS) hot spring associated with direct discharge of thermal fluid from the geothermal reservoir. Manifestations at Uning Bertih, Mt. Pepanji, and Wih Porak were characterized
as diluted bicarbonate hot springs associated with fluid discharge from peripheral of the geothermal system [11]. Geothermometer analysis showed the reservoir as water dominated system with the highest temperature at 240°C [11].

Gravity survey showed high residual gravity anomaly to the northwest and southeast of the study area, consistent with the outcropping of the Mesozoic granitic basement and Paleozoic sediment-metasediment of Kluet Formation. Low residual gravity anomaly is observed at the S-SE flank of Geureudong VC that may indicate low-density volcaniclastic sediment or heated rock mass due to thermal fluid upflow (Figure 2a). Magnetotelluric survey on the study area showed high conductance anomaly which can be interpreted as potential geothermal reservoir with clay cap extending from Wih Pesam to Mt. Pepanji at 1500 to -500 m elevation (Figure 2b and Figure 3). It is interpreted that the thermal fluid upflow is located around Mt. Geureudong, with outflow heading northwestward towards Wih Pesam and southeastward towards Mt. Pepanji [11].

Figure 2. (A) Low residual gravity anomaly is located at the S-SE flank of Geureudong VC associated to low-density rock mass. (B) High conductance anomaly to 1500 m elevation shows the possible extent of geothermal reservoir. Red lines are measured faults, black lines indicated the topography of the area, and yellow line indicated the resistivity cross-section shown in Figure 3 (modified from [11]).

2. Data and Observation Mode
Single Look Complex (SLC) SAR backscatter intensity images with Horizontal – Horizontal (HH) polarization from dual-orbit observation of ALOS-PALSAR Satellite were utilized for this study (Figure 4 and Table 1). The dual-orbit observation mode provides images of the opposite line of sight (LOS), from the ascending mode in which the satellite travels from the south to north, transmitting signals toward the east, and the descending mode in the opposite direction [3]. Dual-orbit observation is crucial for this research to overcome the shortcoming of SAR imagery which produces images with geometrical
distortion caused by the oblique irradiation angle of the microwaves, which shortens the foreside flank and obscures the topographic features behind it [13] [14] [3].

Figure 3. Resistivity profile along the yellow line showed in Figure 2b. Clay cap is shown as low apparent resistivity zone (deep blue) extending from Wih Pesan to Mt. Pepanji. A possible geothermal reservoir is located at the outflow zone below it (light blue to green) [11].

3. Lineament Extraction Method
Orthorectification was performed to the SLC SAR backscatter intensity images to convert the two-dimensional images from sensor coordinate to map projected coordinate [15]. The results of image orthorectification are multilooking (MLI) SAR images suitable for spatial quantitative analysis.
Figure 4. Dual-orbit SAR observations of the same object on the earth surface is utilized to reduce the geometrical distortion effect due to side looking imaging geometry [3].

Table 1. List of ALOS-PALSAR images covering the Geureudong area.

| No. | Scene id       | Path/Frame | Acquisition date | Off nadir angle | Orbit mode |
|-----|----------------|------------|------------------|-----------------|------------|
| 1.  | ALPSRP259300080| 498/80     | 2010-12-06       | 34.3°           | Ascending  |
| 2.  | ALPSRP142750080| 497/80     | 2008-09-28       | 34.3°           | Ascending  |
| 3.  | ALPSRP259300070| 498/70     | 2010-12-06       | 34.3°           | Ascending  |
| 4.  | ALPSRP256820070| 497/70     | 2010-11-19       | 34.3°           | Ascending  |
| 5.  | ALPSRP141943520| 126/3520   | 2008-09-23       | 34.3°           | Descending |
| 6.  | ALPSRP141943530| 126/3530   | 2008-09-23       | 34.3°           | Descending |

3.1. SAR Image Enhancement

Prior to lineament extraction, MLI SAR images undergone image enhancement to optimize the detection of geologically significant lineaments. Image enhancement includes spatial filtering using Laplacian of Gaussian (LoG) filter followed by pixel bandpass filtering and pixel cluster removal.

