Original Article

Morphogenetic of Rembang Anticlinorium Based on Tectonic Geomorphology Characteristics in Watuputih, Central Java, Indonesia

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Abstract

Rembang Anticlinorium is a series en-echelon folds with east – west orientation that formed from late Neogene tectonism. Folds in Watuputih is named Ngiono, Pakel, Gaplokan, Bulu and Brama are composed of Neogene sedimentary rocks. Morphogenetic of Rembang Anticlinorium can be identified by using morphometric indices such as Mountain front sinuosity (Smf), Ratio of valley height and valley width (Vf) and Drainage density (Dd) from 79 sub-basin. The values of these indices are Smf (1.03-3.48), Vf (0.62-8.0) and Dd (1.41-4.00). Relative Tectonic Activity Index (IAT) is ranging from 2 to 4 and classified into low to high tectonic activity. Neogene sedimentary rocks in this area are showing a moderate degree of weathering mainly in the limestone bearing formations. Based on the analysis of morphometric indices and field observation, tectonic and weather play major roles in shaping the landform of Rembang Anticlinorium with erosional force having a greater impact.

Keywords: Tectonic geomorphology, morphometric indices, relative tectonic activity, Rembang anticlinorium, Watuputih

1. Introduction

Watuputih hills region of Central Java is a part of Rembang Anticlinorium with east – west orientation and formed from late Neogene tectonism event (van Bemmelen, 1949). Watuputih hills have some significant importance to the surrounding area, its karst hydrogeology system has many springs with varying discharge and composed of formation with complex geological structures (Setiawan, Syah Alam, & Haryono, 2020). Paciran limestone formation which distributed in Watuputih area is known to have a higher dolomites composition and has been explored for mining needs for many years (Mulyadi, Solihin, Permana, & Yuniati, 2019).

Morphologically this area consists of low to undulating hills with elevation be in the region of 400 m and less above sea level. Topography development in tectonically active regions is due to a complex interaction of erosional processes and tectonic movements of crustal rocks (Topal & Özkul, 2018). Some parts of the Rembang Anticlinorium have an en-echelon folds orientation which suggests that the folding mechanism is passive folding and not active folding (Husein, Sakur, & Setianto, 2016). Tectonic geomorphology by using morphometric indices can be used to determine state of active tectonic of a large area (Buczek & Górnik, 2020; Hidayat, Muslim, Zakaria, Permana, & Wibowo, 2021; Keller & Pinter, 1996; Sukiyah, Sunardi, Sulaksana, & Raditya Rendra, 2018; Winarti, Sukiyah, Syafri, & Nur, 2022; Winarto, Sukiyah, Haryanto, & Haryanto, 2019). Various morphometric indices that are based on the analysis of mountain fronts and drainage basin can be combined to obtain index of relative active tectonics (IAT) which provide the summaries of tectonic activity of an area (el Hamdouni, Irigaray, Fernández, Chacón, & Keller, 2008)

Geomorphological development of folded area has been an intriguing subject for many researchers because folds on the earth surface are one of the most commonly structural features that can be observed by Earth-observing satellites (Das, Saraf, & Shujat, 2010; Delcaillau et al., 2022; Sissakian, Kadhim, & Jab'bar, 2014). This research aims to reveal the factors which contribute to the development of Rembang Anticlinorium based on tectonic geomorphology combine with field evidence.

2. Materials and Methods

2.1 Geological setting

Rembang Anticlinorium is a part of Northeast Java basin which developed at the southeast part of Sunda land (Hall, 2014). Anticline and syncline in the Rembang Anticlinorium have east – west to northwest – southeast orientation and are superimposed one another that indicate the complexity of deformation in this area (van Bemmelen, 1949). Most of the folds in Rembang Anticlinorium is classified as non-cylindrical folds with hinge line that curved and plunging at the end e.g. Ngiono anticline, Pakel anticline, Bulu syncline and Brama anticline (Husein et al., 2016).

