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Tectonic Control of the Nanggulan Formation Based on Morphometric Analysis in Kulon Progo, Indonesia

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Abstract - Outcrop of Nanggulan Formation, surrounded by Old Andesite Formation (OAF) in the eastern part of Kulon Progo Dome, is very limited. Tectonic control is interpreted as a contributing factor. Tectonic activity can be shown by a morphometric aspect. The research purpose was to calculate the valley floor - valley height ratio, stream gradient index, and drainage density of Nanggulan and Old Andesite Formations. The method used is field survey and Shuttle Radar Topography Mission analysis. The field survey focused on Clumprit, Klepu, and Kalisonggo Rivers. The total number of valley segments for the Nanggulan Formation is 223 with the valley length of 4.62 km, while OAF is 101 with a valley length of 3.55 km. SRTM analysis showed that the valley segment in OAF was 55, and valley length was 1.48 km. The valley floor - valley height ratio measured in the Nanggulan Formation is ten valleys and OAF is eight valleys. In Nanggulan Formation, the valley floor - valley height ratio value is from 1.00 to 5.46 (low uplift), whilst in OAF, the results vary: as 1.35 to 4.58 (low uplift), 0.59 (medium uplift), and 0.43 (high uplift). The stream gradient index value of the Nanggulan Formation is 460.47 (medium tectonic), while OAF is 723.84 (high tectonic). The drainage density value of the Nanggulan Formation is 10.35 km/km^2 (very smooth landscape texture) and OAF is 10.35 km/km^2 (somewhat smooth landscape texture). Morphometry proves that Nanggulan Formation tectonic activity is more active, causing the Nanggulan Formation to be exposed to the surface.

Keywords: valley, segment, uplift, landscape, expose, Nanggulan

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Introduction

Background

The Kulon Progo Mountains is unique and interested in earth science due to its morphology showing dome-like. Regionally, three tectonic trends in Kulon Progo contributed to the genetic of high such as Sunda trend (northwest - southwest), Meratus trend (northeast - southwest), and Java trend (east - west) (Syafri *et al.*, 2013). Meratus trend tectonics occurred at Eocene, Sumatra trend tectonics at Upper Miocene, and Java trend tectonics at Pliocene (Widagdo *et al.*, 2016).

On the east side of Kulon Progo Dome, the Nanggulan Formation which is of Middle Eocene - Oligocene (Widagdo *et al.*, 2018), Middle Eocene - Early Upper Eocene (Saputra and Akmaluddin, 2015) outcrops. However, the spread of these formations is very limited. The distribution of Nanggulan Formation is surrounded by volcanic products known as Old Andesite Formation with the age of Late Oligocene - Middle Miocene (Soeria-Atmadja *et al.*, 1994) or Upper Miocene (Akmaluddin *et al.*, 2005).

As a result of Meratus tectonics, Nanggulan Formation is thrusted. The thrust fault triggers the surface exposure of Nanggulan Formation, while the tectonics affecting Old Andesite Formation led to the distribution of volcanic rocks (Widagdo *et al.*, 2018). In more detail, the geological structure causing Nanggulan Formation exposed to the surface is Kalibawang dextral fault in the north, Giripurwo sinistral fault in the south, Nanggulan thrust fault in the northwest, and folds in the centre (Widagdo *et al.,* 2020). These faults and folds occurred in the Late Miocene. The thrust fault is identified by gravity between Nanggulan Formation and Old Andesite Formation (Winarti *et al.*, 2020a).

The focus of this study is on tectonic activity took place in the Nanggulan and Old Andesite Formations, as well as the influence of tectonics on the Nanggulan Formation. The objective of the study is to calculate the morphometry that includes the value of valley floor - valley height ratio (Vf), stream gradient index (Sl), and drainage density (Dd) of Nanggulan Formation and Old Andesite Formation. Kulon Progo Dome, Yogyakarta, Indonesia, is the studied area (Figure 1).

