ZONE OF GEOTHERMAL PROSPECTS BASED ON FAULT FRACTURE DENSITY (FFD) METHOD IN SUMANI REGION, WEST SUMATERA

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ABSTRACT

The presence of geothermal manifestations in the form of hot springs is closely related to the presence of permeability zones in the Sumani geothermal system, West Sumatra. The permeable zone allows fluid circulation where meteoric water seeps to fill the reservoir and emerges on the earth's surface as a manifestation of hot springs. This study aimed to identify those permeable zones based on lineament density analysis using the Fault Fracture Density (FFD) method on ASTER GDEM satellite imagery. Lineaments in this case was assumed to be associated with fractures or faults in geothermal areas. The method was used to analyze the presence of lineament on topographic maps and to clarify all lineaments in the study area by adjusting the irradiation angle of 0°, 225°, 270°, and 315° at a constant altitude of 45°. From the FFD method, high lineament density values were found in the southwest of the study sites. The pattern of lineaments in the research area had northwest - southeast and southwest – northeast. The FFD analysis results were compiled with location of geothermal manifestations and geomorphological analysis which then showed positive results on the emergence of dominant hot springs depending on zones with high lineaments density and was located in the pyroclastic flow geomorphology unit with a difference in elevation between 500-1500 masl and slope of moderately steep to steep; indicating catchment area. Further research was needed to accurately understand about reservoir and the potential of geothermal reserves in the Sumani area.

Keywords: Sumani Geothermal System, Fault Fracture Density, Geomorphological Analysis.

INTRODUCTION

Indonesia has the largest geothermal potential in the world with 11,073 MW of potential resources and 17,506 MW of reserves, with approximately 331 potential points scattered from Sabang to Merauke (ESDM, 2017). One of the areas in Indonesia that has geothermal potential, and can be developed and utilized is in Sumani, West Sumatra. It is enhanced by the presence of geothermal manifestations such as hot springs with temperatures ranging from 34-71 ° C, based on previous research conducted by Hermawan (2011). The presence of this hot spring is estimated to be influenced by the pre-sence of fracture or fault structures in the area.

The Fault Fracture Density (FFD) method is a development of geospatial analysis that can be used to determine the condition of macro structures in an area. This method is applied by calculating linear line density patterns in satellite images to find out weak zones in a research area (Thannoun, 2003). By drawing lineaments in the research area using the FFD method, the lineaments that are associated with the structure are obtained. These lineaments; from valleys, ridges, and rivers; are thought to be caused by fault activities (Chemong and Chenrai, 2013). Lineaments analysis in this study aims to locate an area with the highest lineaments density value which can be assumed to be the center of geothermal fluid movement.

This study aims to describe the geothermal prospect zones in the research area by con-ducting lineament density analysis based on the FFD method. The results are delineated by geo-morphological analysis and the location of the manifestations. Geomorphology analysis aims to study the shape of the earth's surface and the processes that have taken place on the surface of earth since the earth had formed until now.

LITERATURE REVIEW

The Sumani geothermal area is administratively located in the Solok Regency and Solok City, West Sumatra Province. In the Sumani area, a volcanic complex was formed with pyroclastic and lava rocks composition of andesit-basaltic as the product. This area is located in the large Sumatran fault zone with a zone of depression in the central part of the study area.

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The geological structure in the study area is dominated by the relatively northwest-southeast trending fault structures that are part of the large Sumatran fault and the fault trending southwest-northeast. The structure of this fault is estimated to cause the emergence of hot springs in several research locations.

Based on its regional geology, Sumatra island is on the edge of the Eurasian continental plate with a south-southwest movement which then interacts with the Indian-Australian oceanic plate that moves north-northeast. The interaction of these two plates produced subductions combination which occured between the Tertiary to Recent, resulting the formation of a magma arc path, the Bukit Barisan Mountains. The magmatic arc and the back arc basin cut almost along the Sumatra Island which is a dextral-strike slip fault and is known as the Semangko fault or the great Sumatran fault.

Based on the geological map made by the Hermawan (2011) (Figure 1) and regional geological maps by Silitonga and Kastowo (1995), rock types in the study area could be classified into 12 rock units with stratigraphic sequences from the oldest to the youngest, i.e.:

a. **Meta-Limestone Unit (PKg)**, the oldest unit, was present in the northwest of the research area. This rock unit consisted of limestone that had been altered. According to the regional geological maps, these rocks were the members of the limestone formations of Kuatan from Perm-Carbon (Silitonga & Kastowo, 1995).

b. **Metamorphic Unit (Trm)** consisted of slaty metamorphic rock. These rock units were intruded by younger granite rocks. According to the regional geological maps, these rocks were the members of the shale of the Tuhur formation from Triassic age (Silitonga & Kastowo, 1995).

c. **Granite Intrusion Unit (Trig)**, consisted of igneous rock with granite composition. According to the regional geological maps, It was mostly granite from Triassic age (Silitonga & Kastowo, 1995).

d. **Andesite Intrusion Unit (Tia)** consisted of andesite composition igneous rocks. According to the regional geological maps, it was mostly andesite from Late Miocene age (Silitonga & Kastowo, 1995).

e. **Tertiary Vukanik Unit (Tvl)** consisted of breccia and lava with an andesitic-basaltic composition. This rock unit had undergone transportation with unknown origin. Based on relative dating to other rock units, this unit was estimated to be from Pliocene age.

f. **Lake Deposition Unit (Qed)**, consisted of repetition of limestones, sandstones, and conglomerates. This unit formed by filling depression zone due to tectonic activity of the large Sumatran fault, and was estimated to be from Early Pliestocene age.

g. **Tinjau Laut Lava Unit (QTl)**, consisted of andesit-basaltic lava flows. This unit was a lava product from Tinjau Laut Hill which was estimated to originate from the first quarter volcanic activity that developed in the research area. Based on relative dating, this rock unit was estimated to be of the Plistocene age.

h. **Tinjau Laut Pyroclastic Flow Unit (QTap)**, consisted of pyroclastic flow in the form of ash-lapilli tuff with an andesitic-dacite composition and this unit was a product of eruptions from Tinjau Laut Hill. This unit was estimated to be from Pleistocene age.

i. **Phreatic Deposition Unit (Qef)**, consisted of pyroclastic flow in the form of ash-lapilli with fragments in the form of andesite-basaltic rocks. This unit was estimated to be from Pleistocene age.

j. **Cubadak Lava Unit (QCl)**, consisted of andesite-dasitic lava. This rock unit was a lava product from Cubadak hill, which formed the Cubadak cone, morphology and was thought to be the youngest volcanic product from Pleistocene age.

k. **Gajah Dubalang Lava Unit (QGl)**, consisted of andesite-dasitic lava. This rock unit was a lava product from Gajah Dubalang Hill. This unit was estimated to be from Pleistocene age.

l. **Aluvium (Qa)**, consisted of loose materials in the form of clay, sand, andesite chunks, basalt, granite and limestone. The process of deposition of this unit still continues as we speak.