Rembang Anticlinorium in Watuputih area composed of rock formation from early Miocene to Pleistocene epoch (Faturrakhman & Kusumah, 2017; Novita, Sanjaya, Margono, Rijani, & Mawardi, 2017) (Figure 1). The oldest formation in the research area is Tawun formation that composed of bioclastic limestone and sandy marl formed in the early Miocene. Tawun formation overlaying the Ngrayong formation and formed in the middle Miocene which composed of very fine to medium quartz sandstone with shale, claystone intercalations and dominated by foreshore to tide dominated facies (Surjono, Setyowiyoto, & Sugai, 2017). Bulu formation formed in the late middle Miocene composed of layered clastic limestone (packstone – wackestone) and shows locally jointed rocks.

Wonocolo formation formed in the late middle Miocene is composed of calcareous sandstone with sandy marl intercalations and has been known to be a potential oil reserve with unique characteristic because it has a variety of organic matter sources (Zetra, Burhan, Firdaus, Nugrahaeni, & Gunawan, 2021). Ledok formation formed in the late Miocene is composed of layered glauconitic sandstones from coarse to fine and cemented by carbonates. Mundu formation formed in Pliocene and composed of massive marl rich in planktonic foraminifera. Paciran formation formed in Pliocene – Pleistocene is composed of layered clastic limestone and distributed mainly in Watuputih hills and encircled by Bulu formation. The youngest rock formation in this research area is Gutak Volcanic Rocks that formed in Quaternary Period is composed of dacitic – andecitic lava, andecitic breccia and andesitic intrusions.

2.2 Tectonic Geomorphology

Tectonic geomorphology by using geomorphic indices can be used to studying active tectonic and relative tectonic deformation in an area (Bull, 1984; el Hamdouni et al., 2008; Hidayat et al., 2021; Keller & Pinter, 1996). This research used three geomorphic indices: 1) the ratio of valley floor width to valley height (Vf), 2) mountain front sinuosity (Smf) and 3) drainage density (Dd) (Table 1). These geomorphic indices are beneficial for understanding the tectonic geomorphology in an area because it combined morphometric properties of mountain front (Smf), valley topography (Vf) and drainage basin (Dd).

2.2.1 The ratio of the valley floor and valley height (Vf)

The ratio of the valley floor and valley height is a geomorphic index which calculated the ratio of the width of the valley floor to its average height (Bull & McFadden, 1977). High

Vf value is associated with a low uplifting rate and will have a “U” shape valley because of extensive river cut at the bottom of the valley. Low Vf value is linked with active tectonic since incision to the valley wall will result in a “V” shape valley.

2.2.2 Mountain Front Sinuosity (Smf)

Mountain front sinuosity (Smf) is a geomorphological index that reflects the balance between erosion forces that tend to cut along the ridges and tectonic forces that tend to produce a straight mountain front (Keller & Pinter, 1996). Mountain front sinuosity can also combined with other geomorphological index such as Drainage density of facets (Ddf) to get a better insight of a tectonically active area (Topal, Keller, Bufe, & Koçyiğit, 2016). High Smf value is associated with tectonic activity dominate the mountain front and linked with a straight mountain front. Low Smf value indicate that erosion activity dominated the mountain front and linked with irregular shape mountain front.

2.2.3 Drainage Density (Dd)

Drainage density is defined as the closeness in spacing of channels with low drainage density and high drainage density refer to coarse and fine texture, respectively (Strahler, 1964). This geomorphological index can be used to reflect the tectonic activity and lithological aspect in an area, an area that is deformed by tectonic activity will have a higher drainage density from physically erosive lithology. Lithologically, an area with a low drainage density value will be composed of rocks with high porosity so water will not flow to a run off but instead permeate to the rock layers below (Sukiyah, 2017).

2.3 Relative Tectonic Activity Index (IAT)

Relative Tectonic Activity Index (IAT) is a method for evaluating relative active tectonics based on geomorphic indices beneficial in evaluating morphology and topography. IAT is obtained from the different class averages of each geomorphic indices parameter.

$$IAT = \frac{S}{n} \quad (4)$$

Where S is the sum of tectonic class value and n is the number of geomorphic indices that has been used. The result is classified into 4 classes to determine the level of active tectonic relativity with class 1 is very high (1.0-1.5), class 2 is high (1.5-2.0), class 3 is medium (2.0-2.5) and class 4 is low (2.5-3.0) (el Hamdouni et al., 2008).

