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RESEARCH ARTICLE

Identifying Dominant Structural Pattern of Semarang City Using Digital Elevation Model and Landsat 8-OLI Imagery

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Abstract

Semarang City is an area in the northern part of Java Island, administratively the Capital of Central Java Province. Because Semarang City is the provincial capital, Semarang City has a relatively dense population. Geologically, the city of Semarang is an area that consists of various types of lithology and is traversed by various regional geological structures. In this case, understanding the existence and distribution of geological structures in the city of Semarang is essential, considering that geological structures are one of the controllers for natural disasters such as landslides and earthquakes. This study analyzed the existence and distribution of geological structures in the city of Semarang based on the lineaments observed from digital elevation models and satellite imagery. This study aims to identify the dominant structural pattern in Semarang City, determine the relationship between fault fracture density (FFD) with regional geological structure and lithology, and determine the fault zone area in Semarang City based on FFD & lineament analysis. The method used in this analysis is to process DEM data and Landsat 8-OLI imagery, then interpret the lineaments in the form of rosset diagrams and the density in the form of FFD maps. The results of the rosset diagram analysis show that Semarang City has various structural lineament patterns, namely: North–South, Northeast–Southwest, and Northwest–Southeast, with the North–South pattern as the dominant pattern. Based on the results of the lineament density distribution on the FFD map, it is known that the area traversed by the Semarang regional geological structure has a high lineament density value which is interpreted that the area is a weak zone with high structural intensity. From this study, it can also be seen that there is no significant relationship between the type of lithology and the density value on the FFD map. The distribution of lineament density is not affected by the type of lithology, except in the northern and northeastern parts of Semarang city, which consist of alluvium. Based on these results, it can be interpreted that the fault zone area is associated with areas that have high-density values on the FFD map. Distribution of the fault zone area of Semarang City is spreading over the Banyumanik, Gunungpati, and Mijen Districts, which are relatively in the southern and central parts of Semarang City.

Keywords: fault fracture density, structural pattern, fault zone, lithology, Semarang City

1. Introduction

Semarang City is an area on Java Island, Central Java Province's capital. Geologically, this area has various types of lithology and structure. Based on the regional Geological Map of Magelang and Semarang (Thanden et al., 1996) and the regional Geological Map of Salatiga (Budhitrisna, 1992), the geological structures found in the city of Semarang are generally in the form of asymmetrical folds and faults consisting of normal faults, strike-slip faults and reverse faults.

The existence of geological structures in the city of Semarang is essential for analysis because active geological structures can trigger natural disasters, such as ground motions, which can cause harm to humans and the environment. There are several studies on the geological structure in the city of Semarang, including (Poedjoprajitno et al., 2008;Hidayat, 2013;Wardhana et al., 2014;Nugraha et al., 2016;Nurwidyanto et al., 2019), however, research on the geological structure in the city of Semarang using remote sensing analysis is still relatively rare.

One way to identify the presence of geological structures using remote sensing in the study area is lineament analysis. The data used in lineament identification is DEM (Digital Elevation Model). Another method that can be used to identify geological structures can be done using satellite imagery with the type of Landsat 8-OLI imagery that can be used to determine the geomorphological forms that will be found in the field and also to find out the lineaments of geological structures in the study area. The interpretations carried out are in the form of lithology, geomorphology, and lineament drawing. Lineament itself is a line or linear structure that can be mapped from the surface and is a morphological expression of the geological structure (Majumdar & Bhattacharya, 1988;Vassilas et al., 2002).

In addition, to determine areas with high geological structure intensity in study area, Fault Fracture Density analysis could be carried out to identify areas with the highest structural density.Fault Fracture Density (FFD) is a calculation of the lineation density pattern on satellite imagery, which aims to identify weak zones and other geological conditions in the study area (Thannoun, 2013; Widiatmoko et al., 2021).

An example of research regarding the identification of geological structures using the Landsat image analysis method and field observations in the Kaligarang area, Semarang City, was conducted by (Hidayat, 2013). The results of this study state that there is a major fault line trending N-S, the Kaligarang fault. The Kaligarang fault line is recorded in several parts of the southern city of Semarang, which is dominated by Quaternary rocks. The results of analysis and field observations show that this fault is still active or has the potential to be active in the future.

In this paper, we aim to identify the dominant lineament pattern in Semarang City, determine the relationship between fault fracture density (FFD) with lithology and regional structure, and determine the fault zone area in Semarang City based on lineament and FFD analysis.

2. Regional Geology

Administratively, the study area is located in the city of Semarang, Central Java Province, with an area of 373.7 km^2 which is geographically located at the coordinates 110°16'20" – 110°30'29" East Longitude and 6°55'34" – 7°07'04" South Latitude. Geologically, the lithology of Semarang City is composed of Quaternary alluvial deposits in the northern part and the dominance of volcanic rocks in the southern part. In addition, geological structures are found in the form of faults and folds in the southern part of Semarang City. The stratigraphy of Semarang City based on (Thanden et al., 1996) from old to young is as follows (Figure 1):