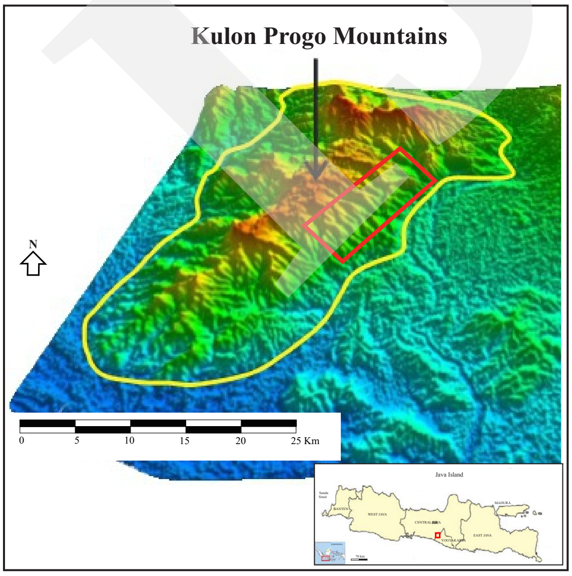

Figure 1. Location of the studied area.

Gentana *et al.* (2018) investigated whether tectonic activity influenced drainage density (Dd) and bifurcation ratio values (Rb). They concluded that the level of tectonic activity in Way Belu Drainage Basin was medium to high. As a reference, the rate of tectonic activity in Cimanuk Watershed based on the topography and geological map, field observation, bifurcation ratio (Rb), drainage density (Dd), and index of mountain front sinuosity (Smf), Sukiyah *et al.* (2018) stated that the Cimanuk Watershed has active tectonics.

Geological Settings

The Nanggulan Formation and Old Andesite Formation make up the Kulon Progo Mountains at the bottom. They both have various rock characters, forming different morphologies. The Nanggulan Formation is usually found on weakly undulated hills, while Old Andesite Formation occupies steep hills (Winarti *et al.*, 2020a). The Nanggulan Formation consists of terrestrial deposits at the bottom, and gradually changes upward into shallow marine sediments. Sandstone is shown at the bottom of this formation, gradually upward there is claystone with fine- to coarse- grained sandstone insertions. Much of Nanggulan Formation lithology contains tuff and a thin coal layer (Harjanto, 2011). The Nanggulan Formation dominantly comprises sandstone and claystone, with quartz sandstone, lignite intercalation, and calcareous claystone in some places (Winarti *et al.*, 2020a).

According to gravity data collected along the Klepu and Kalisonggo Rivers, the thickness of the Nanggulan Formation in the northwest is between 240 m to 360 m, while it is 600 m to 960 m in the southeast indicating that the formation has become thinner towards the northwest (Winarti *et al.*, 2020b). This formation contains Total Organic Carbon (TOC) between 0.36% to 1.00% (shale) and 12.80% (coal shale) formed in shallow marine environments (Late Eocene) and in salty swamp environments (Early Eocene) (Amijaya *et al.,* 2016).

The Old Andesite Formation rides on top of a Nanggulan Formation unconformity. This formation is composed of breccias with andesite fragments, andesite intrusions, dacite intrusions, basalt intrusions, lapilli tuff, tuff, lapilli breccias, andesitic lava, agglomerates, and volcanic sandstones (Widagdo *et al.,* 2018). The thickness of the Old Andesite Formation calculated from gravity data along the Klepu and Kalisonggo Rivers is 600 - 720 m in the northwest and 120 - 480 m in the southeast, indicating that the thickness tends to increase in the northwest (Winarti *et al.,* 2020b).

The Jonggrangan Formation is composed of conglomerates, carbonate tuffs, Mollusk-contained sandstone, claystone with lignite inserts above Old Andesite Formation. While the upper part consists of layered limestone and coral limestone. Sentolo Formation comprises limestone and calcareous claystone. Both have an interfingering relationship (Widagdo *et al.,* 2018).

The Kulon Progo Mountains is part of the East Java Basin fragment of the Gondwana Microcontinent, and have a boundary structure extending northeast – southwest from the Kulon Progo, Mount Merapi, and Muria (Smyth *et al*., 2007). These boundaries have an irregular shape and are related to complex tectonics.

Tectonics occurring in Kulon Progo have a different effect on Nanggulan Formation and Old Andesite Formation. Lineaments of the Southern Mountains and Kulon Progo Mountains were formed due to the compression during the Tertiary. North - south and northeast - southwest lineaments are associated with synistral faults taking place in the Late Eocene - Middle Miocene, southeast - northwest lineaments are associated with dextral faults formed in the Pliocene, while west - east lineament is related to normal faults (Barianto *et al.,* 2009).

The trend of regional structures based on the result of gravity measurement on the eastern part of Kulon Progo Mountains shows the presence of thrust and normal faults. These faults caused the uplift and subsidence in some layers, leading to Nanggulan Formation to emerge around the Progo River (Winardi *et al*., 2013).