2.4 Method

The data for analyzing geomorphic indices are DEM TerraSAR-X with a spatial resolution of 9m. The stream network and sub-basin delineation is generated using hydrological and spatial analysis tools in GIS Software. The research area has been divided to 79 sub-basins with 3^{rd} order to easily interpret the various aspects of drainage pattern, geomorphic indices and various parameters in numerical terms (Singh, Arya, & Singh, 2020). Analysis from the calculated geomorphic indices are combined with field observations to identify the underlying factors that contribute to the development of landscape in Rembang Anticlinorium.

3. Results

3.1 The ratio of the valley floor and valley height (Vf)

The Vf value is calculated to determine the geometry of valley in association with tectonics or erosion and calculated from 79 sub-basin. Vf value in the research area ranging from 0.8–8.0 and classified to class 3 and class 2 shown in Figure 2. Based on Vf analysis it is known that the valley in the research area is having a relatively U-shaped with some V-shaped valleys scattered in the middle to southern parts. Low Vf value is also mainly at the edge of an anticline when its starts to plunge like Ngiono, Pakel and Gaplokan anticlines. These low Vf values are resulted from vertical incision from high tectonic activity.

3.2 Mountain Front Sinuosity (Smf)

The Smf is calculated in 25 mountain fronts that used to evaluate relative tectonic activity along the mountain fronts in the research area. Smf values is ranging from 1.036 to 3.488 and classified to class 1 to 3 are shown in Figure 3. Most of the Smf values are classified into class 2 and mainly occurred along the Ngiono, Pakel and Brama fold limbs. Class 1 Smf occurs in the western and eastern parts of the research area mainly in Ngiono anticline and indicate a straight mountain fronts. These mountain fronts are formed from many scarps that indicate a high tectonic activity. Class 3 Smf occurs in the northern and southern parts of Rembang Anticlinorium and indicates that erosive processes are more dominant and have eroded these mountain fronts.

3.3 Drainage Density (Dd)

Dd is calculated from 79 sub-basin in the research area to find the connection between tectonic activity and lithology. Dd values is ranging from 1.6 to 4.0 and mainly classified to class 3 and some are classified to class 2 as shown in Figure 4. Most of the Dd values are classified into class 3 and are influenced by the lithological properties in the research area which is mainly sedimentary rocks. Sedimentary rocks are attributed to have a high level of porosity with previous study from Surjono et al (2017) shows that Ngrayong formation porosity ranging from 25.97% to 40.21%, permeability ranging from 94.6 to 3385 millidarcies and exhibit well to excellent reservoir qualities.

3.4 Relative Tectonic Activity Index (IAT)

Analysis of IAT from 79 sub-basin in the research area by using Vf, Smf and Dd has been completed with IAT class is classified into 3 classes which is class 2 to 4 as shown in Table 2 and Figure 5. 1.2%, 20% and 78.8 of the 79 sub-basins are in class 2 (high activity), class 3 (moderate activity), and class 4 (low activity), respectively. These values indicate that most of the research area is in class 4, meaning that erosion process is having a greater impact on landform development compare to tectonic process. IAT class 3 values which indicate moderate tectonic activity are scattered from the western to eastern parts of the research area and mainly develop near strike-slip faults.

3.5 Geological Field Evidence

Geological data such as rock type, geological structures manifestation and geomorphology assessment of Watuputih hills have been collected to determine the factors that contribute to the development of Rembang Anticlinorium. Based on field observation Rembang Anticlinorium is composed of several lithology from different rock formations with varying degree of weathering. Some location has been found to have intense geological structures like fault and intense joint (Figure 6a,b). Most of the sedimentary rocks shown an east – west strike orientation with low to moderate dip angle (10° - 51°). The eastern part of the research area is mainly composed clastic limestones from Bulu and Paciran formations that have shown a moderate degree of karstification with the development of cave system and stalactite, these limestone bearing formations in these parts have also shown a high degree of chemical weathering with the development of solution hole and sinkhole (Figure 6c,d).