METHODS

The data used in this study is ASTER GDEM satellite image data (*Advanced Spaceborne Thermal Emission & Reflection Radiometer*

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Global Digital Elevation Model) of research area with a spatial resolution of 15 m and a contour interval of 12.5 m. ASTER GDEM was used to determine the orientation pattern of lineaments by using FFD map.

Then the lineaments pattern was drawn manually by changing four irradiation angles to get a different direction of irradiation, i.e. 0°, 225°, 270°, 315° and altitude 45°. The irradiation angle variation was chosen because the line pattern produced in the study area was clearly visible. The constant irradiation height of 45 ° aimed to get the same shadow size as the object that was exposed to the light.

The result of drawing lineaments were the linaments of rivers, ridges, which indicated a fracture zone. Then the lineaments density values were calculated and grouped in grids per 1.8 x 1.8 km. This value was placed in the middle of the grid that showed the length of each line in each grid. The results of this lineaments analysis were lineaments density maps that provided an overview of regions with the highest lineaments density values that were indicated as permeable zones that served as the main pathway for circulating geothermal fluid movements.

The lineaments density map was then correlated with the data from the results of geomorphological analysis, indications of structure based on geological maps, and the location of geothermal manifestations. Geomorphological analysis was carried out by using remote sensing methods to understand the landscape and its features, and to identify catchment areas with high elevation and with steep slope. The final result of this study aimed to describe the zones of the Sumani area geothermal prospect zone.

RESULTS AND DISCUSSION

Geomorphological Analysis

Geomorphological analysis is a method to understand the appearance of the surface of the earth and how it came to be. Geomorphological analysis on the research area was conducted by interpretating satellite imagery that was processed on computer software and correlated with the geological map of Hermawan (2011). Three geomorphological analyses were conducted, namely morphographic analysis to find out the shape of the land and the pattern of river flowing that develops, morphometric analysis to determine the slope, and morpho-genetic analysis to determine the processes that influence the formation of these landscapes. The final results of these analyzes were then displayed in the form of a geomorphological map (Figure 2).

Displayed in figure 2, the research area was divided into several geomorphological units, classified based on its landforms, such as:

1. Fluvial Landform

➢ Alluvial Plain Unit

The alluvial plain unit was situated in the center of research area and occupied about 10% of the study area. This unit consisted of alluvium of loose material from rock debris in the upstream part of the river with a rounded form of fragments to cover the bound (Hermawan, 2011). Morphogenetically, the dominant pro-cess affected the formation of this morphology was the exogenous process in the form of weathering. Based on morphographic analysis, this unit was characterized by rivers with U-shape and dendritic drainage pattern. Mean-dering river, generally present in the unit, showed a mature stage of erosion. This unit occupied areas with elevation ranging between 200 to 500 m and had flat to gentle slopes with slope that was valued between 0% to 7%.

2. Structural Landforms

➢ Denudational Fault Plain Unit

The denudational fault plain unit was situated in the center of research area and occupied about 12% of the study area. This unit consisted of lake sediments of intersbedded claystones, sandstones and conglomerates (Hermawan, 2011). Morphogenetically, the dominant process affecting the formation of this morphology was the endogenous process in the form of tectonic activity that produced fault structures. Based on morphographic analysis, this unit was characterized by rivers with U-shape and dendritic drainage pattern. This unit occupied an area with elevation ranging between 200 to 500 m, and had flat to wavy slopes that was valued between 0 to 13%.

➢ Fault Hill Unit

The fault hill unit occupied about 15% in the research area. Its was situated in the east and northwest of the research area. The northwest region consisted of metalimestones while the eastern region consisted of metamorphic rocks similar to slate. Megascopically, the limestone was light gray and massive. It was composed of many calcite veins that were strongly strained. Meanwhile, the slate stones had brownish-gray color. They were composed of quartz, feldspar, sericite in a slaty cleavage

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structure. The minerals of the slate stones appeared in the form of soft hypidioblastic granules. (PSDMBP Survey Team, 2011). This slate stones emerged in the eastern part of the large Sumatran fault. Thus morphogenetically, the dominant process affecting the formation of this morphology was the endogenous process in the form of tectonic activity. Based on morphographic analysis, this unit was generally characterized by a river with parallel and dendritic flow patterns. This unit occupied an area with elevation ranging between 500 to 1,700 m, and had moderate to steep slopes that was valued between 20 to 55%.

3. Volcanic Landforms

➢ Intrusive Hill Units

This intrusive hilly unit occupied about 15% of the study area. The dominant distribution was located in the east region. This unit consisted of granite rocks. Megascopically, the granite was had gray color; faneritic texture; minerals of feldspar, biotite, and hornblende (Hermawan, 2011). Morphogenetically, the dominant process affecting the formation of this morphology was the endogenous process of volcanic activity that forms intrusive hills. Based on the morphography analysis, this unit was generally characterized by rivers with radial centrifugal pattern. This unit occupied an area with elevation ranging between 500 to 1,500 m, and had moderate to steep slope with slope that was valued between 20 to 55%.

➢ Caldera Hill Unit

This caldera hill unit occupied about 5% in the research area. This unit was situated mainly in the southwest region of the research area. This unit consisted of phreatic deposits composed of ash-sized to to lapilli-sized pyroclastic rocks with andesit-basaltic rock fragments with some parts were from previously formed volcanic body (Hermawan, 2011). Morphogenetically, the dominant process affecting the formation of this morphology was the endogenous process of volcanic activity in the form of phreatic eruption. This phreatic eruption was caused bby the hydrothermal fluid that accumulated below the surface with pressure greater than the pressure of previously-formed load which had direct contact with the hydrothermal fluid. Based on morphographic analysis, this unit was characterized by rivers that developed in a generally dendritic flow patterns. This unit occupied an area with elevation ranging between 500 to 1,500 m, and had moderate to steep slopes that was valued between 20 to 55%.

