Songklanakarin J. Sci. Technol.
45 (2), 219–227, Mar. – Apr. 2023

http://www.sjst.psu.ac.th

Original Article

Morphogenetics of Rembang anticlinorium based on tectonic geomorphology characteristics in Watuputih, Central Java, Indonesia

Muhammad Luthfi Faturrakhman[1, 3*], Emi Sukiyah[2], and Jamal[3]

[1] *Program of Geological Engineering, Faculty of Geological Engineering, Universitas Padjadjaran, Bandung, 40132 Indonesia*

[2] *Department of Geoscience, Faculty of Geological Engineering, Universitas Padjadjaran, Bandung, 40132 Indonesia*

[3] *Center for Geological Survey, Geological Agency, Bandung, 40122 Indonesia*

Received: 16 September 2022; Revised: 17 February 2023; Accepted: 24 February 2023

Abstract

Rembang Anticlinorium is a series en-echelon folds with east – west orientation that formed from late Neogene tectonism. The folds in Watuputih named Ngiono, Pakel, Gaplokan, Bulu and Brama are composed of Neogene sedimentary rocks. Morphogenetics 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-basins. The ranges 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) ranges from 2 to 4, from a low to a high tectonic activity. Neogene sedimentary rocks in this area show a moderate degree of weathering mainly in the limestone bearing formations. Based on the analysis of morphometric indices and field observations, tectonics and weather play the major roles in shaping the landform of Rembang Anticlinorium with erosional forces having the 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 has formed in late Neogene tectonism events (van Bemmelen, 1949). Watuputih hills have significant importance to the surrounding area, and its karst hydrogeology system has many springs with varying discharges, composed in formations with complex geological structures (Setiawan, Syah Alam, & Haryono, 2020). Paciran limestone formation distributed in the Watuputih area is known to have a high dolomite content 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 elevations around 400 m and less, from the sea level. Topography development in tectonically active regions is due to complex interactions 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 mechanism was by passive folding and not by active folding (Husein, Sakur, & Setianto, 2016). Tectonic geomorphology quantified by morphometric indices can be used to determine state of active tectonics in 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 basins can be combined to obtain an index of relative active tectonics (IAT), which

*Corresponding author
Email address: muhammad21317@mail.unpad.ac.id

summarizes the tectonic activity in an area (el Hamdouni, Irigaray, Fernández, Chacón, & Keller, 2008)

Geomorphological development of this folded area has been an intriguing subject for many researchers, because the folds on Earth's surface are among the most common structural features that can be observed by satellites (Das, Saraf, & Shujat, 2010; Delcaillau *et al.*, 2022; Sissakian, Kadhim, & Jab'bar, 2014). This research aimed to reveal the factors that contribute to the development of Rembang Anticlinorium based on tectonic geomorphology combined 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 the Sunda land (Hall, 2014). Anticline and syncline in the Rembang Anticlinorium have east – west to northwest – southeast orientations, and are superimposed on one another, indicating complexity of the deformations in this area (van Bemmelen, 1949). Most of the folds in Rembang Anticlinorium are classified as non-cylindrical folds with hinge line, 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 is composed of rock formations 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 composed of bioclastic limestone and sandy marl formed in the early Miocene. Tawun formation is overlayed by the Ngrayong formation that was formed in the middle Miocene and is composed of very fine to medium quartz sandstone with shale, with claystone intercalations, and is dominated by foreshore to tide dominated facies (Surjono, Setyowiyoto, & Sugai, 2017). Bulu formation formed in the late middle Miocene and is composed of layered clastic limestone (packstone – wackestone) and shows locally jointed rocks.

Wonocolo formation formed in the late middle Miocene and 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 ranging from coarse to fine and cemented by carbonates. Mundu formation formed in Pliocene is 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 and is composed of dacitic – andecitic lava, andecitic breccia, and andesitic intrusions.

2.2 Tectonic geomorphology

Tectonic geomorphology quantified by geomorphic indices can be used to studying active tectonic and relative tectonic deformations 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 of combining 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 calculated as the ratio of the width of the valley floor to its average height (Bull & McFadden, 1977). High Vf is associated with a low uplifting rate and will have a "U" shaped valley because of extensive river cut at the bottom of the valley. Low Vf is linked with active tectonics since incision to the valley wall will result in a "V" shaped valley.