4. Discussion

Tectonic geomorphology by using morphometric indices has provided the Relative Tectonic Activity Index (IAT) of Watuputih hills. The use of IAT to evaluate the relativity of active tectonics has been broadly used by previous study, especially to identify tectonic in association with active faults (Bull, 1984; el Hamdouni et al., 2008; Hidayat et al., 2021; Keller & Pinter, 1996). Morphometric indices have been used in this research to determine the tectonic activity from the shape of steep hills, the shape of mountain fronts and river flow pattern. Field observation the research area has found the evidence of tectonic influence and weathering effect in the morphogenetic of Rembang Anticlinorium.

The morphometric indices analysis of steep hills and mountain fronts shape shows that the values of each index in the research area are controlled from the rate of tectonic activity. High tectonic activity will have an effect on shaping the mountain fronts into a straight line with steep hills with V-shape and it is shown in low values of Smf and Vf (Figure 2 and 3). The development of en-echelon folds in this research area has been attributed to tectonic deformation of a strike-slip in the basement fault with ENE-WSW orientation (Campbell, 1958; Husein, Kret, & Aditya, 2015)

The morphometric indices of drainage pattern in the research area are showing a relatively low Dd value in most of the sub-basin. The low value of Dd is mainly attributed to the distribution of sedimentary rocks in the research area. Most of the research area is composed of sandstone and limestone with some marl and claystone intercalated from different formations. The limestone bearing formations in the research area show a moderate degree of chemical weathering with many have formed an underground cave streams which make the surface flows have a rough texture.

The result of IAT analysis shows that the research area is dominated by low tectonic activity (Class 4). However, in the western and eastern parts of the research area some sub-basins are classified to moderate tectonic activity (Class 3). The western and eastern parts of the research are composed of steep-hills with several V-shaped valleys and relatively straight mountain fronts mainly in the eastern part. This is influenced by the tectonic activity from some of the strike-slip faults, which some are considered an active fault and have the potential for becoming an earthquake sources with magnitude Mmax 6.5 and Mw 7.0 (Soehaimi, Sopyan, Ma'mur, & Agustin, 2021).

Field observation shows that tectonic and weathering play major roles in shaping the landform in Watuputih hills, this is shown by several evidence found in the field. Weathering is associated with rock strength and have a relevance with morphometric study (Topal, 2019). Rock strength in the research area is mainly moderate class based on the rock strength classification for geomorphology studies (Selby, 1980). The exposure of the oldest rock in the research area which is limestone of Tawun formation in the axial surface of Ngiono, Pakel and Brama anticlines is showing that weathering has shape the landform. The limestone bearing formations like Paciran and Bulu formations also show a moderate degree of chemical weathering with the development of solution hole, cave, sinkhole and stalactite – stalagmite (Figure 6C and 6D). Some sedimentary rocks also show signs of deformation such as intense joint and fault (Figure 6A and 6B).

5. Conclusions

Tectonic geomorphology combined with field observation has been used as a tool to analyze the influence of tectonic and weathering in morphogenetic of Rembang Anticlinorium. Analysis of the ratio of the valley floor and valley height (Vf), mountain front sinuosity (Smf) and drainage density (Dd) has been used to obtained the Relative Tectonic Activity Index (IAT). IAT value in the research area has been classified into 3 classes with low tectonic activity (Class 4) is the dominant class. Low tectonic activity means that the erosional forces are more dominant in shaping the landform of Rembang Anticlinorium. Field observation has been found some evidence in related to tectonic activity mainly near the occurrence of strike-slip faults. Based on the analysis of morphometric indices and field observation, tectonic and weathering play major roles in shaping the landform of Rembang Anticlinorium with erosional force having a greater impact.