➢ Lava Flow Ridge Unit

This lava flow ridge unit was situated in the west, southwest, north and northeast regions. It occupied about 23% in the study area. The western part consisted of dubalang and cubadak elephant lava with andesitic – dasitic composition, the southwest part is composed of sea-view lava with andesitic-basaltic composi-tion, then the north to northeast consisted of tertiary volcanic products of lava and breccia with andesitic-basaltic composition. In general, the lava stones had gray color; porphyritic – afanitic texture; had minerals of plagioclase, biotite, pyroxene, hornblende, and strongly strained (Hermawan, 2011). Morphogenetically, the dominant process affected the formation of this morphology was endogenous process of volcanic activities. Based on morphographic analysis, this unit was characterized by rivers with parallel and dendritic flow patterns. This unit occupied an area with elevation ranging between 500 to 1,500 m, and had steep slopes that was valued between 55 to 140%.

➢ Piroclastic Flow Ridge Unit

This pyroclastic flow ridge unit occupied around 20% of the study area. The spread was in the southwest to the center region. This geomorphological unit was composed of pyroclastic flow deposits in the form of lapili – ash tuffs with andesitic – dasitic composition. Megascopically, the tuff had light brownish in color, had composition of volcanic and quartz glasses with medium sortation and close contained (PSDMBP Survey Team, 2011). Morphogenetically, the dominant process affected the formation of this morphology was the endogenous process of volcanic activities. Based on morphographic analysis, this unit was characterized by rivers with parallel and dendritic flow patterns. This unit occupied an area with elevation ranging between 500 to 1,500 m, and had steep slopes what was valued between 55 to 140%.

Lineaments Analysis FFD Method

The topographic appearance of the Sumani geothermal region showed that the formation of deformation was controlled by several faults and fractures. This was because the Sumani geothermal area was located in the large Sumatra fault zone. The structure of fractures was very important since it was closely related to the escape of hydrothermal fluid and the hydrological cycle. In other words, an area that has a high fracture intensity is an indication of the high fluid

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entering a zone (Soengkono, 1999). Such area can be interpreted as permeable zone which serves as a circulation, exit, and entry, of fluid from the reservoir of the geothermal system.

The following were the results of lineaments drawings in the Sumani Geothermal area from four different irradiation angle, along with a rosette diagram to determine the direction of the dominant line from each irradiation angle.

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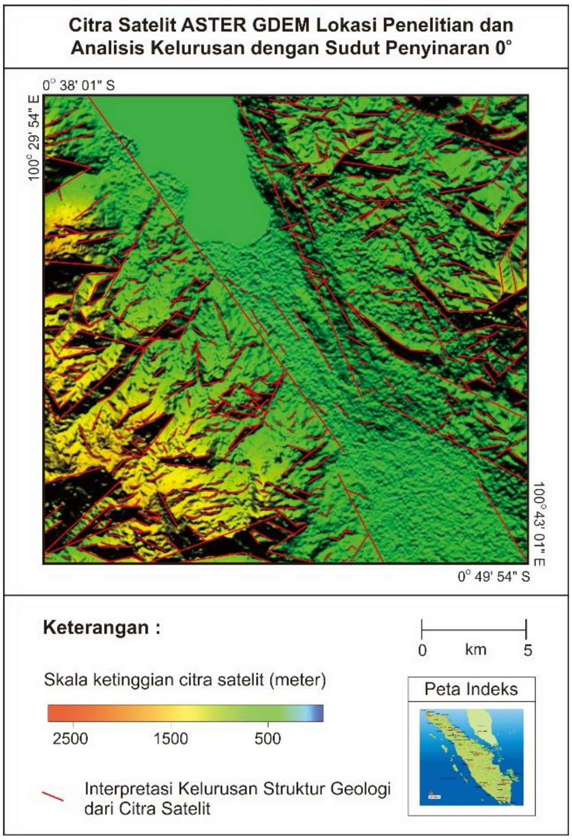

Figure 3. Fracture Density Analysis by ASTER GDEM from Irradiation Direction of 0°

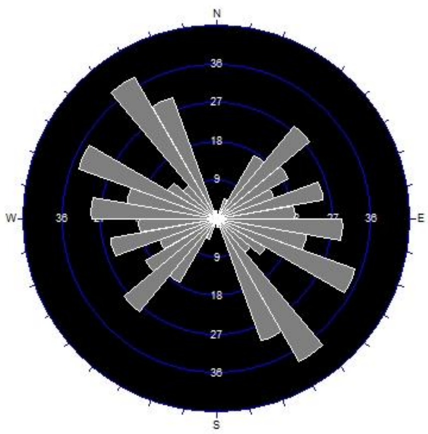

Figure 4. Rose Diagram of Lineament Pattern from Irradiation Direction of 0° showing NW-SE as dominant orientation

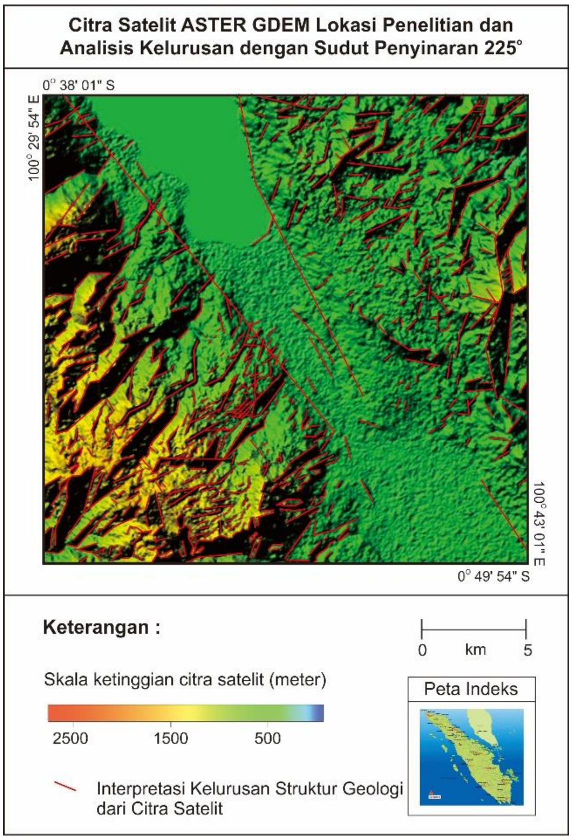

Figure 5. Fracture Density Analysis by ASTER GDEM from Irradiation Direction of 225°.