Methods And Materials

Methods

The research approach used two methods, field survey and laboratory analysis. The field survey was performed in three rivers, namely Clumprit, Klepu, and Kalisonggo. The laboratory work involves analyzing Shuttle Radar Topography Mission images with a focus on steep topography and steep valleys.

Data obtained from both methods include direction of valley segment, length of valley segment, elevation of valley floor, difference in elevation of valley, width of valley, and elevation of cliff. These data are used to calculate the valley floor − valley height ratio (Vf), stream gradient index (SL), and drainage density (Dd). To identify the tectonic activity in a region, these three parameters were used.

The value of valley floor - valley height ratio (*Vf*) was used in determining the rate of uplift in area with the formula as follows (Bull, 2007):

$$Vf = \frac{2Vfw}{[(Eld-Esc)+(Erd-Esc)]} \quad \text{..................(1)}$$

Where:

Vfw: width of valley floor,

Eld: value of left height,

Erd: value of right height, and

Esc: value of height from the valley floor.

Illustration of measuring the width of valley floor, height of cliffs, and height of valley floor is shown in Figure 2.

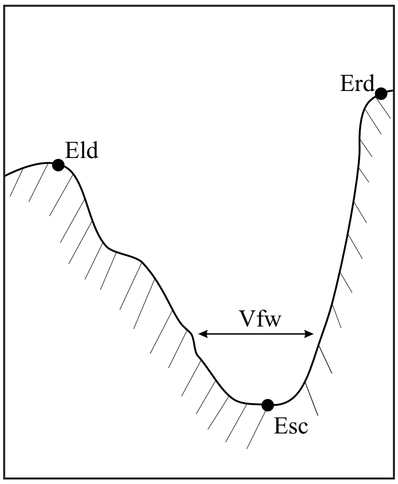

Figure 2. Illustration of measuring valley floor - valley height ratio (Source: Bull, 2007 modified).

The classification of tectonic activity is based on the value of valley floor − valley height ratio which could be divided into some classes (Table 1).

Table 1. Classification of Tectonic Activity Based on Valley Floor − Valley Height Ratio Value (Source: Keller and Pinter, 1996, modified by Sukiyah, 2017)

Valley floor − Valley height ratio (Vf)	Class	Tectonic Activity	Description
< 0.50	I	High level of uplift	V shape of valley
0.50 – 1.00	II	Medium level of uplift	V shape of valley
1.00 – 10.00	III	Low level of uplift	U shape of valley
>10.00	IV	Very low of uplift	U shape of valley

Tectonic activity is also determined by calculating the value of stream gradient index (*SL*), with the formula as follows (Keller and Pinter, 2002):

$$SL = \frac{\Delta H}{\Delta L} \; x \; L \quad \text{.......................................(2)}$$

Where:

ΔH: difference of elevation from measurement point,

ΔL: length or horizontal distance of river from measurement point,

L: total of river length from measurement point to downstream.

Stream gradient index values are grouped into three classes as indicators for the determination of tectonic activity (Table 2).

Table 2. Classification of Tectonic Activity Based on Stream Gradient Index Value (Source: Tawil, 2019)

Stream Gradient Index (SL)	Class	Relative Tectonic Aktivity
≥ 500	1	High tectonic level
300 ≤ Sl < 500	2	Medium tectonic level
< 300	3	Low tectonic level

The high stream gradient index value in areas is composed of soft rock reflecting the tectonic activity that has occurred recently (Tawil, 2019). The illustration to get stream gradient index value is in Figure 3.

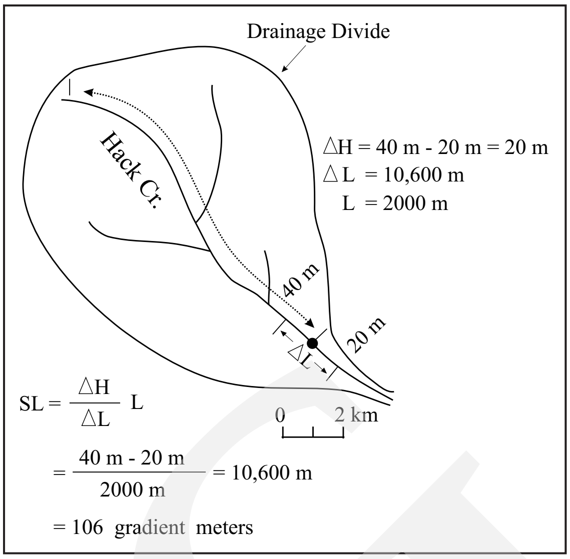

Figure 3. Illustration of measuring valley floor − valley height ratio (Source: Keller and Pinter, 2002).