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Figure

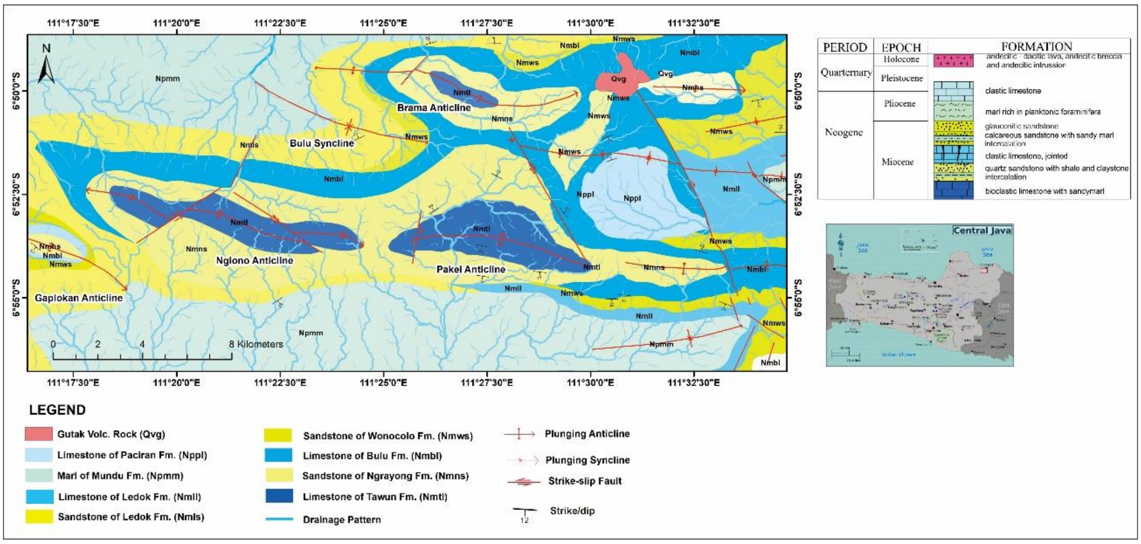


Figure 1 Regional Geological Map of Watuputih Hills in Central Java (modified after Faturrakhman & Kusumah, 2017; Novita et al., 2017)

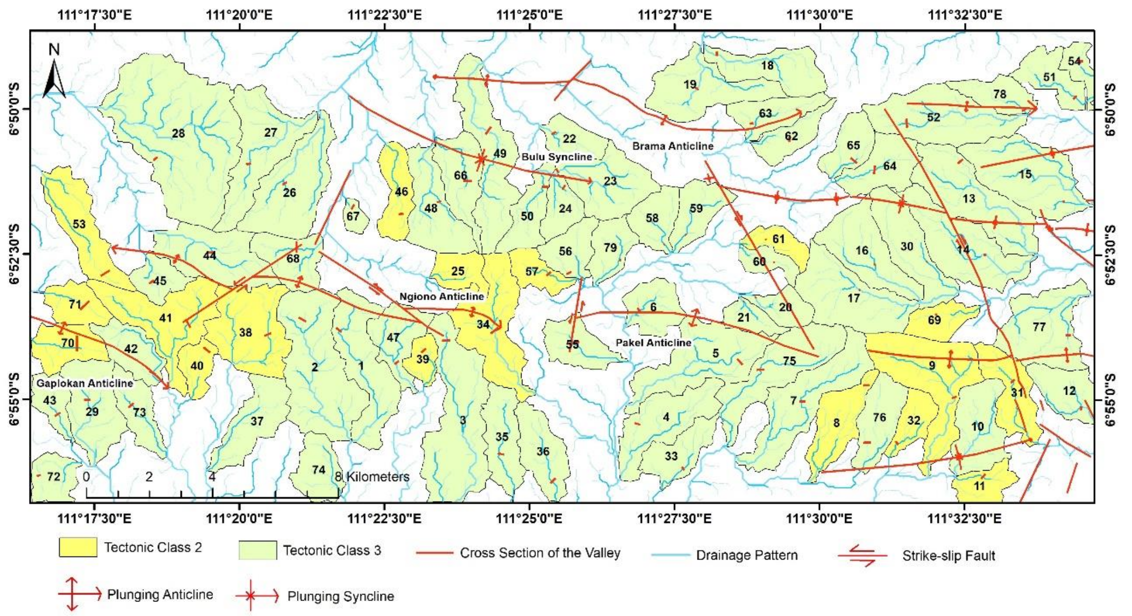


Figure 2 Classification of sub-basins in the research area based on the measurement of the ratio of the valley floor and valley height (Vf) with each number represent a sub-basins number