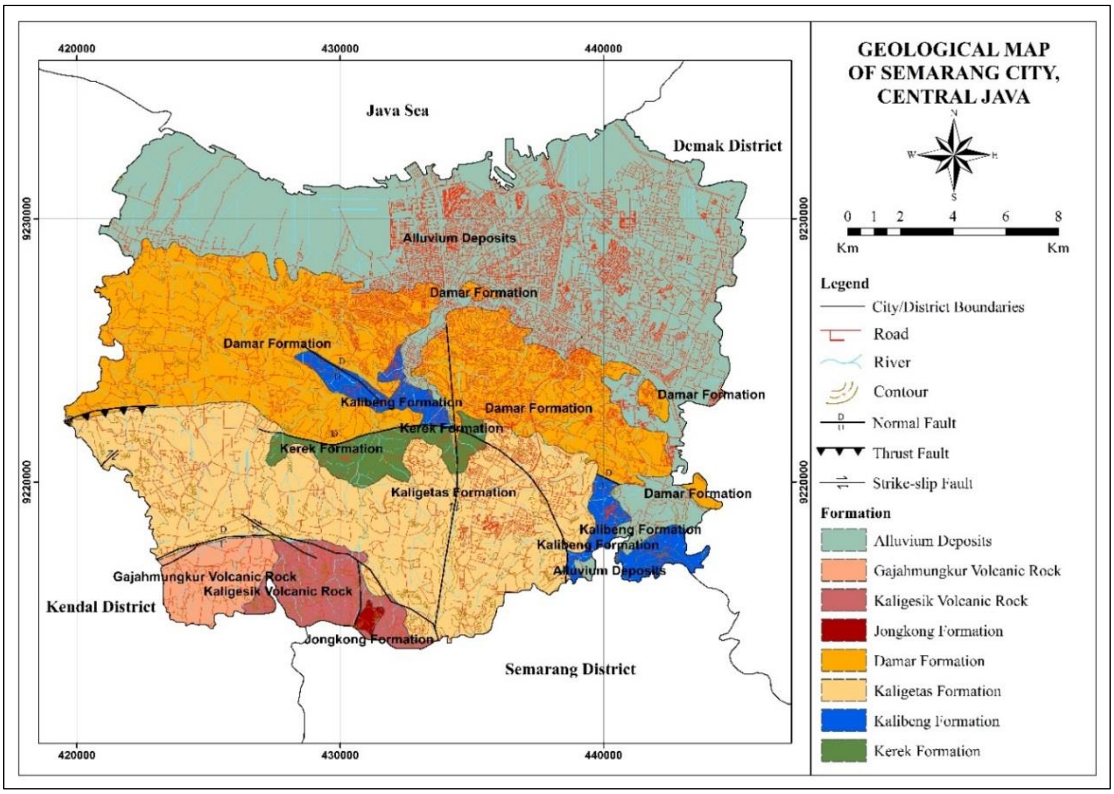

Fig 1. Geological Map of Semarang City (modified from Thanden et al., 1996)

a. Kerek Formation.
   The Kerek Formation comprises alternating claystone, marl, tuffaceous sandstone, conglomerate, volcanic breccia, and limestone with a thickness of more than 400 meters and of Miocene age.
b. Kalibeng Formation.
   The Kalibeng Formation comprises marl, tuffaceous sandstones, and limestones of Late Miocene – Pliocene age.
c. Kaligetas Formation.
   The Kaligetas Formation comprises volcanic breccia and lava with intercalation of fine to coarse lava and tuff, claystone containing mollusks, and tuffaceous sandstone were locally found at the bottom of the formation. This formation is about 50 – 200 meters thick and is of Plio – Pleistocene age, with fine – medium grain size and moderate porosity.
d. Damar Formation.
   The Damar Formation comprises tuffaceous sandstone, conglomerate, and volcanic breccia of Plio – Pleistocene age. The tuffaceous sandstone is brownish-yellow in color with fine–coarse grain sizes This formation was partially deposited in a non-marine environment.
e. Jongkong Formation
   The Jongkong Formation comprises blackish-brown andesitic breccia, augite hornblende, and Pleistocene lava flows. This formation was previously known as the Old Ungaran volcanic rock.
f. Kaligesik Volcanic Rock.
   Kaligesik Volcanic rock comprises basalt lava, gray-black in color, which is Pleistocene – Holocene in age.
g. Gajah Mungkur Volcanic Rocks.
   The Gajah Mungkur Volcanic Rock is composed of lithology in the form of andesitic lava.
h. Alluvium deposit.
   Alluvium deposit consists of coast, river, and lake deposits of Holocene age or younger. The beach deposits consist of clay, silt, sand, and mixtures of them, reaching a thickness of 50 meters or more.

2.1. Geological Structure

According to (Wardhana et al., 2014), the geological structure in Semarang City generally consists of normal faults, strike-slip faults, and reverse faults. Normal faults in Semarang City have a relatively W-E direction with a slightly convex part to the North, which generally occurs in rocks from the tertiary-aged Kerek and Kalibeng Formations, as well as the quarter-aged Damar Formation.

In their paper, (Poedjoprajitno et al., 2008) stated that the Semarang and its surrounding area have experienced several periods of tectonic deformation. In the tertiary period, faults trending N-S in the form of dextral faults were produced, faults trending NE-SW in the form of normal faults, and faults trending W-E in the form of sinistral faults. In the Quaternary period, these faults experienced reactivation. Faults trending N-

S are reactivated into sinistral faults, one of which is the Kaligarang Fault. Faults trending NE-SW are reactivated to become thrust faults, namely the Kali Pengkol Fault and Kali Kreo Fault, and faults trending W-E are reactivated to become dextral faults.

3. Methodology

This research is about estimating the density of fault fracture by using remote sensing data. The method used in this research is combination of geographic information system, remote sensing image interpretation, and field checking. This research was conducted using DEMNAS image, digital elevation model data with a spatial resolution of 8 m, and Landsat 8 OLI L1 imagery with a spatial resolution of 30 m, which will later be validated using data from field checkings. DEMNAS image and Landsat 8 OLI L1 imagery were extracted and processed using multiple software such as ArcMap, GlobalMapper, Google Earth, ENVI, and Rockwork to obtain lineament maps, rose diagram charts, lineament density/ Fault Fracture Density (FFD) map, hillshade, and slope map.