Tectonic control in the area can be determined by calculating the drainage density (*Dd*), a value that shows the ratio of the total length of river segments (*ΣLs*/km) to the total watershed (*A*/km^2), with the formula as follows (Verstappen, 1983):

$$Dd = \frac{\Sigma Ls}{A} \quad \text{...(3)}$$

The drainage density values are divided into six landscape texture, from very coarse to very fine (Table 3). The higher drainage density value means that there is a lot of runoff in the basin that is formed due to tectonic factors.

Table 3. Classification of Landscape Texture in Quarterly Volcanic Areas Based on of Drainage Density (Source: Sukiyah, 2017)

Texture	Dd (km/sq.km)
Very coarse	0.00 – 1.37
Coarse	1.38 – 2.75
Medium	2.76 – 4.13
Somewhat smooth	4.14 – 5.51
Smooth	5.52 – 6.89
Very smooth	6.90 – 8.27

Materials

The field tools used comprise a geological compass, a GPS, and a measuring instrument with positions on the Clumprit, Klepu, and Kalisonggo

Rivers. Data collected include the amount of valley segments in Nanggulan Formation as many as 223 with a total valley length of 4.62 km, while the amount of valley segments in Old Andesite Formation is 101 with a total valley length of 3.55 km.

The results of SRTM image analysis resulted in as many as fifty-five valley segments of Old Andesite Formation, with a total valley length of 1.48 km. The value of valley floor – valley height ratio is measured in eighteen valleys representing ten valley in Nanggulan Formation, and eight valley in Old Andesite Formation (Figure 4). The past tectonic activity is verified with seismic data that still occurs recently.

Result

Value of Valley Floor – Valley Height Ratio (Vf)

The Clumprit, Klepu, and Kalisonggo Rivers flow over the Nanggulan and Old Andesite Formations, making them ideal for representing the measurement of Vf values. The distribution of Vf measurements in the Nanggulan Formation is in the Clumprit River (three segments), Klepu River (four segments), and Kalisonggo River (three segments), with values ranging from 1.004673 to 5.459318.

The Vf value of 1.004673 was read in segment No. 7 (Klepu River), while the Vf value of 5.459318 was read in segment No. 13. (Ka-