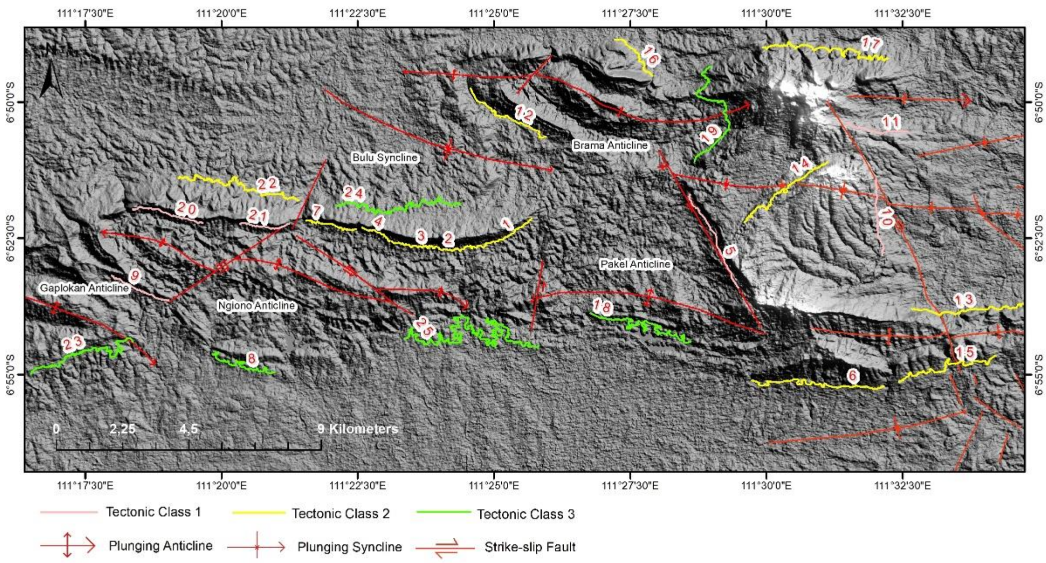


Figure 3 Classification of mountain fronts in the research area based on the measurement of mountain front sinuosity (Smf) with each number represent the considered mountain front