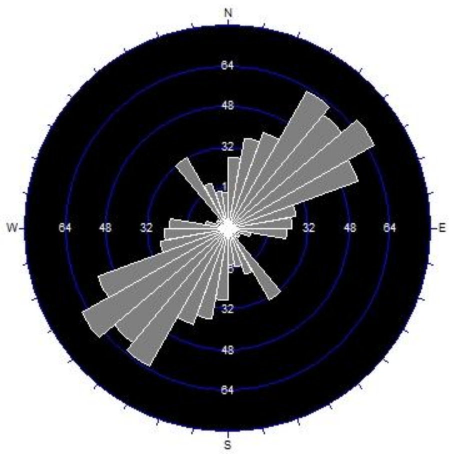

Figure 6. Rose Diagram of Lineament Pattern from Irradiation Direction of 225° showing SW-NE as dominant orientation

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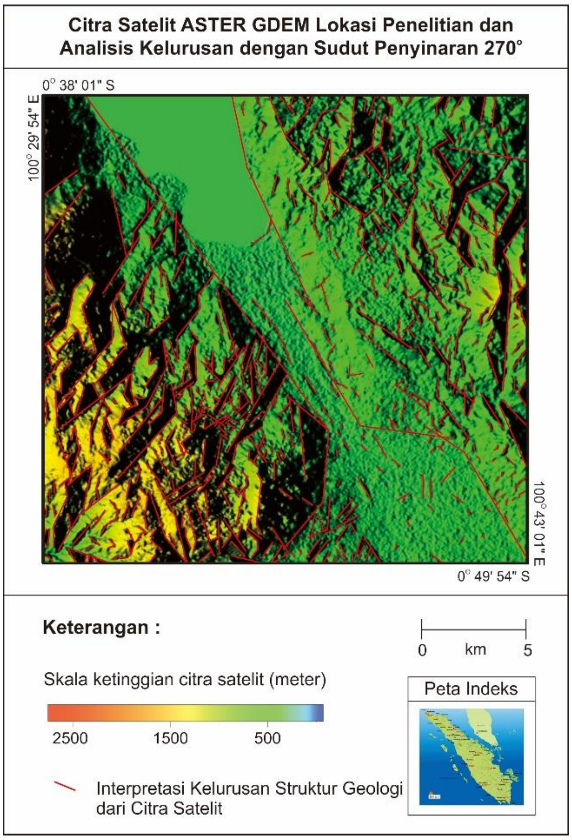

Figure 7. Fracture Density Analysis by ASTER GDEM from Irradiation Direction of 270°.

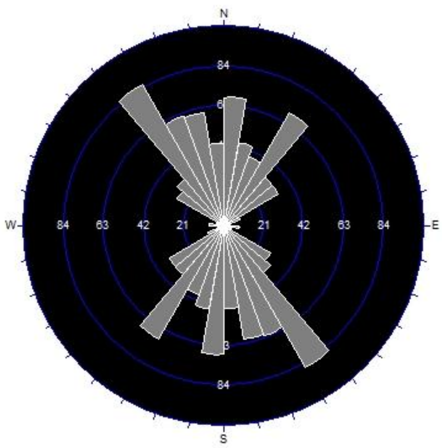

Figure 8. Rose Diagram of Lineament Pattern from Irradiation Pattern of 270° showing NW-SE as dominant orientation

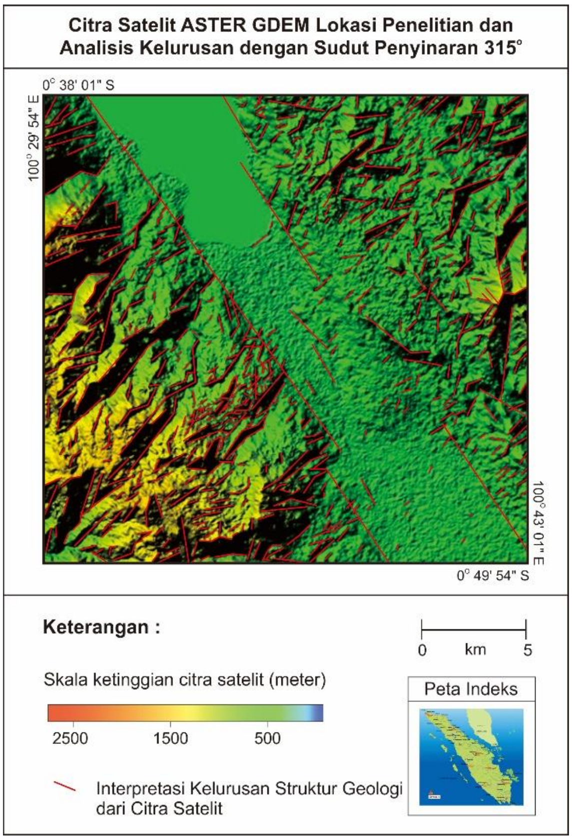

Figure 9. Fracture Density Analysis by ASTER GDEM from Irradiation Direction of 315°.

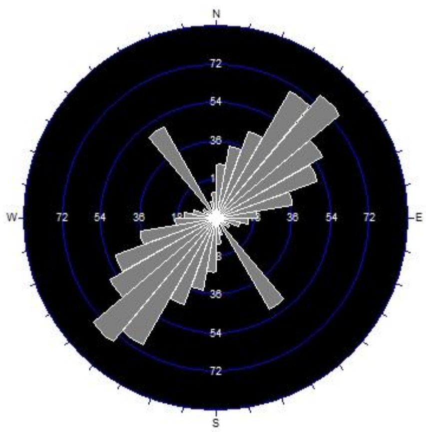

Figure 10. Rose Diagram of Lineament Pattern from Irradiation Pattern of 315° showing SW-NE as dominant orientation

The interpretation of the geological structure reflected by lineaments density showed that the direction of the dominant lineament were northwest - southeast and northwest southeast. The direction was parallel with the regional geological structure of the study area, which was dominated by relatively northwest-southeast trending fault structures which were

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part of the large Sumatran fault and faults trending southwest - northeast.

After analyzing lineaments in the image with four different irradiation angles, the results of the line drawings of each irradiation angle were combined, then the satellite image of the research area was divided based on the grid 1.8 x 1.8 km with an area of 3.24 km^2 (Figure 11) in order to understand more details of the lineaments density in the study area. Next, each grid box was calculated by the total alignment length in that area (Figure 12). The total value of line length density in satellite images of the Sumani Geothermal region ranged from 0 - 10.23 km per 3,24 km^2. In general, areas with high density values in the study area were associated with volcanic igneous rocks. Therefore, the existence of fractures and faults would have igneous rocks that have primary permeability to have a large secondary permeability (Santoso, 2004).

Calculation of lineaments density was then displayed in the form of a lineaments density contour map (Figure 13). Seen in figure 13, the Sumani geothermal area could be grouped into 4 density classes, namely high density (7,5–10,5 km/km^2) which was shown in red, medium density (5,5–7,5 km/km^2) which was shown in yellow, low density (1,5–5,5 km/km^2) which was shown in green, very low density (0–2,5 km/km^2) which was shown in blue. Based on FFD analysis, the location with the highest fracture density value was in the southwest part of the study area.