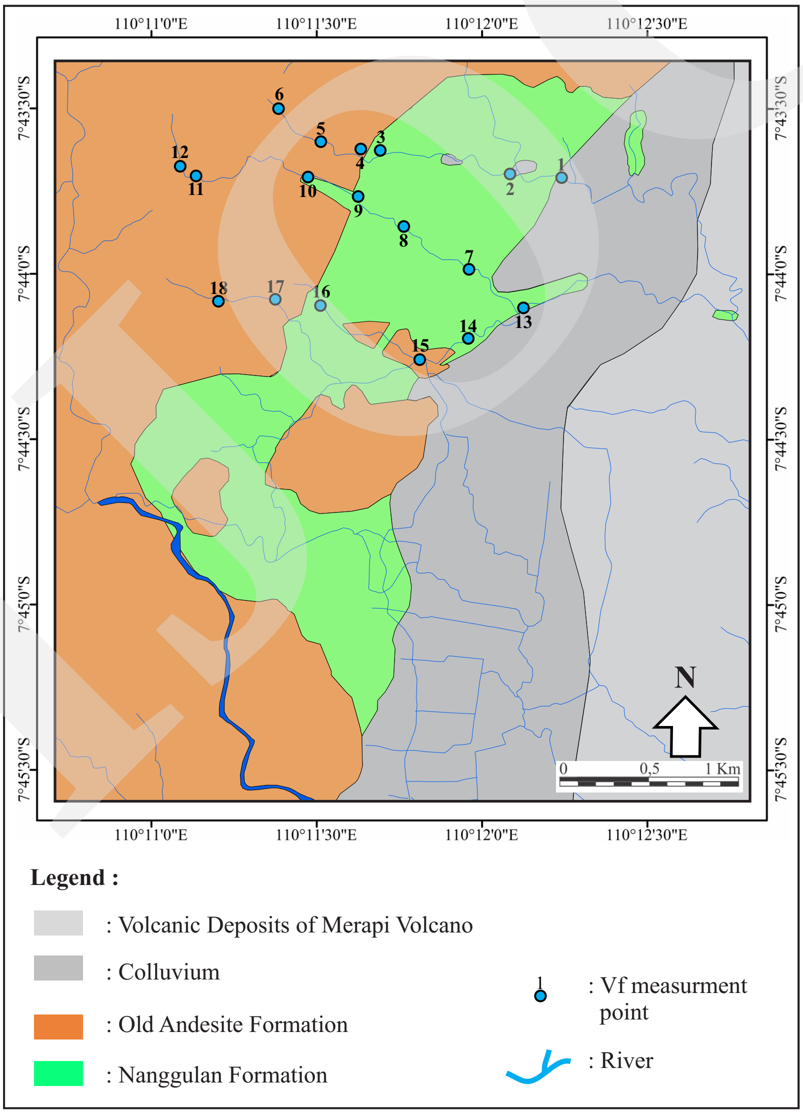

Figure 4. Locality map of valley floor - valley height ratio measurement.

lisonggo River). Based on the tectonic activity classification (Table 1), the results of the Vf calculation in the Nanggulan Formation are classified as class III.

Based on the results of the valley floor − valley height ratio (Vf), it is concluded that the Nanggulan Formation has a low level of uplift. The results of the Vf calculation for the Nanggulan Formation are presented in Table 4.

The distribution of Vf measurements in the Old Andesite Formation is in the Clumprit River (three segments), Klepu River (two segments), and Kalisonggo River (three segments). The Vf value of the Old Andesite Formation varies from 0.428346 in segment No. 12 (Klepu River) to 4.582278 in segment No. 17 (Kalisonggo River).

The Vf value range is divided into three groups: low (Vf = 0.428346), medium (Vf = 0.598131), and high (Vf = 1.354086 − 4.582278). According to the tectonic activity classification (Table 5), then the low Vf is classified as class I, which indicates a high level of uplift. The medium Vf value is classified as class II, indicating a medium level of uplift. A high Vf value is classified as class III, indicating a low level of uplift.

Stream Gradient Index (SL)

To get the value of stream gradient index, the river segments along Clumprit, Klepu, and Kalisonggo Rivers were measured. Those rivers flow on Nanggulan and Old Andesite Formation, and therefore the value of stream gradient index could represent both formations. The stream gradient index of the Nanggulan Formation is 460.47 which includes to class II (medium tectonic level), while the stream gradient index of the Old Andesite Formation is 723.84 including to class I (low tectonic level) (high tectonic level).

The result of stream gradient index value calculation shows that the tectonic activity of Old

Table 4. Calculation of Valley Floor - Valley Height Ratio and Tectonic Activity Level on Nanggulan Formation

Segment	River	Esc (m)	Vfw (m)	2 x Vfw (m)	Eld-Esc (m)	Erd-Esc (m)	Eld (m)	Erd (m)	Vf	(*)Class	(*)Tectonic Activity
1	Clumprit	106	6.98	13.96	0.35	3.30	106.35	109.30	3.824658	III	Low level of uplift
2	Clumprit	117	4.15	8.30	3.10	1.14	120.10	118.14	1.957547	III	Low level of uplift
3	Clumprit	169	3.83	7.66	0.85	0.88	169.85	169.88	4.427746	III	Low level of uplift
7	Klepu	117	4.30	8.60	3.66	4.90	120.66	121.90	1.004673	III	Low level of uplift
8	Klepu	143	4.66	9.32	1.77	3.15	144.77	146.15	1.894309	III	Low level of uplift
9	Klepu	170	4.95	9.90	2.31	5.34	172.31	175.34	1.294118	III	Low level of uplift
10	Klepu	194	7.70	15.4	2.44	2.40	196.44	196.40	3.181818	III	Low level of uplift
13	Kalisonggo	102	10.40	20.8	1.86	1.95	103.86	103.95	5.459318	III	Low level of uplift
14	Kalisonggo	108	6.50	130	1.76	2.10	109.76	110.10	3.367876	III	Low level of uplift
16	Kalisonggo	174	4.80	9.60	2.00	3.70	176.00	177.70	1.684211	III	Low level of uplift

(*) Classification of tectonic activity by Keller and Pinter (1996), modified Sukiyah (2017).