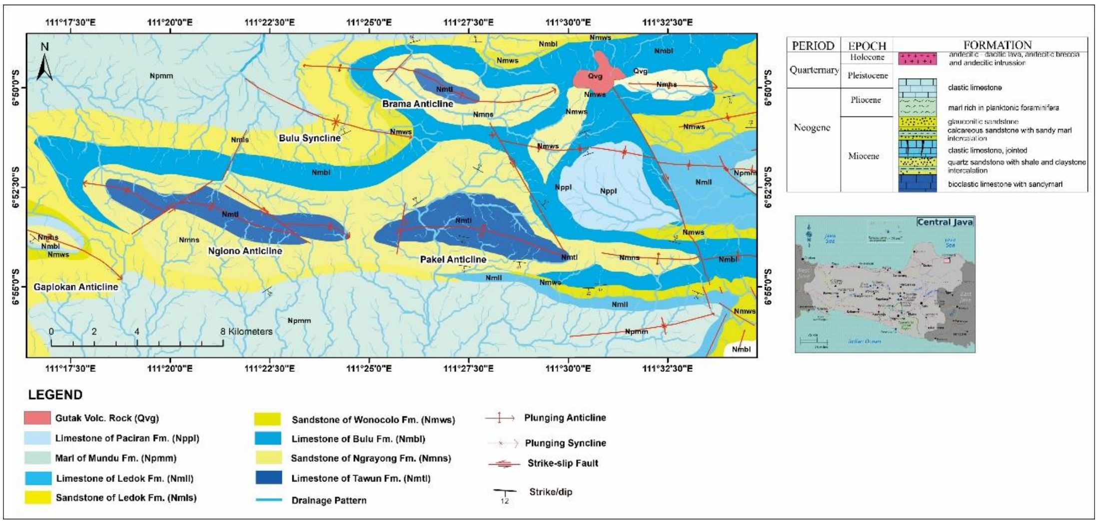
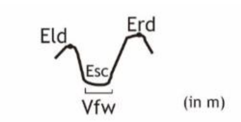
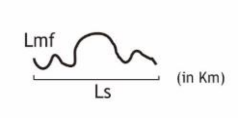
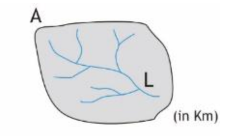


Figure 1. Regional geological map of Watuputih Hills in Central Java (modified after Faturrakhman & Kusumah, 2017; Novita *et al.*, 2017)

Table 1. Morphometric indices used in tectonic geomorphology analysis of Rembang Anticlinorium

Morphometric index	Mathematical formula	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)

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 be combined with other geomorphological indexes such as Drainage density of facets (Ddf) to get a better insight of a tectonically active area (Topal, Keller, Bufe, & Koçyiğit, 2016). High Smf is associated with tectonic activity dominating the mountain front and is linked with a straight mountain front. Low Smf indicates that erosion activity dominated the mountain front and is linked with irregular shaped 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 referring to coarse and fine textures, respectively (Strahler, 1964). This geomorphological index can be used to reflect the tectonic activity and lithological aspects 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 will be composed of rocks with high porosity so the water will not flow to a runoff but instead permeates to the rock layers below (Sukiyah, 2017).

2.3 Relative tectonic activity index (IAT)

Relative Tectonic Activity Index (IAT) is an indicator 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 parameter.

$$IAT = \frac{S}{n} \quad (1)$$

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

2.4 Methods

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

3. Results

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

The Vf was calculated to determine the geometry of valley in association with tectonics or erosion, for 79 sub-basins. Vf in the research ranged within 0.8–8.0 falling into classes 3 and 2, as shown in Figure 2. Based on Vf analysis it is known that the valley in the research area was relatively U-shaped with some V-shaped valleys scattered in the middle to southern parts. Low Vf is also mainly at the edge of an anticline, when its starts to plunge, like Ngiono, Pakel and Gaplokan anticlines. These low Vf values resulted from vertical incisions induced by high tectonic activity.

3.2 Mountain front sinuosity (Smf)

The Smf was calculated for 25 mountain fronts, used to evaluate relative tectonic activity along the mountain fronts in the research area. Smf ranged from 1.036 to 3.488 and fell into classes 1 to 3, as shown in Figure 3. Most of the Smf values fell into class 2 and mainly occurred along the Ngiono, Pakel and Brama fold limbs. Class 1 Smf occurred in the western and eastern parts of the research area, mainly in Ngiono anticline, and indicates a straight mountain front. 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-basins in the research area to find a connection between tectonic activity and lithology. Dd values ranged from 1.6 to 4.0 and were mainly classified to class 3, with some falling into class 2, as shown in Figure 4. Most of the Dd values are of class 3 and are influenced by the lithological properties in the research area which is mainly composed of sedimentary rocks. Sedimentary rocks have a high porosity in the previous study by Surjono *et al.* (2017), showing Ngrayong formation porosity from 25.97% to 40.21%, permeability from 94.6 to 3385 milliDarcies, and exhibiting good to excellent reservoir quality.