Furthermore, the data from the FFD analysis are compiled with data from the geomorphological analysis, location of hot spring manifestations and geological structure data in the form of fault indications from the geological map and the results show a positive correlation (Figure 14).

Displayed in the map in Figure 13, zones with high fracture density were generally located in the southwestern part of the research area or northeast of the hills, viewed by the sea, where there was one point with a high density reaching 10 km/km^2. Based on the geological map, there were several indications of faults in the zone. This zone was interpreted to have the highest permeability and was the main path for geothermal fluid movement in the study area. Judging from the geomorphological aspects of this zone occupies areas with differences in altitude ranging from 500-1,500 m, and with a slope steepness between 55-140%, which was steep to steep so it was likely to become a catchment area. Catchment area formed when high areas with steep slope formed a topography that channels water (run-off) to the lower valley area. In addition, this zone became the point of the emergence of hot water manifestations on the surface, namely hot water Karambia, Lawi, Lakuak and Tubatiah. The recharge zone was expected to originate from the southwest (from Tinjau Laut Hill) or from the north under the assumption that it had a higher morphography than the location with the manifestation.

CONCLUSIONS

Based on the foregoing description, the geomorphological units in the study area were divided into 7 alluvial plain, fractured denudational plain structures, fault zone hilly, intrusive hill, caldera hilly, lava flow ridges, and pyroclastic flow ridges.

After lineaments analysis using the FFD (Fracture Fault Density) method by manually extracting straight lines of fractures and ridges through the ASTER GDEM satellite imagery, FFD maps were calculated and made. The results of this analysis showed that the lineaments or fracture density values with the highest values were from the southwestern part of the study area. Fractures in rocks becomes one of the factors to have fluid flows into rock layer (aquifer). In other words, an area with a high fracture density is an indication of the high fluid entering a zone (Soengkono, 1999).

Furthermore, the FFD map results were compiled with the location of hot water manifestations and the results of geomorphological analysis. The location of manifestations of dominance hot water was found in areas with high lineaments density values. The geomorphological unit in this area was a pyroclastic flow ridge unit with differences in altitude ranging from 500-1,500 m, and slope between 55-140%, which was rather steep to steep so it was likely to become a catchment area. Thus, based on the merger of the data from the analysis results it was indicated that the prospect zone is located in the southwestern part of the study area.

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Thousand gratitudes are delivered specially for *Center for Mineral, Coal, and Geothermal Resources* for allowing and guiding researchers to join the *Panti drilling team* and obtain these data as an analysis of geothermal studies. Thank you to the lecturer at the Faculty of Geology, Padjadjaran University who has guided the author in completing this research.

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Appendix I.

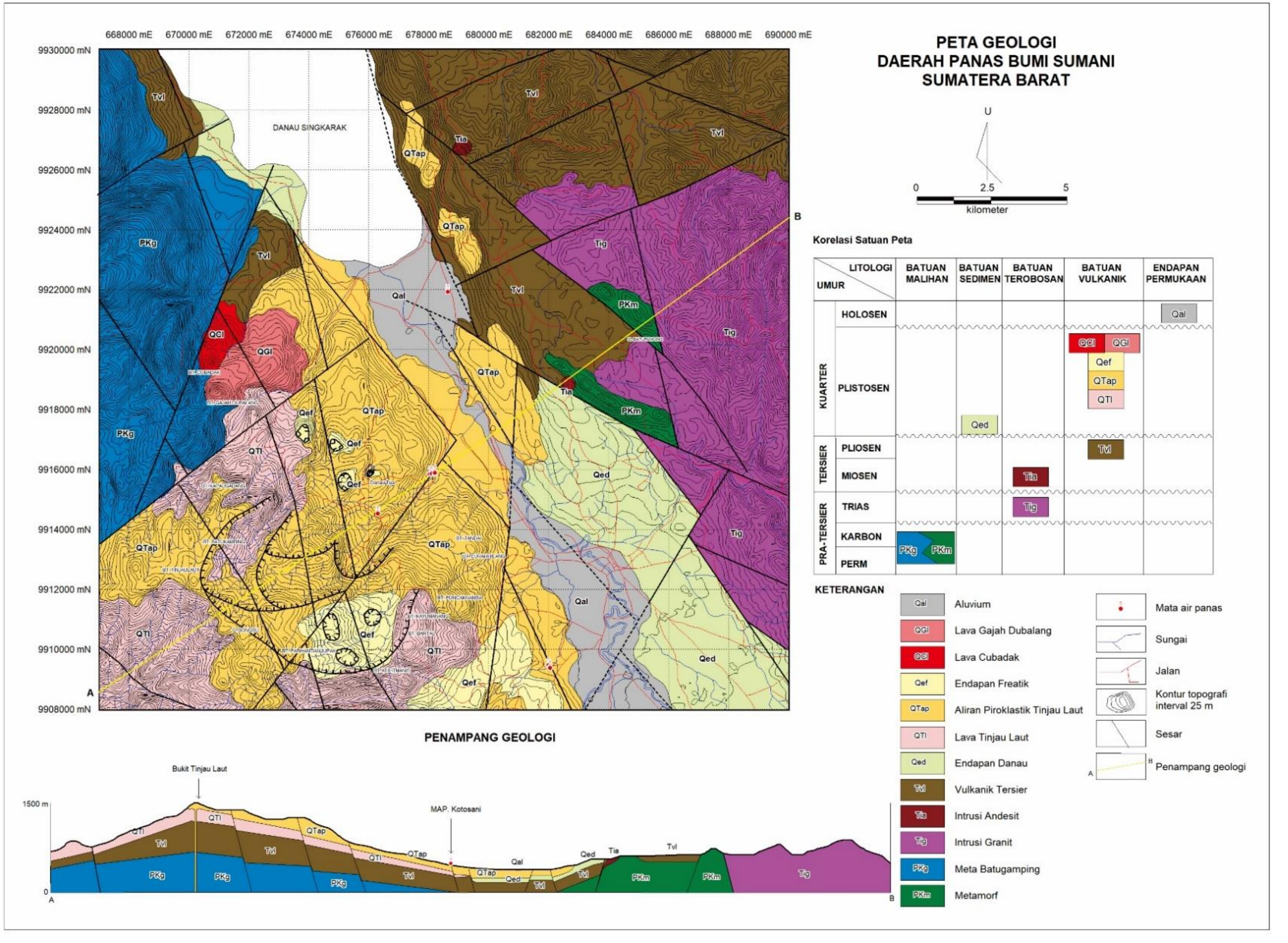

Figure 1. Regional Geologi Map of Sumani Geothermal Area, West Sumatra (Hermawan and Dudi, 2011)

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Appendix II.