Table 5. Calculation of Valley Floor - Valley Height Ratio and Tectonic Activity Level on Old Andesite Formation

Segment	River	Esc (m)	Vfw (m)	2 x Vfw (m)	Eld-Esc (m)	Erd-Esc (m)	Eld (m)	Erd (m)	Vf	(*)Class	(*)Tectonic Activity
4	Clumprit	173	4.79	9.58	1.90	3.52	174.90	176.52	1.767528	III	Low level of uplift
5	Clumprit	200	3.68	7.36	3.40	1.43	203.40	201.43	1.523810	III	Low level of uplift
6	Clumprit	266	3.20	6.40	6.30	4.40	272.30	270.40	0.598131	II	Medium level of uplift
11	Klepu	310	3.10	6.20	2.10	1.87	312.10	311.87	1.561713	III	Low level of uplift
12	Klepu	338	2.72	5.44	5.00	7.70	343.00	345.70	0.428346	I	High level of uplift
15	Kalisonggo	124	7.30	14.60	1.90	2.50	125.90	126.50	3.318182	III	Low level of
17	Kalisonggo	198	5.43	10.86	1.13	1.24	199.13	199.24	4.582278	III	Low level of uplift
18	Kalisonggo	246	1.74	3.48	1.80	0.77	247.80	246.77	1.354086	III	Low level of uplift

(*) Classification of tectonic activity by Keller and Pinter (1996), modified Sukiyah (2017).

Andesite Formation is higher than that of Nanggulan Formation. The result of stream gradient index value is in Table 6.

Table 6. Calculation of Stream Gradient Index Value and Relative Tectonic Activity Level in Nanggulan and Old Andesite Formation

Formation	River	Stream Gradient Index (SL)	Average Stream Gradient Index	Class	(*)Relative Tectonic Aktivity
Nanggulan	Clumprit	80.45–2292.21	460.47	2	Medium tectonic level
	Klepu	97.29–1604.99			
	Kalisonggo	48.06–1293.48			
Old Andesite	Clumprit	422.44–2251.71	723.84	1	High tectonic level
	Klepu	490.07–1066.99			
	Kalisonggo	48.17–1123.51			

(*) Classification of relative tectonic activity by Tawil (2019)

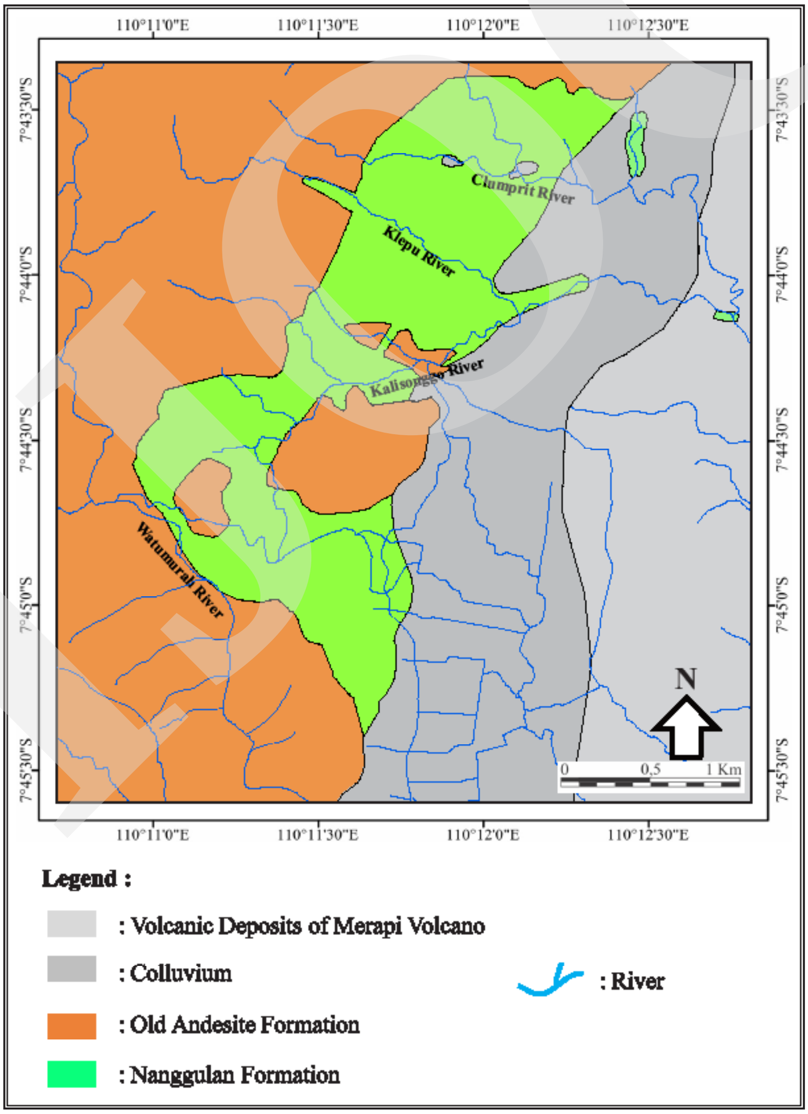

Figure 5. Rivers which flow in the studied area.