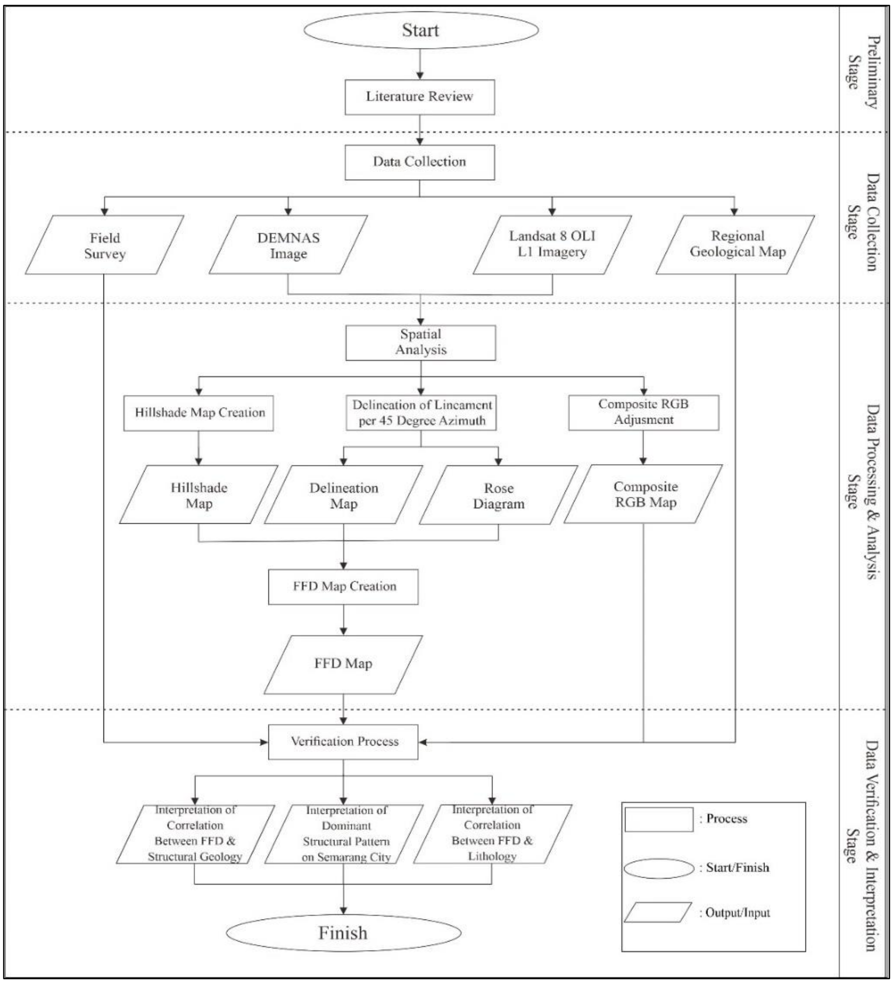

Fig 2. Flow Chart of the Research

Table 1. Specifications of imagery data used in this research

Imagery data	Specification	
DEMNAS	Spatial Resolution	8 m
	Datum	EGM 2008
	Format	Geotiff 32 bit
Landsat 8 OLI L1	Spatial Resolution	30 m
	Number of Band	11
	Datum	WGS84 49S

That processing was done to obtain information and as initial material for interpreting geological structure conditions in the city of Semarang. Fault Fracture Density map was created using weighting and equations according to (Liu and Mason, 2016). Based on the results of making a Fault Fracture Density map using weights and equations according to (Liu and Mason, 2016):

$$D = \frac{\sum_n wL}{A_{SR}}$$

Where:
D = Density
w = lineation weight value
L = Length of the lineation in the area influence
ASR = Area of influence

The weight value for the lineation of the structure was based lineament length class by (Han et al., 2018) on the following table (Table 2):

Table 2. Lineaments length class (Han et al., 2018)

Weight	Class	Length range (km)
I	Very short	< 0.4
II	Short	0.4 – 0.7
III	Medium	0.7 – 1.0
IV	Long	1.0 – 1.5
V	Very long	> 1.5

The results of remote sensing processing are then verified using field observations to check and validate the FFD interpretation data carried out with the appearance of geological structures in the field. The results of the field checking then be used as a basis for interpreting the development of geological structures in the City of Semarang.

3.1. Step-by-Step Procedures

The steps taken in conducting this research shown by Figure 2 as follows:

a. Preliminary Stage

The preliminary stage was done by conducting a literature study based on previous research regarding the processing of lineament data and the condition of the geological structure of the research area.

b. Data Collection Stage

The data collection stage was done by downloading DEMNAS and Landsat 8-OLI imagery data from the USGS Earth Explorer website.

c. Data Processing and Analysis Stage

The processing and data analysis stage was done by extracting and processing DEMNAS image data and Landsat 8 OLI L1 imagery to obtain lineament maps, RGB composite maps, rose diagrams, fault fracture density map, hillshade, and slope maps using software such as ArcMap, GlobalMapper, QGIS, ENVI, and Rockwork. Geological and geomorphological lineament such as hills and fault/fold aligned hills is delineated based on the lineament as seen and interpreted from hill shade map and DEMNAS image data with 45 degree of azimuth. From the results of the map, an initial interpretation and analysis process was carried out.

d. Verification Stage of Data Analysis & Interpretation

The verification stage was done by conducting field checking using primary data from direct field surveys and secondary data from previous research, such as regional geological maps and previous literature studies, which are used as references in determining the pattern of structure formation and its relation to lineament density.

4. Results and Discussions

Generated FFD map can be seen in Figure 3, which shows density values between 0 – 4.11 km/km^2. The city of Semarang could be divided into five classes: very high, high, medium, low, and very low density. Areas with high density are marked in red on the map and can be interpreted as areas with long and intense lineation lines that are interpreted as areas that have high fault or fracture intensity compared to areas with low density with green color on the map.

Based on the results of the FFD map distribution, it is known that Semarang City is dominated by areas with very low fault fracture density (0 – 0.37 km/km^2) which are spread in the northern part of Semarang city, which includes several districts such as North Semarang, Pedurungan, Central Semarang, Genuk, etc. While the central–southern part of Semarang city has a medium–very high density values (1.03 – 4.11 km/km^2), including Gunungpati, Banyumanik, Tembalang, Mijen, and Gajahmungkur districts.