LoG filter is a two-steps process that smooths the image using Gaussian filter and enhances image edges using Laplacian filter which highlights regions of rapid intensity change [16]. The Laplacian filter exploits the second-order derivative of pixel intensity to locate edges. LoG operator is expressed with the following mathematical function:

\[
\text{LoG}(x, y) = \frac{1}{\pi \theta^4} \left(1 - \frac{x^2 - y^2}{2\theta^2}\right) e^{-\frac{x^2 - y^2}{2\theta^2}}
\]  

where \((x, y)\) is the pixel coordinate and \(\theta\) is the selected masking constant of 1.65 that have been shown to optimize the detection of features as small as 11×11 pixels in dimension [14].

Next is the implementation of pixel bandpass filtering which eliminates pixels that do not represent edges based on its digital number (DN) value. The second derivative image after LoG highlights edges as pixels with the highest DN value range (global maximum range). Therefore, any pixels that DN value
less than the global DN maximum range are eliminated. In this research, a range of 150-250 is found to represent linear features in the images.

The result of LoG and pixel bandpass filtering are images that still contain noises in the form of pixel clusters that do not convey any geological meaning. Therefore, pixel cluster filtering is applied which eliminates clusters of connected pixels less than 40 pixels in size. This size is found to be the most effective in removing geologically meaningless pixel clusters.

3.2. Lineament Extraction

Lineament extraction from the enhanced SAR images is performed using the modified Segment Tracing Algorithm (mSTA) [3]. The algorithm follows the principles of Segment Tracing Algorithm (STA) which searches for local pixel relationships inside an analysis window of $11 \times 11$ pixels in size around a target pixel with 16 searching directions of $11.25^\circ$ interval (Figure 5a) [17]. The direction of possible line segment, $k_{\text{min}}$, is defined as the direction that minimizes $\varepsilon_j$ which is the difference of DN value between the centre pixel ($Z^*$) in the search window and the neighbouring pixels ($Z_i$) along the line $j$ as shown by the following expression:

$$
\varepsilon_j = \sum_{\alpha=-\alpha}^{\alpha} \cos\left(\frac{\pi}{4\alpha}\right)(Z^* - Z_i)^2 \quad \text{for} \quad j = 1, \ldots, 16
$$

(2)

where the $\cos\left(\frac{\pi}{4\alpha}\right)$ term signifies the weighted coefficient to amplify the difference between pixels and $\alpha$ signifies the number of pixels from the center to the edges ($\alpha=5$). To reduce the effect of noises from the image which may cause multiple $k_{\text{min}}$ to be detected, three neighbouring $\varepsilon_j$ are averaged as follow:

$$
E_j = (\varepsilon_{j-1} + \varepsilon_j + \varepsilon_{j+1})/3
$$

(3)

Any directions that reduce $E_j$ is assigned as $k_{\text{min}}$ [3]. The result of the above process is line segments. Line segments extracted from enhanced SAR images of the ascending and descending orbit will be grouped to create lineaments.

Grouping is performed using an ellipse window which major and minor axes are controlled by the length of the major and minor geologic structures observed in the study area [3]. The major faults in the study area are oriented NW-SE and the shortest measured fault of that direction is 2261 m. Therefore, 2261 m was assigned as the length of the major axis. On the other hand, the minor faults are oriented NE-SW and the shortest observed fault of that direction is 1071 m in length and was assigned as the length of the minor axis.

Ellipse window is centred at a target line segment and any line segments within the ellipse window will be grouped if they satisfy the necessary conditions (Figure 5b). The condition is that at least one end of the line segments should be within the ellipse window boundary and the line segments should be oriented within $\pm11.25^\circ$ to the orientation of the target line segment.
Figure 5. (A) Search window of 11×11 pixels in dimension with 16 line of analyses spaced at 11.25° from each other [4]. (B) Line segments grouping using ellipse window [3].

The lineaments were analysed spatially with 0.5×0.5 km cell size to determine lineament frequency density, length density, and intersection density. Lineament frequency density measures the number of lineaments found within a cell, lineament length density measures the total length of lineaments within a cell, and lineament intersection density measures the number of lineament intersection points within a cell. The results were used to validate the extracted lineament with field observation data (Figure 6).