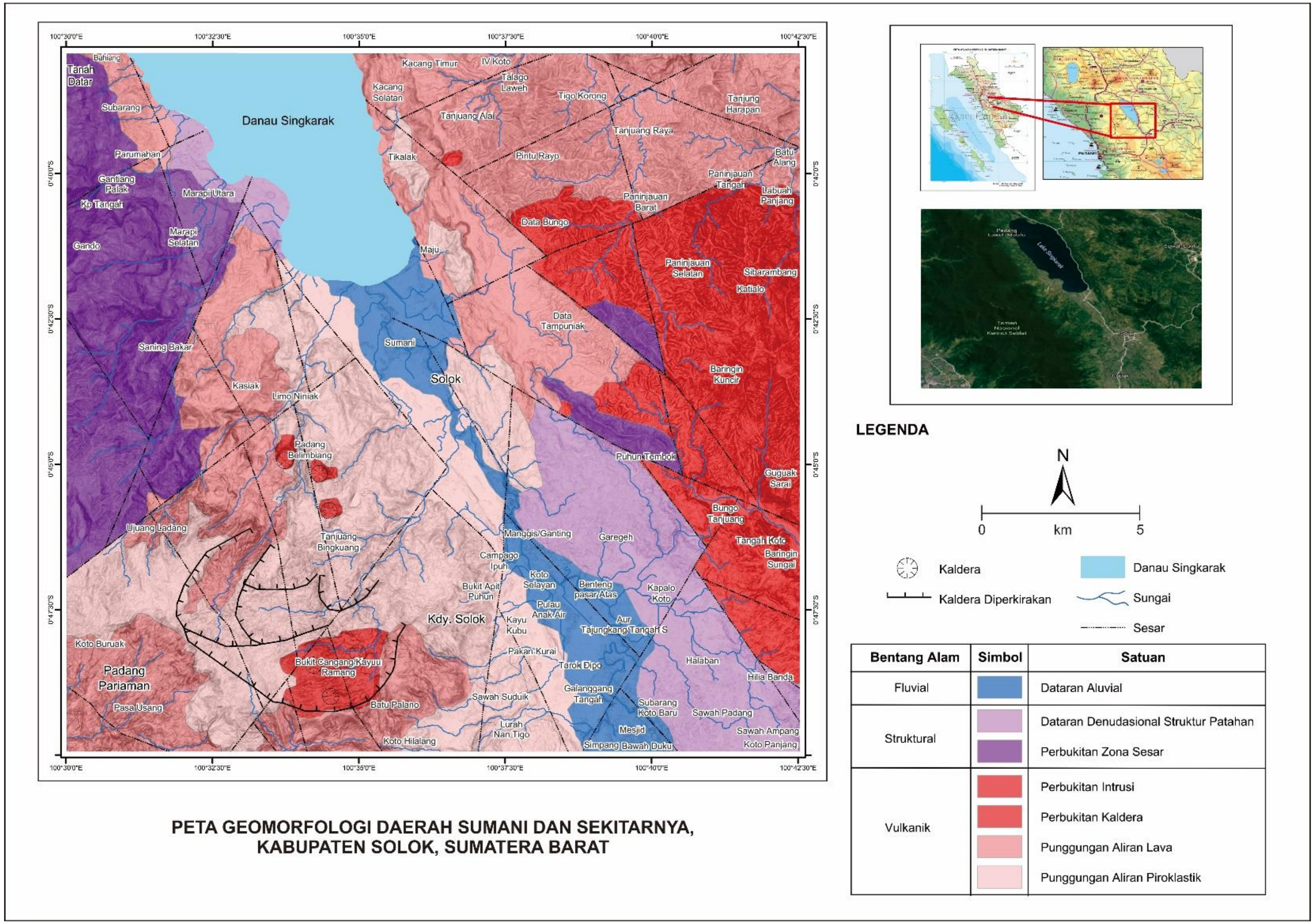

Figure 2. the geomorphological map in the study area showing 7 units, i.e. alluvial plain, fractured denudational plain structures, fault zone hilly, intrusive hill, caldera hilly, lava flow ridges, and pyroclastic flow ridges.

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Appendix III.