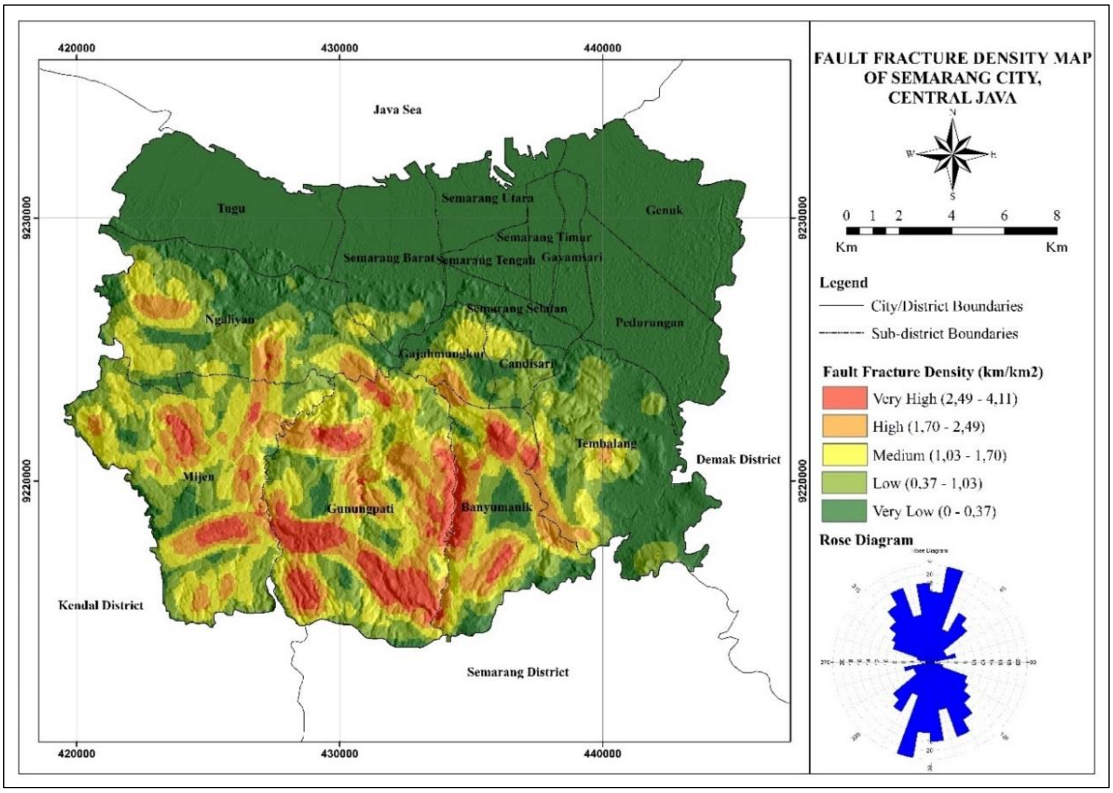

Fig 3. Fault Fracture Density (FFD) map and rose diagram of Semarang City.

4.1. Analysis of Structural Patterns in Semarang City

Based on rose diagram analysis as shown in Figure 3, the city of Semarang is dominated by lineaments trending North–South (N-S). In addition, there are also lineaments trending West-East (W-E), Northwest-Southeast (NW-SE), and Northeast-Southwest (NE-SW). The dominance of the N-S lineaments in Semarang City is interpreted as a result of structural patterns and faults in Semarang City, which are formed due to the influence of main stress in the N-S direction, as revealed by (Pramumijoyo, 2000). The existence of N-S trending lineament is interpreted to have begun to develop in the Tertiary-Quaternary period, which is marked by the existence of lineaments in several rock formations in the city of Semarang, such as the Kerek Formation, Damar Formation, and the Kaligetas Formation as presented by (Hidayat, 2013). One of the active faults in the city of Semarang is the Kaligarang fault which has been active since the Tertiary to Quaternary period as a sinistral strike-slip fault with a relatively N-S direction (Helmy, 2008; Poedjoprajitno et al., 2008). This Kaligarang Fault crosses along the Garang River from the Gajahmungkur area in the North to Mount Swakul in the south (Helmy., 2008). Among N-S lineament pattern (Figure 4) are interpreted to be formed at the same time as the emergence of the Ungaran volcano.

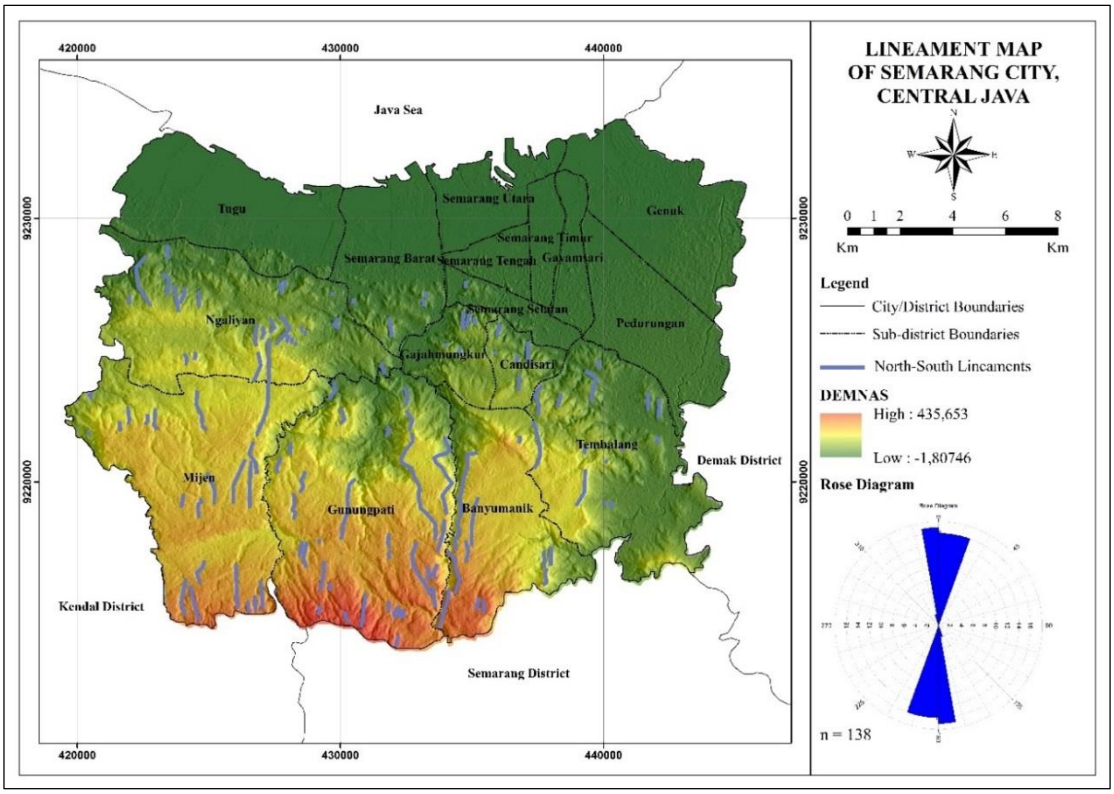

Fig 4. N-S trending Lineament map of Semarang City

This interpretation is evidenced by the distribution of the N-S pattern, which is spread mainly in the southern part of Semarang, namely Banyumanik and Gunungpati districts, and is close to the Ungaran volcano. The lithology in this area is also dominated by volcanic products such as volcanic breccias and lava deposits.

So it is interpreted that when the Ungaran volcano formed, a radial structure was formed, spreading around the Ungaran volcano, including the southern part of Semarang. In addition, the existence of a radial river pattern around the Ungaran volcano also causes erosion processes around it and formed steep hills.