4. Results and Discussion

4.1. Geological Validation

Lineaments in a geothermal field correlate to the emergence of geologic phenomena on the surface, including structures (i.e., faults, folds, and joints) and thermal fluid manifestations (i.e., hot springs, geyser, solfatara, and heated ground) [18] [4] [3]. Inspection of the extracted lineaments shows the clustering of lineaments around faults and volcanic features. Lineaments clustering around faults tend to be parallel – subparallel to the fault while lineaments clustering around volcanic features tends to be distributed radially. Dominant lineament orientations are on agreement with the orientation of measured major and minor faults which indicates that the lineaments are fault controlled (Figure 6e).

Spatial analyses found that measured faults and thermal manifestations found in the study area correlate strongly with the emergence of lineament density anomaly, including lineament frequency density, length density, and intersection density (Figure 6b-6d). Thermal manifestations, including hot springs and solfatara, occur exclusively on medium to high-density anomaly.
Figure 6. (A) Lineaments overlaid on top of the elevation map. Spatial analyses result showing the correlation between high-density anomaly of (B) lineament frequency, (C) lineament length, and (D) lineament intersection in the study area to the emergence of geologic phenomena, including faults, volcanic features, and geothermal manifestations. (E) The extracted lineaments assumed to represent fracture system have been characterized to have two dominant orientations consistent to the orientation of the major and minor faults, including major orientation of NW-SE and minor orientation of NE-SW.

4.2. Fluid Flow in Correlation to Fracture Geometry

Two characteristics of fluid flow were determined, including breakthrough time and flow rate in correlation to fracture geometry. Breakthrough is the time that fluid takes to travel from one point to another and the flow rate is the volume of fluid that passage per unit of time. Four cases of fluid flow simulation were performed for five years period.

Two main cases of fluid flow simulation were performed with injector and producer wells arranged parallel to the dominant (major and minor) fracture orientations, including the major NW-SE arrangement and the minor NE-SW arrangement. Two control cases of fluid flow simulation were performed with injector and producer wells arranged independently from the dominant fracture orientations, including N-S arrangement and E-W arrangement.

Simulation results show that fluid flow which is parallel to the dominant fracture orientations produce equally high flow rates (Figure 9). However, it is found that breakthrough time is faster when injector and producer are arranged parallel to the minor fracture direction of NE-SW. On the other hand, fluid flows in which directions are independent of the dominant fracture directions produce lower flow rates and the flowing fluid never reached producer wells within the simulation period (Figure 7c-d and Figure 9).
This is consistent with the previous study which found that the preferred orientation of major fractures leads to permeability anisotropy, in which rock may be more permeable parallel to the dominant fracture directions than in other orientations [19]. This explains why the rate of flow parallel to dominant fracture directions is equally higher overall. Breakthrough time parallel to the minor fracture direction (NE-SW) is found to be faster because the flow path coincides with a corridor of high-density interconnected fractures (high intersection density) which provides a fluid flow highway that allows faster passage of fluid from the source to the producer. Fluid flow through the other major fracture direction (NW-SE) is slower because there are less interconnected fractures running along that direction. Therefore, fluid would find the path with higher flowing capacity, which may involve more convoluted pathways (Figure 8).

![Figure 7](image_url)

**Figure 7.** (A) Simple geologic model for preliminary fluid flow simulation. (B) Extend of area used for fluid flow simulation is shown by red rectangle. Simulation results are shown by Figure 7.c-d and Figure 8 with yearly time-step shown by T. (C) The simulation result with E-W wells arrangement. (D) The result of simulation with N-S wells arrangement.
4.3. Fluid Flow from Upflow to Outflow
When fluid gets heated by geothermal heat source, it becomes buoyant and starts to ascend upward, creating the upflow zone. As the fluid moves upward, some of the heat is lost to the surrounding rocks which made the fluid loses its buoyancy. When the force of gravity overcomes the thermal buoyancy and as it encounters the clay-rich alteration zone (clay cap), the fluid collapses and starts to move laterally, creating the outflow zone. Outflow zone and to some extent the upflow zone, provide the optimum conditions to extract geothermal energy. Fractures play an important role in every step of these processes because thermal fluid will preferentially flow through highly fractured rocks, which have higher permeability.