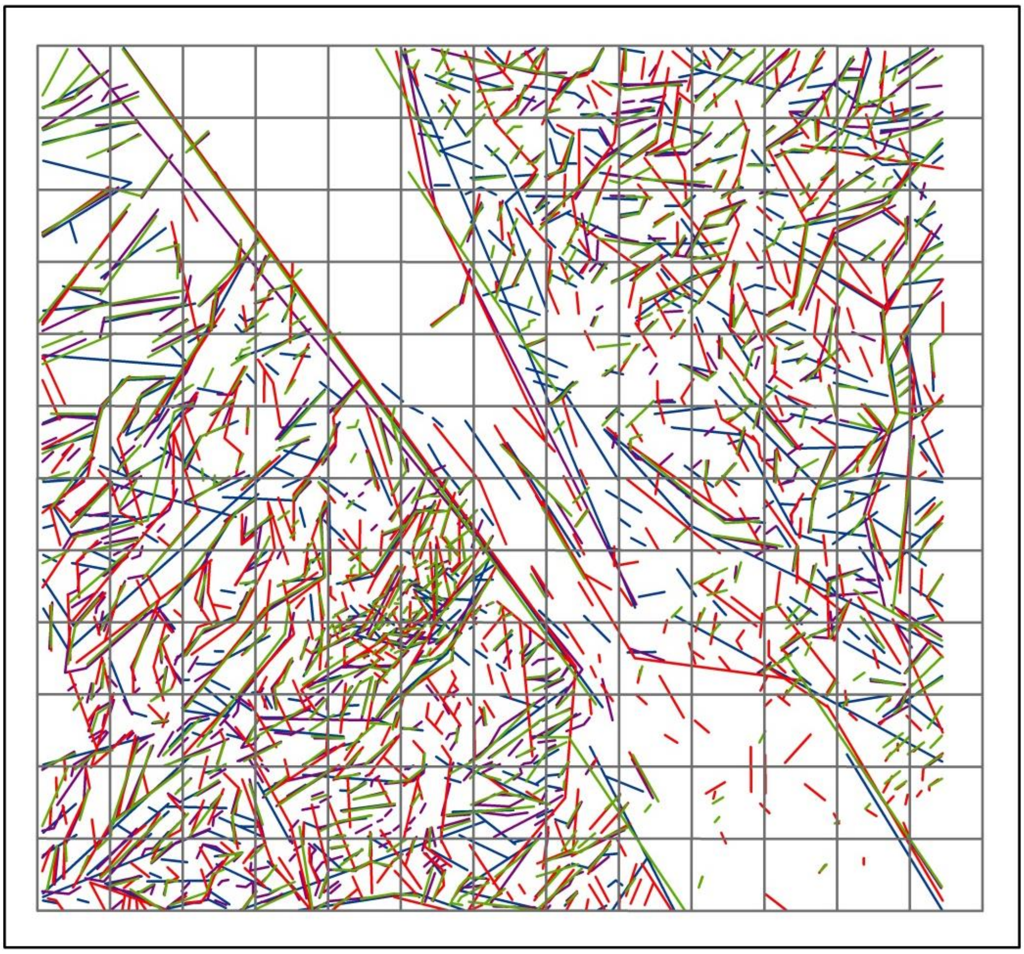

Figure 3. Lineaments Drawing of Sumani Geothermal Area from 4 different angles of Irradiation (blue = 0°, purple = 225°, red = 270°, green = 315°)

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Appendix IV.

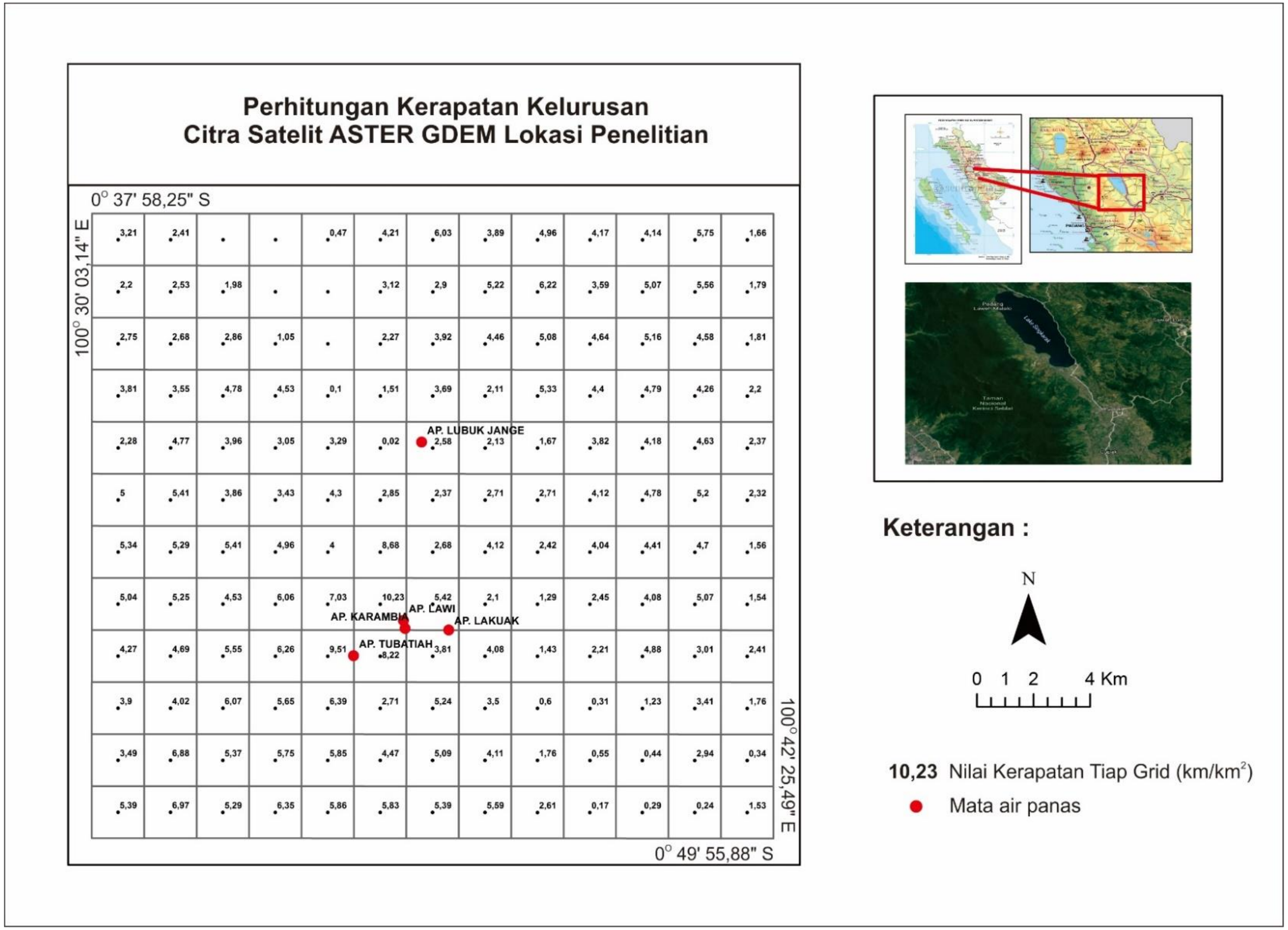

Figure 4. Lineaments Density by Citra Satelit ASTER GDEM compiled with the hotspring manifestation.

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Appendix V.