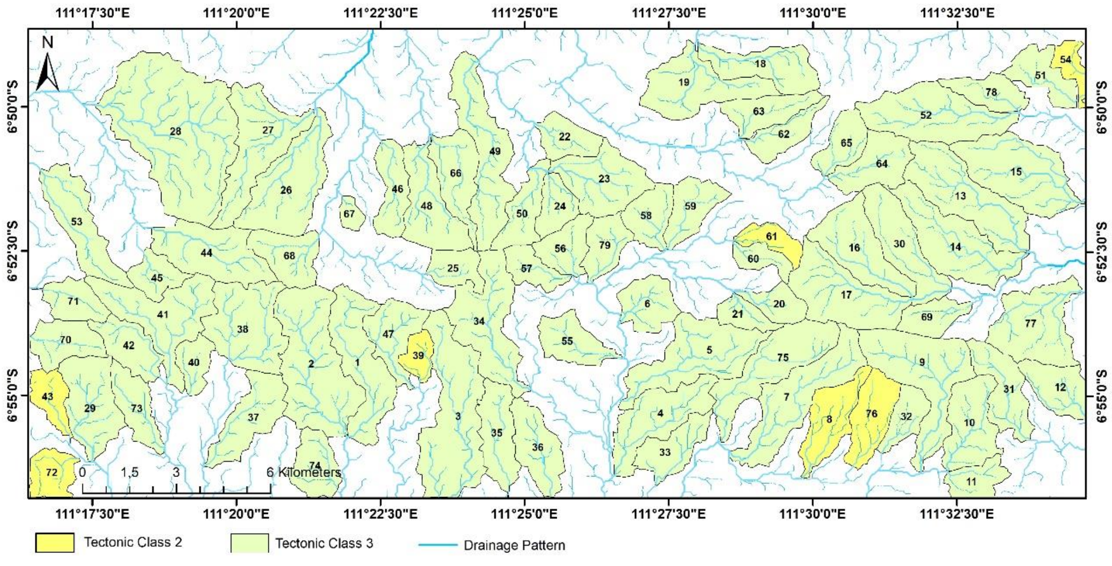


Figure 4 Classification of sub-basins in the research area based on the measurement of drainage density (Dd) with each number represent a sub-basins number

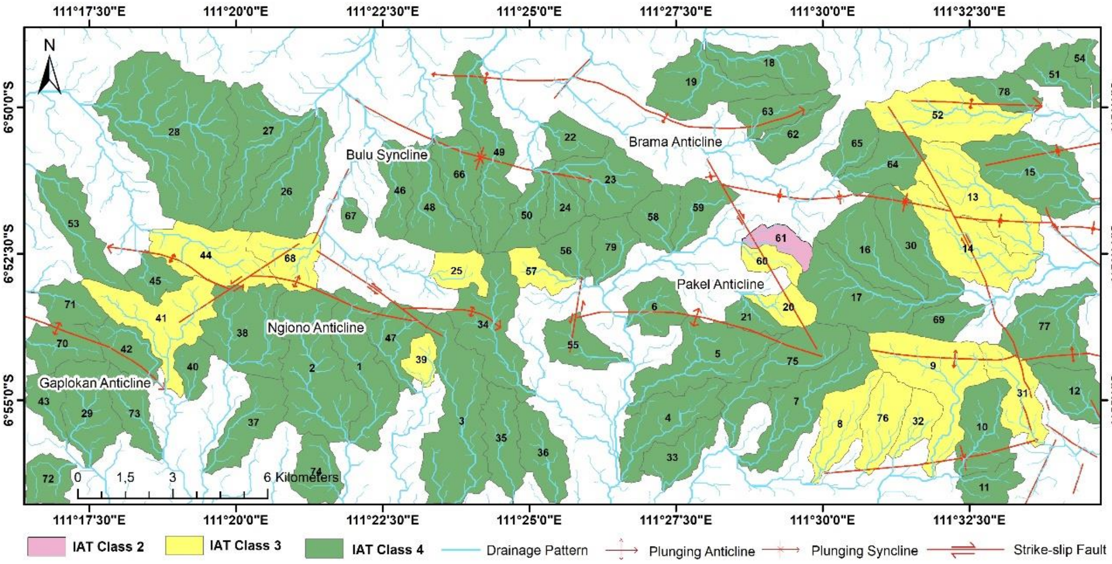


Figure 5 Classification of the Relative Tectonic Activity Index (IAT) from sub-basins in the research area

Figure 6 a) Faulting indication in clastic limestone from Paciran Fm., b) Intense joint limestone from Bulu Fm., c) Solution hole in limestone from chemical weathering, d) sinkhole that formed a cave named manuk cave in Gunem

Table

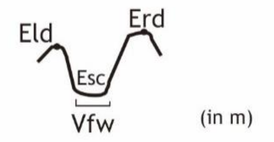
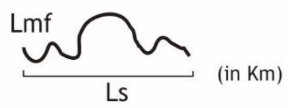
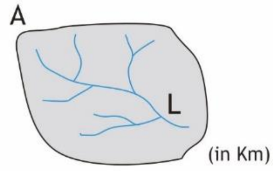
Morphometric Indices	***Mathematical Derivation***	***Measurement Procedure***	***Explanation***	***Source***
The Ratio of The Valley Floor and Valley Height (Vf)	$\frac{2Vfw}{(Eld-Esc)+(Erd-Esc)}$		Vf < 0.5 High Tectonic Activity Vf 0.1 -1 Moderate Tectonic Activity Vf > Low Tectonic Activity	Bull & McFadden (1977) El Hamdouni et al (2008)
Mountain Front Sinuosity (Smf)	$\frac{Lmf}{Ls}$		Smf < 1.1 High Tectonic Activity Smf 1.1 – 1.5 Moderate Tectonic Activity Smf > 1.5 Low Tectonic Activity	Bull & McFadden (1977) El Hamdouni et al (2008) Keller & Pinter (1996)
Drainage Density (Dd)	$\frac{\sum L}{A}$		Area that has been deformed from tectonic activity will have a higher drainage density from physically erosive lithology	Horton (1945) Sukiyah (2009)