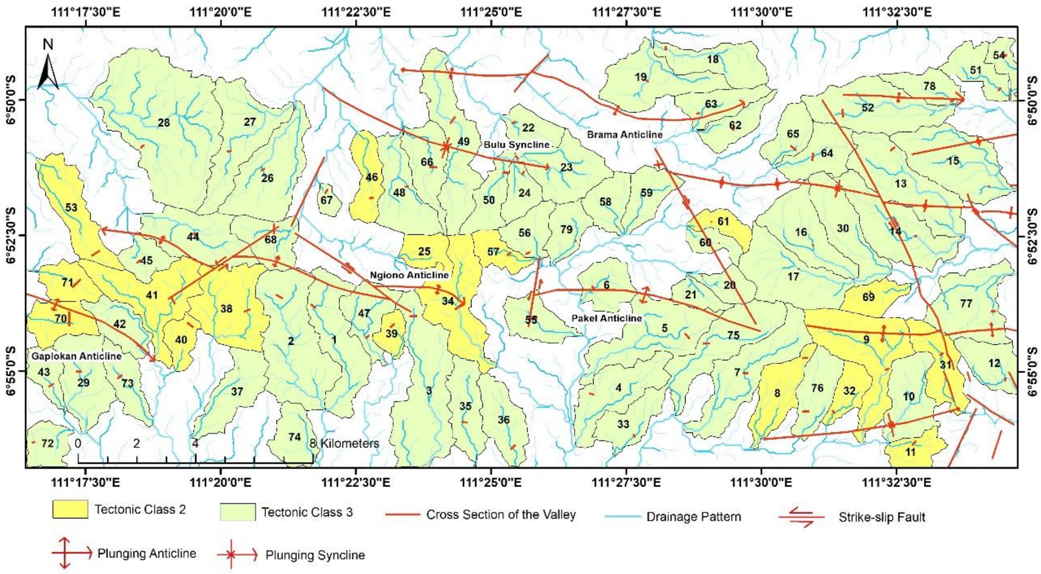


Figure 2. Classification of sub-basins in the research area, based on the ratio of valley floor and valley height (Vf) with each number labeling a sub-basin.

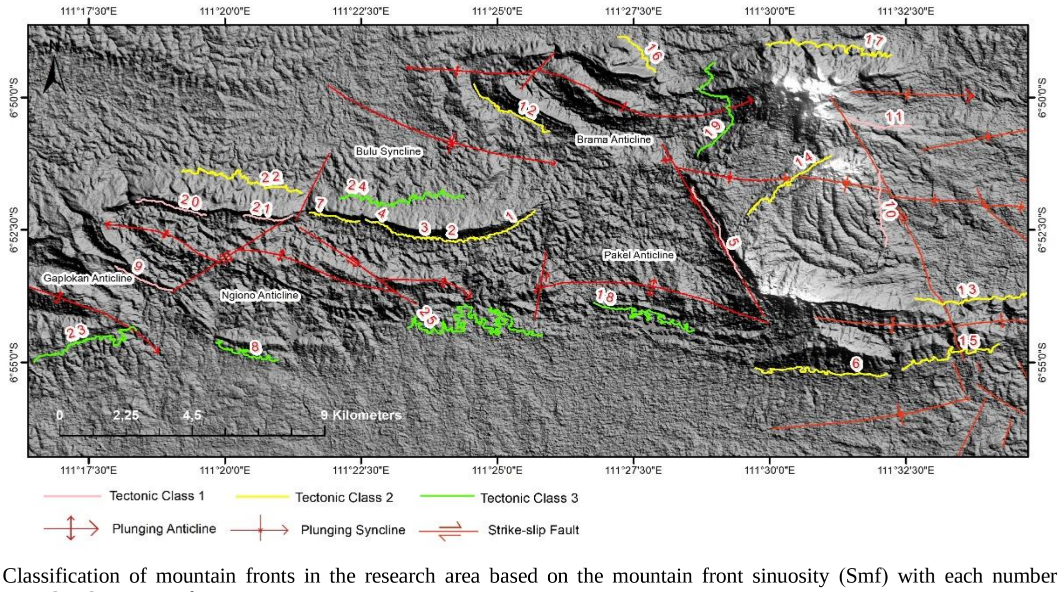


Figure 3. Classification of mountain fronts in the research area based on the mountain front sinuosity (Smf) with each number labeling a considered mountain front.