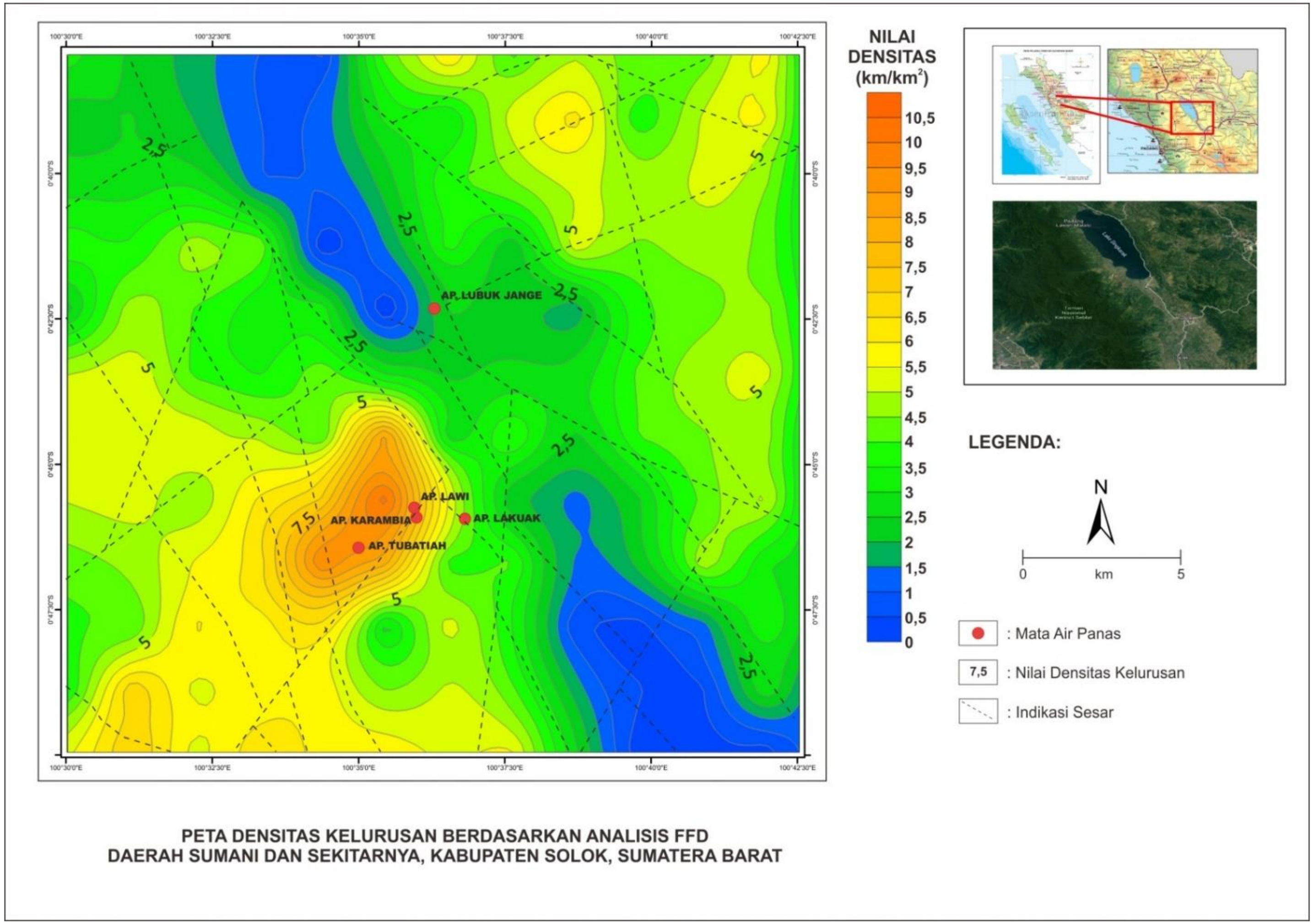

Figure 5. Lineament Density Contour Map by FFD analysis showing that the area surrounding Karambia hotspring, Lawi, Lakuak, and had a relatively high value of lineament density

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Appendix VI.

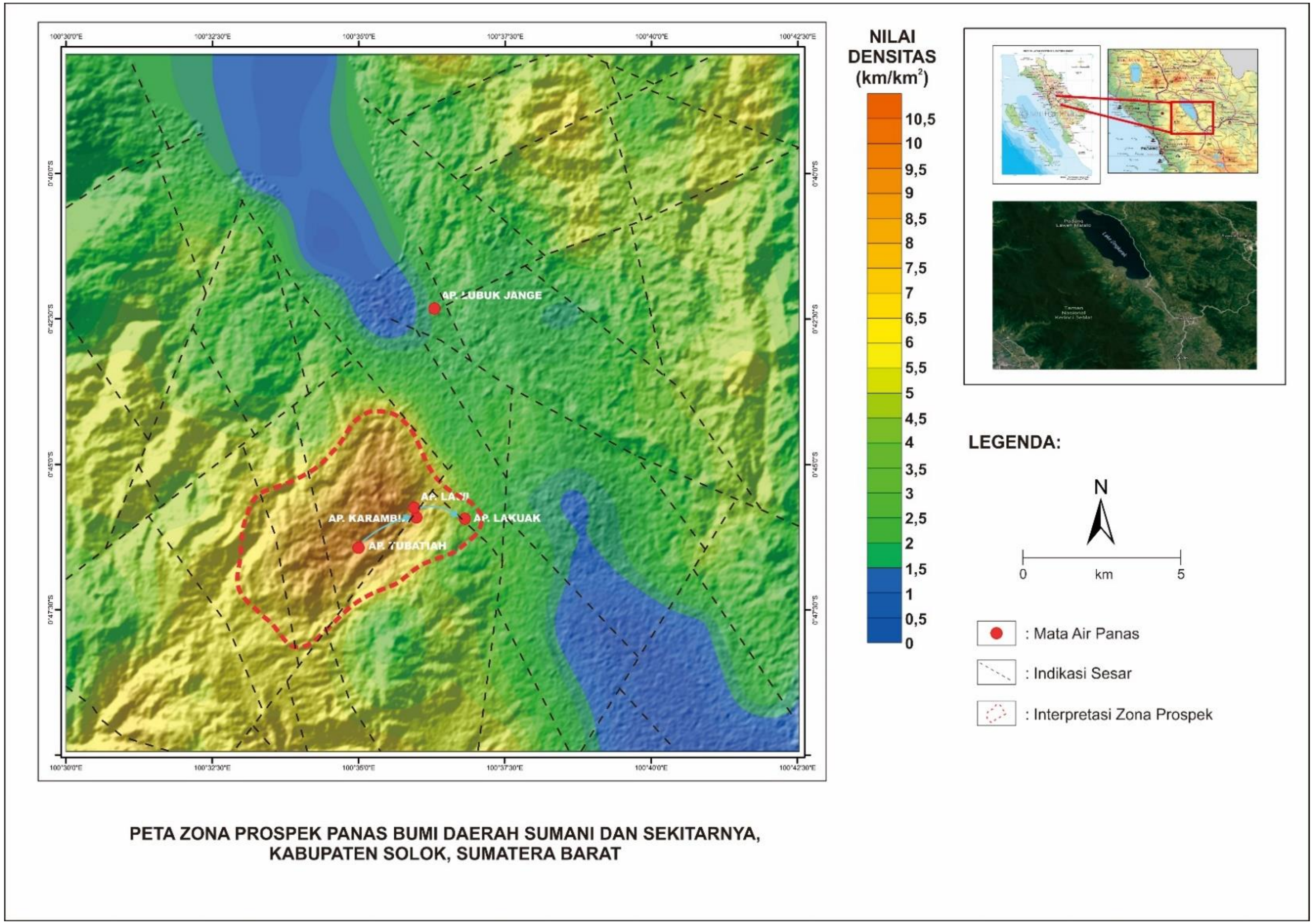

Figure 6. Sumani Geothermal Prospect Zone from the compilation of FFD analysis and geomorphological analysis. the location of hotspring and geological structure, an indication of regional structure, showed positive correlation.

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