Table 1. Morphometric Indices used in Tectonic Geomorphology analysis of Rembang Anticlinorium

Sub-basins	Smf	Vf	Dd	S/n	IAT	Tectonic Activity
1	-	3	3	3	4	Low
2	-	3	3	3	4	Low
3	3	3	3	3	4	Low
4	-	3	3	3	4	Low
5	3	3	3	3	4	Low
6	3	3	3	3	4	Low
7	2	3	3	2.66	4	Low
8	2	2	2	2	3	Moderate
9	2	2	3	2.33	3	Moderate
10	2	3	3	2.66	4	Low
11	-	2	3	2.50	4	Low
12	2	3	3	2.66	4	Low
13	1	3	3	2.33	3	Moderate
14	1	3	3	2.33	3	Moderate
15	-	3	3	3	4	Low
16	-	3	3	3	4	Low
17	-	3	3	3	4	Low
18	3	3	3	3	4	Low
19	2	3	3	2.66	4	Low
20	1	3	3	2.33	3	Moderate
21	-	3	3	3	4	Low
22	2	3	3	2.66	4	Low
23	-	3	3	3	4	Low
24	-	3	3	3	4	Low
25	2	2	3	2.33	3	Moderate
26	2	3	3	2.66	4	Low
27	2	3	3	2.66	4	Low
28	2	3	3	2.66	4	Low
29	3	3	3	3	4	Low
30	-	3	3	3	4	Low
31	2	2	3	2.33	3	Moderate
32	2	2	3	2.33	3	Moderate
33	-	3	3	3	4	Low
34	3	2	3	2.66	4	Low
35	-	3	3	3	4	Low
36	-	3	3	3	4	Low
37	3	3	3	3	4	Low
38	-	2	3	2.50	4	Low
39	3	2	2	2.33	3	Moderate
40	-	2	3	2.50	4	Low
41	1	2	3	2	3	Moderate
42	3	3	3	3	4	Low
43	3	3	2	2.66	4	Low
44	1	3	3	2.33	3	Moderate

45	-	3	3	3	4	Low
46	3	2	3	2.66	4	Low
47	-	3	3	3	4	Low
48	3	3	3	3	4	Low
49	-	3	3	3	4	Low
50	-	3	3	3	4	Low
51	-	3	3	3	4	Low
52	1	3	3	2.33	3	Moderate
53	-	2	3	2.50	4	Low
54	-	3	2	2.50	4	Low
55	3	3	3	3	4	Low
56	2	3	3	2.66	4	Low
57	2	2	3	2.33	3	Moderate
58	-	3	3	3	4	Low
59	-	3	3	3	4	Low
60	1	3	3	2.33	3	Moderate
61	1	2	2	1.66	2	High
62	3	3	3	3	4	Low
63	3	3	3	3	4	Low
64	2	3	3	2.66	4	Low
65	-	3	3	3	4	Low
66	3	3	3	3	4	Low
67	3	3	3	3	4	Low
68	1	3	3	2.33	3	Moderate
69	-	2	3	2.50	4	Low
70	-	2	3	2.50	4	Low
71	-	2	3	2.50	4	Low
72	-	3	2	2.50	4	Low
73	3	3	3	3	4	Low
74	-	3	3	3	4	Low
75	-	3	3	3	4	Low
76	2	3	2	2.33	3	Moderate
77	2	3	3	2.66	4	Low
78	-	3	3	3	4	Low
79	-	3	3	3	4	Low

Table 2 Classification of Relative Tectonic Activity Index (IAT) based on the calculation of geomorphic indices (Smf, Vf, Dd)