The NE-SW lineament pattern shown in Figure 5 is spread dominantly in the central to southern parts of Semarang City, including the Gunungpati, Mijen, Banyumanik, and surrounding areas. The formation of the NE-SW lineament in the southern part of Semarang city is interpreted as a result of tectonic influences, namely the existence of regional faults in the form of normal faults that extend from Boja Kendal - Mijen District and strike-slip faults that extend from Ungaran volcano - Gunungpati and Banyumanik. In addition to endogenous factors, it is interpreted that the exogenous factor also exists in forming lineaments. This factor showed in the form of erosion from the radial drainage pattern of the Ungaran volcano and the dendritic pattern in the northern part of Semarang City. These drainage patterns cause the formation of river lineaments that form the NE-SW pattern. A relatively long lineament characterizes the lineament affected by the reactivation of the structure, while the lineament due to river erosion is relatively short The formation of the W-E lineament pattern, as shown in Figure 6, is interpreted to occur due to the compression stress trending N-S originating from the subduction activity of the Indo-Australian plate. This compression stress also causes the formation of the Kuto Fault in the form of a thrust Fault in the western part of Semarang City, which continues to Kendal (Lumbanbatu, 2009). In addition, there is also a volcanism factor from Ungaran Volcano, which causes the formation of a circular normal fault located in the southern part of Semarang City.

The formation of the NW-SE lineament pattern, as shown in Figure 7 in the southern part of the city of Semarang based on the regional geological map of Semarang and its surroundings (Thanden et al., 1996) is interpreted to occur in connection with the formation of the Kendeng fold and fault zones. During the Late Miocene to Early Pliocene Kendeng Zone, there was a compressional phase trending N-S resulting from the subduction of the Indian Ocean plate beneath the Eurasian plate producing imbricated faults associated with folds (fault propagation folds). Then, during the Late Pliocene to Early Pleistocene, compressional tectonics from the Java subduction produced folds and faults that trended in a NW-SE direction (Putro, 2013).