Fluid flow is simulated from the upflow zone around Mt. Geureudong to the outflow zones at Wih Pesam and Mt. Pepanji through the fractures represented by the lineaments detected from the SAR images (Figure 10b). The simulation results show that fluid flow propagates faster and more extensively towards the NW-SE direction (major fracture orientation), consistent with the outflow direction. It is found that the path that the fluid takes from the injector to the producer follows the path of the fracture system, preferentially flowing through corridor of highly fractured rock. It must be kept in mind that the preferential flow path which coincides with this direction may also be caused by the geometry of the reservoir layer which tends to dip steeply towards these directions. Direction with a steeper dip angle provides more potential energy for the fluid to flow in that direction, therefore the fluid can propagate faster and more extensively.
Figure 9. Fluid flow characteristics in fractured reservoir based on preliminary simulation results. (a) The injected fluid flow rate at the producer wells. The production of injected fluid indicates the breakthrough time, where breakthrough time at injection parallel to dominant fracture directions is higher overall compared to flow directions independent from fracture direction. (b) Flow rate is maximized when fluid flow is parallel to fracture directions.
It is found that fluid flow is comparatively faster towards Mt. Pepanji than the flow towards Wih Pesam. There are two causes to this result, one is that there are spatially more interconnected fractures which connect the upflow zone to the outflow zone at Mt. Pepanji. Second is that the geometry of the reservoir on Mt. Pepanji side is slightly steeper compared to the reservoir geometry towards Wih Pesam which provides more potential energy to the fluids to flow to this direction (Figure 10).

5. Conclusions
This study evaluates the application of lineaments for fracture modelling, fluid flow path prediction, and fluid flow characterization in geothermal system which lacks subsurface data. Surface data, namely SAR images were utilized to infer geologic lineaments that can be attributed to rock fractures, including joints and deep-seated faults. A novel method was developed to enhance SAR images to optimize the detection of geologically meaningful lineaments in the study area. mSTA and statistical approach were used respectively to extract line segments and to transform them into geologic lineaments. Spatial analyses showed good agreement between the distribution of lineaments to the emergence of observed faults, volcanic features, and surface thermal manifestations. Lineaments rose diagram showed trend similarity to the observed geologic structures, therefore it was concluded that the lineaments were dominantly controlled by the structures.

Secondly, a simple geologic model was created with the assumption that lineaments represented subsurface fractures that extended vertically downward. The characteristics of fluid flow and its flow path through the fracture system were simulated. This study assumed that the extracted lineaments represented fractures, in which fluid flow is dominant. It was found that fluid flow is heavily controlled by the geometry of the fractures, namely its dominant orientations, density, and connectivity. Fluid flows that were parallel to fracture dominant orientations generally have a higher flow rate and flow faster. However, the presence of high connectivity and high fracture density corridor (spatial anisotropy) may enhance flow parallel to that direction.

Finally, fluid flow was simulated on a tentative geologic model of the Geureudong geothermal system. The model incorporated lineaments as fractures where fluid flowed dominantly. It is found that flow rate and breakthrough time were optimized in area that contained dense, highly interconnected fractures. Fluid preferentially flows towards this area as well. However, reservoir geometry should be taken into account because the directions at which fluid flow was optimized coincided with the presence of steep reservoir geometry which might provide higher gravity potential flow path that allows fluid to flow further and faster.
Figure 10. (A) Tentative geologic model of the Geureudong geothermal system. The fracture system is visualized by filtering the rock matrix. (B) Simulation results are visualized as water saturation change per time. Preferential fluid flow path coincides with the direction of outflow to Wih Pesam and Mt. Pepanji. This is caused by the presence of highly connected fractures on that direction and influenced by the steep reservoir geometry towards that direction (shown by Figure 10b ~ T = 5).
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