Drainage Density (Dd)

The value of drainage density of the river in the studied area (Figure 5) can be calculated to determine the landscape texture. The result of measurement of drainage density from Nanggulan (10.35 km/km^2) and Old Andesite Formation (5.44 km/km^2) (Table 7) indicates that landscape texture of Nanggulan Formation is very smooth, while Old Andesite Formation is somewhat smooth.

Earthquake

Department of Meteorology Climate and Geophysics (2019, vide Winarti, 2021) recorded the earthquake in Kulon Progo area is quite active. Recently from January 2015 to May 2019, the earthquake occurred forty-six times with the magnitude of <6. The earthquake might occur under the sea with the depth of 5 − 126 km. Based on data recorded by USGS (2019) in Kulon Progo area the earthquake occurs with the magnitude of 4.10 - 6.30 RS (Table 8).

Discussion

The older Nanggulan Formation has a low level of uplift, while in Old Andesite Formation, the uplift level is medium to high in some segments of valley. In general, this is due to the Nanggulan Formation comprises sedimentary rocks that are more elastic, so that they do not crack or break easily under pressure.

The Old Andesite Formation is mainly composed of volcanic rocks that are more brittle and more resistant. In this formation, the process of erosion is only intensive along the weak zone, so that the formed valley is steeper, while Nanggulan Formation is easy to erode, and as a result a gentle valley is formed.

The texture of landscape in Nanggulan Formation is very smooth, indicating that there is a lot of runoff in this formation. Cracks in the lithology due to deformation can form runoff. These cracks are easily eroded, forming river valleys. On sandstone deposited upstream, a drag fault is identified (Figure 6). It is evidenced that those locations were affected by a reverse fault.

The sandstone outcrops in Klepu River indicates a fault plane with slickensides (Figure 7), identifying a strike- slip fault with sinistral fault movement. The data indicate that Nanggulan Formation has several faults due to tectonics. Referring to the geological map (Winarti *et al.*, 2020a), it is known that Nanggulan Formation comprises an anticline structure, strike- slip fault, and reverse fault. While in Old Andesite Formation, there is only a reverse fault, so that Nanggulan Formation is more tectonically controlled.

Drainage density and outcrop data show that the tectonic activity of Nanggulan Formation is more active than that of Old Andesite Formation,

Table 7. Value of Drainage Density and Landscape Texture Class in The Nanggulan and Old Andesite Formation

Formation	Area (km^2)	Length of Segment (km)	Amount of Segments	Drainage Density (km/sq.km)	(*)Landscape Texture
Nanggulan	3.19	33.01	20	10.35	Very smooth
Old Andesite	13.81	75.11	58	5.44	Somewhat smooth

(*) Classification of landscape texture by Sukiyah (2017)

Table 8. Earthquake in Kulon Progo Area {Source: https://earthquake.usgs.gov/earthquakes/browse> (08/02/2019)}

Original Time	Latitude (S)	Longitude (E)	Depth (km)	Magnitude (SR)	Place
2001-05-25T05:06:10.680Z	7.87	110.18	143.10	6.30	Java, Indonesia
2006-08-02T08:35:11.140Z	7.64	110.20	10.00	4.10	Java, Indonesia
2006-09-20T01:28:05.240Z	7.68	110.29	10.00	3.70	Java, Indonesia
2013-02-06T16:26:46.840Z	7.60	110.10	138.10	4.10	16 km SW of Mertoyudan, Indonesia
2016-07-17T22:59:04.050Z	7.55	110.25	12.01	4.40	4 km SE of Mertoyudan, Indonesia