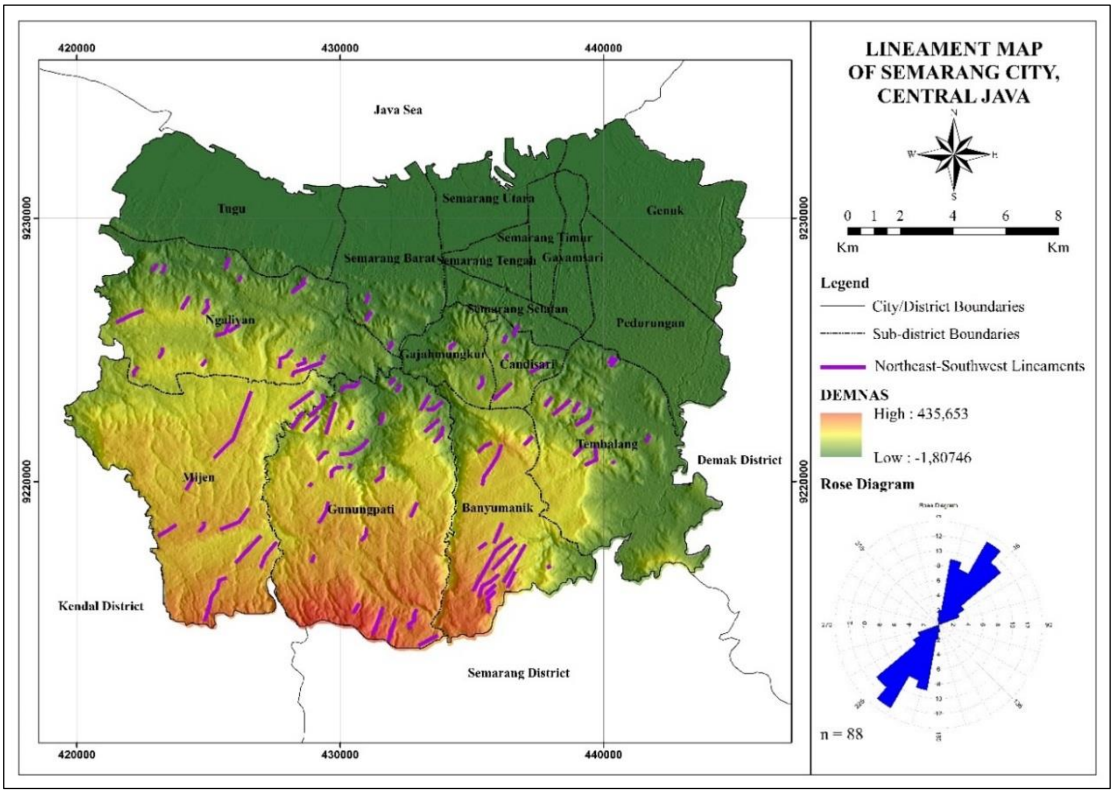

Fig 5. NE-SW trending Lineament map of Semarang City

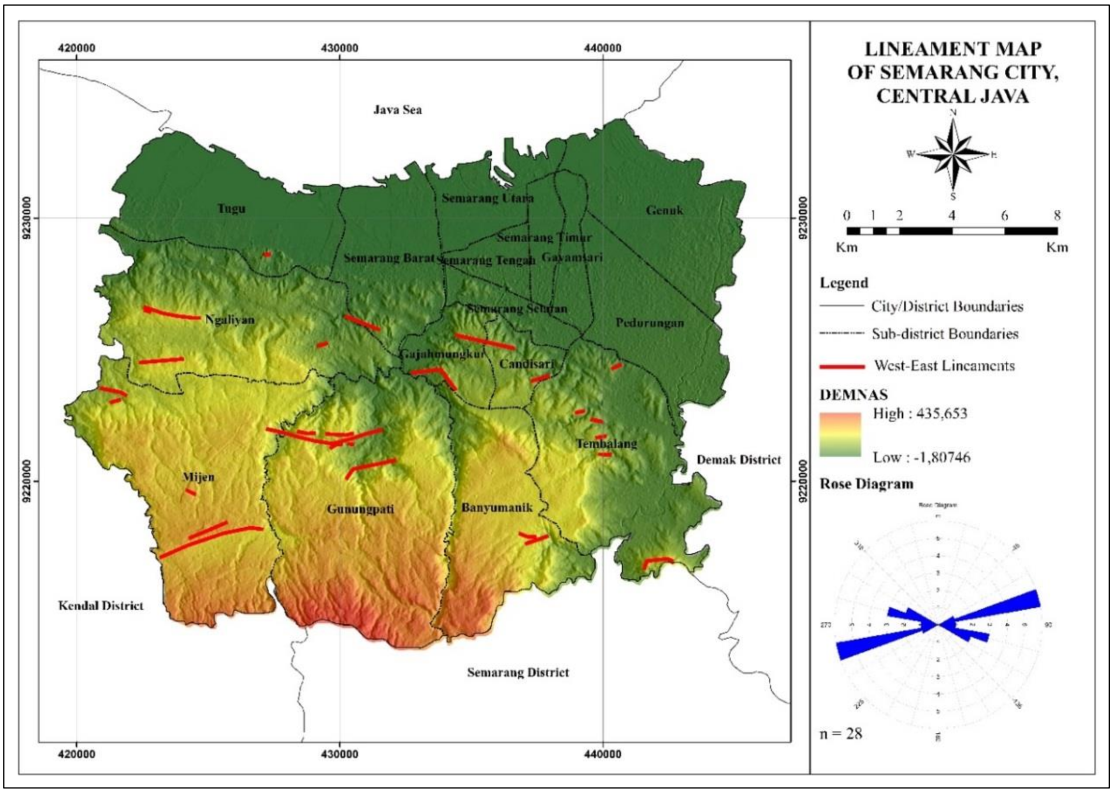

Fig 6. W-E trending Lineament map of Semarang City

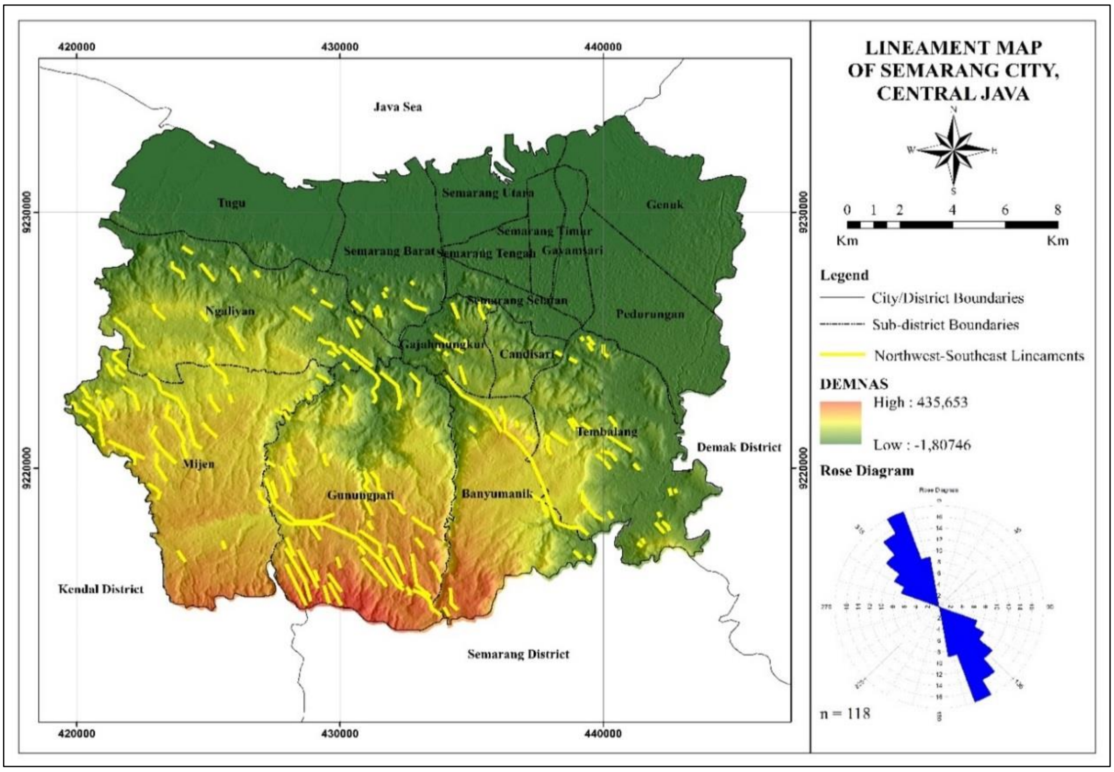

Fig 7. NW-SE trending Lineament map of Semarang City

4.2. Relationship between Fault Fracture Density and Geological Structure

Based on the map in Figure 8, it can be seen that fault fracture density moderately correlates with geological structure. This is shown by the fact that regional geological structures from (Thanden et al., 1996) coincide with higher density values of Fault Fracture Density (shown in red). The geological structures consist of normal, strike-slip, and thrust faults. Normal faults have relatively W-E trending, part of them slightly convex towards the North. Strike-slip faults have N-S to NW-SE trending. Based on the field checking for verification results at several observation points as shown in Figure 9, the lineament density in Semarang City could be divided into four classifications with different characteristics or structural features:

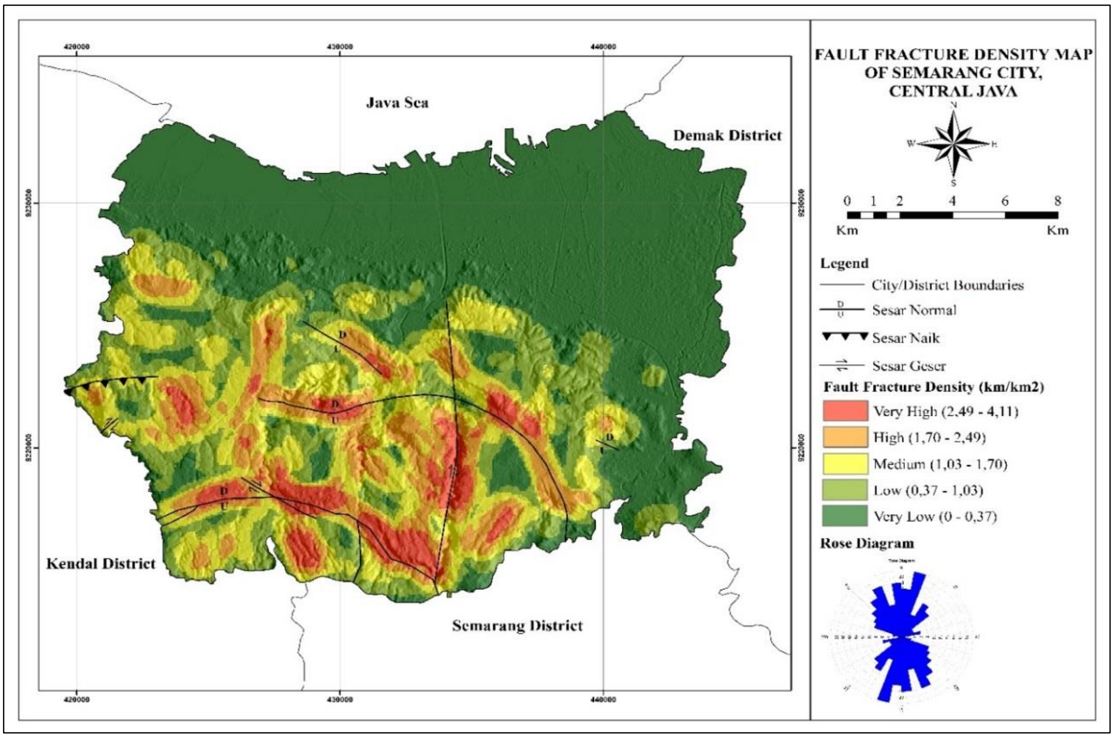

Figure 8. Overlay between FFD map with regional geological structure of Semarang City

a. Very High Density Area

Based on the results of field checking at one of the observation sites in a very high density area located in the Gunungpati area, there is an outcrop of sandstone and breccia part of the damar formation with high intensity of fractures. According to (Thanden et al., 1996), this area is a regional fault in the city of Semarang with undulating – steep hilly morphology so that it has a long straight line with high intensity of fractures that indicates the presence of endogenous force acting dominantly in this area. This is added by the existence of varied resistance lithology that might causes the fracture density in this area to become high.

b. Medium – High Density Area

Based on the results of field checking at one of the outcrops in a medium-high density area located in the Kencana Jaya Hill area, there is a lithology in the form of breccias and sandstones originating from the Damar formation with quite intense structure in the form of gash fracture and shear fractures. Areas with medium to high density are scattered in the central part of Semarang city and crossed by regional faults with hilly relief conditions and are composed of lithology with varied resistances, indicating that there is an endogenous force acting dominantly in the area that causes fracture density tend to be moderate–high.

c. Low – Medium Density Area

Based on the results of field checking at one of the outcrops in the low – medium density area located on a cliff at the side of the road in the Ngemplak area, Simongan, there is a geological structure in the form of a fault with strike direction of N 160° E and quite intense shear fractures in volcanic breccia and tuffaceous sandstone lithology from Damar formation. Areas with low – medium density are scattered in the central part of Semarang city, which is dominated by areas with relatively undulating conditions and varied lithology.

d. Very Low Density Area

Based on the results of field checking in one of the outcrops in a very low density area is located in Jabungan area, it is known that this area has very low structural intensity, as evidenced by the outcrops of sandstones with clay intercalation of Kerek formation.

This outcrop lacks any geological structures, either in the form of faults or fractures. This is also supported by the morphology of the location that located in the river area of the Jabungan area. The morphology has a relatively low elevation and lack of lithological variation, so it is might be interpreted because that the dominant force acting in that area is exogenous force in the form of erosion, which makes the fracture density in the area tend to be very low.

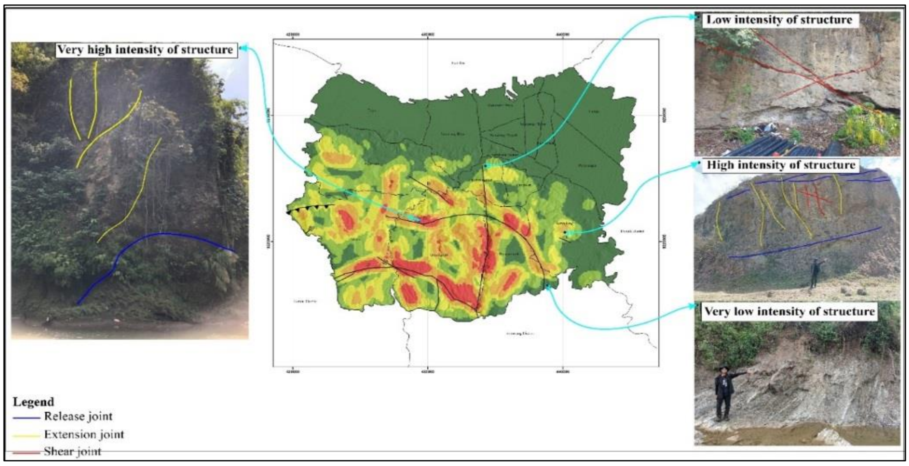

Fig 9. Locations of field checking for verification results of relationship between fault fracture density and geological structure

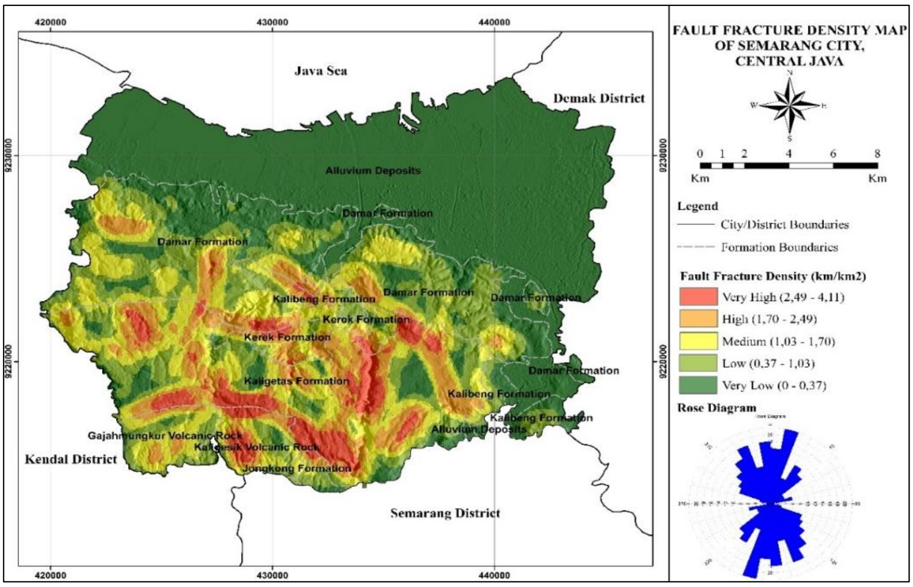

Figure 10. Relationship between Fault Fracture Density and Geological Formation

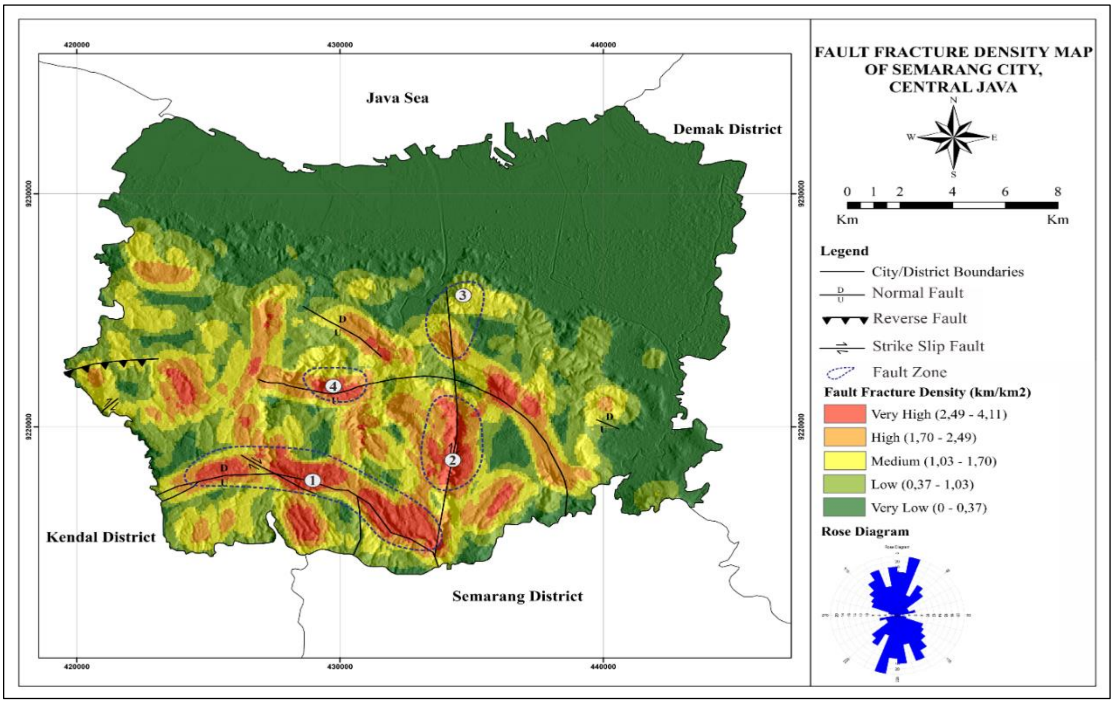

Fig 11. Fault Zones

4.3. Correlation between Fault Fracture Density and Lithology of Study Area

Based on the overlay between the FFD and lithology maps represented by the distribution of geological formations in the Semarang area (Figure 10), it can be seen that the distribution of fractures/lineaments density is not significantly affected by the type of lithology, except in the northern and northeastern parts of Semarang city which consist of alluvium.

In the central to the western and southern parts, the distribution of fractures/lineaments does not appear to be restricted by the type of lithology (represented by the distribution of lithologic formations on the map). In the part that has lithology in the form of alluvium, it can be seen that there is no significant amount of fractures/ geological lineaments. This is interpreted to occur because the distribution of fractures/geological lineaments in this research is interpreted based on lineaments in DEMNAS image data and hillshade map, while alluvium is deposited on denudational landform that have high erosion rates so that it is difficult to find the presence of geological lineaments in alluvium. In addition, alluvium is the youngest lithological unit in Semarang city, meanwhile the deformation period in Semarang city mostly occurred in the tertiary period (Poedjoprajitno et al., 2008) as evidenced by existence of regional faults on Kerek Formation, Kalibeng Formation, and Kaligetas Formation (Thanden et al., 1996). Based on ground checking (Figure 9), it is also shown that there is no geological structures found in the alluvium deposits so it is interpreted that alluvium might not experience any formation of geological structures by tectonics that occur as in older lithology in other formations.

Indeed, high FFD values may indicate the presence of fault zones or the contrast of hard and soft rock materials (Wibowo, 2010). However, the contrast of rock materials in the city of Semarang is not very visible in the existing formations, and is only visible between alluvium and non-alluvium material (other formations in Semarang City).

4.4. Fault Zone interpretation based on FFD map in Semarang City

Fault zones are weak zones that result in reduced rock strength, causing many fractures/joints around them, which causes water to seep easily (Sunan et al., 2021). In field conditions, fault zones are usually marked by manifestations of springs, including geothermal springs (Tutu et al.., 2015). In this case, mapping Fault zones are essential for assessing seismic risk (Caine et al., 1996). One method that can be used to determine fault zones is to use FFD (Fault Fracture Density) maps, where these maps can be used to assess the intensity of geological structures present at a location. This Fault Zone area is usually also associated with areas that have high-density values on the Fault Fracture Density map. Based on the interpretation of the Fault Fracture Density map, areas suspected to be fault zones are obtained.

The fault zone is marked by a dotted line on the map, which is an area with high density and is traversed by regional structures, and there are several manifestations of springs. Figure 11 shows that the areas indicated as fault zones are spread over several areas, namely Gunungpati and Candisari (southwestern and central parts of Semarang City). From Figure 11, 4 fault zones are identified. The fault zone 1 is in the Gunungpati area with very high density (2.49-4.11 km/km^2), traversed by regional faults, and has manifestation of a water spring, namely Sendang Morocono. Fault zone 2 is in the Gunungpati area. This zone also has high density, and there are manifestations of springs in the form of springs, namely Sendang Lanang and Sendang Gede Pucung. Fault zone 3 is located at Garang river. There are also springs interpreted as a result of the continuity of the Kaligarang regional fault. Meanwhile, fault zone 4 is also located in the Gunungpati with high density and based on field checking, this area has high structural intensity and high deformation.

5. 5. Conclusion

The conclusion from this paper are (1) Semarang city has various structural patterns such as N-S pattern, W-E pattern, NE-SW pattern, and NW-SE pattern which is caused by volcanic activity, regional fault activity, and exogenous force. (2) Based on the density of lineaments, it is shown that regional geological structures coincide with higher density values of Fault Fracture Density, meanwhile the relationship between lithology types and density values on the FFD map is unclear among the study area's lithology formations. (3) Fault zones in Semarang are scattered in some areas that traversed by regional structures and have the highest lineament density. The existence of this fault zone shown that Semarang city has many weak zones, so that the area is easily eroded and triggers the occurrence of natural disaster such as ground movement and landslide.

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