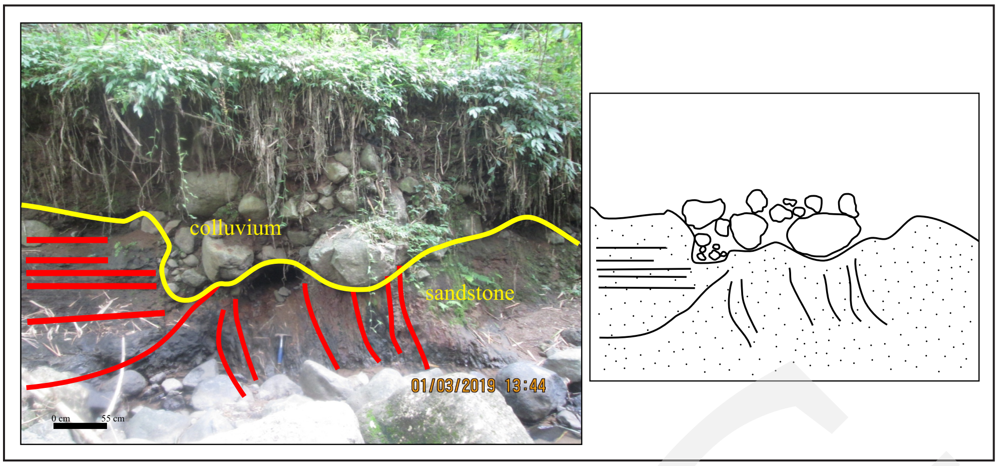

Figure 6. Drag fault in Klepu River (S: 7°43’43.64”, E: 110°11’31.70”) as an evidence of reverse fault in Nanggulan Formation.

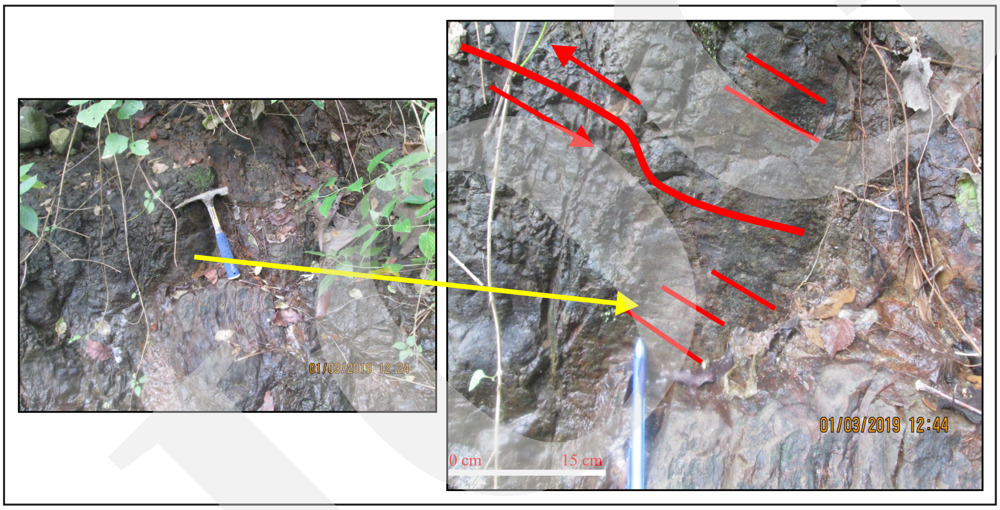

Figure 7. Fault plane and slickenside on sandstone in Klepu River (S: 7°43’49.18”, E: 110°11’40.81”) at downstream was interpreted as an evidence of strike- slip fault.

and causes Nanggulan Formation to be exposed to the surface.

Earthquake activity that has continued until recently proves that the tectonics in Kulon Progo are still active. The earthquake triggered the reactivation of faults in the Kulon Progo Mountains. Another impact of earthquakes is the hazard of landslides.

Conclusions

The tectonic activity in Kulon Progo Mountains is determined by the morphometric aspect such as the valley floor - valley height ratio, stream gradient index, and drainage density of Nanggulan and Old Andesite Formations.

Based on the valley floor − valley height ratio, the Nanggulan Formation has a low uplift level, while Old Andesite Formation has a low uplift to high uplift level. The value of stream gradient index of formation shows that the tectonics in Nanggulan Formation are of medium level, while the tectonics in Old Andesite Formation are of high level. The contrasting rock characters between Nanggulan and Old Andesite Formation get an influence on both morphometric aspects.

Nanggulan Formation has a high tectonic activity when viewed from the drainage density value, supported by outcrop data to impact the surface exposure of the formation.

The Kulon Progo Mountains, at the bottom, have geological phenomena such as active tectonic activity up until recently.

The claystone that dominates the Nanggulan Formation must be studied deeply in order to identify the effects of active tectonic activities.

Acknowledgments

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