3.4 Relative tectonic activity index (IAT)

Analysis of IAT from 79 sub-basins in the research area by using Vf, Smf and Dd has been completed, with IAT falling into 3 classes from 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. This indicates that most of the research area is in class 4, meaning that erosion processes have a greater impact on landform development than tectonic processes. IAT class 3 indicates moderate tectonic activity scattered from the western to eastern parts of the research area, and has mainly developed near strike-slip faults.

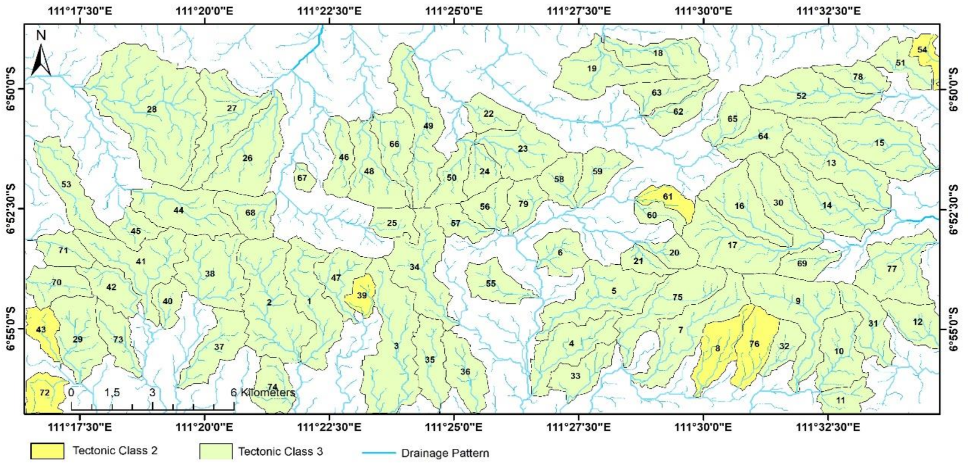


Figure 4. Classification of sub-basins in the research area based on the drainage density (Dd) with each number labeling a sub-basin.

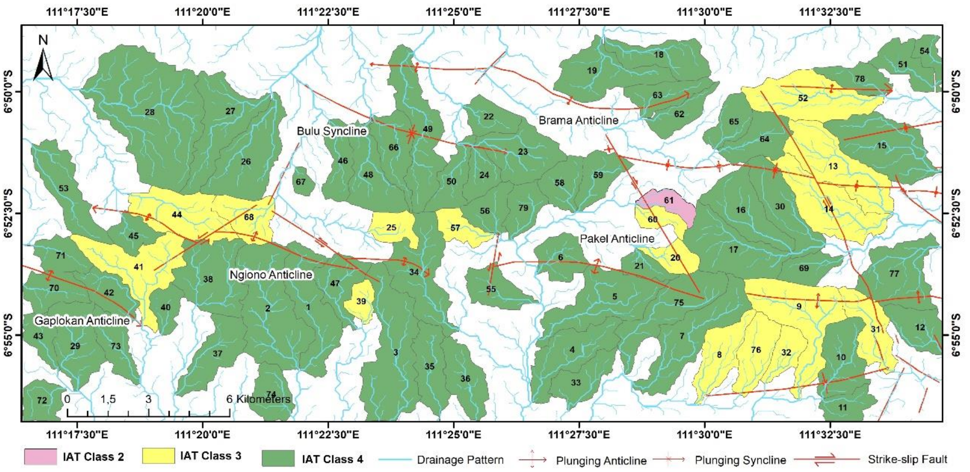


Figure 5. Classification of the relative tectonic activity index (IAT) for sub-basins in the research area

Table 2. Classification of relative tectonic activity index (IAT) calculated from other geomorphic indices (Smf, Vf, Dd).

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

Table 2. Continued.

Sub-basins	Smf	Vf	Dd	S/n	IAT	Tectonic Activity
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

4. Discussion

Tectonic geomorphology using morphometric indices has provided the Relative Tectonic Activity Index (IAT) of Watuputih hills. The use of IAT to evaluate the relative role of active tectonics has been broadly used in previous studies, especially to identify tectonics 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 patterns. Field observations in the research area found evidence of tectonic influences and weathering effects in the morphogenetics of Rembang Anticlinorium.

The morphometric index analysis of steep hills and mountain front shapes shows that each index in the research area is controlled by the rate of tectonic activity. High tectonic activity will have an effect on shaping the mountain fronts into a straight line with steep hills having V-shapes, and is shown in low values of Smf and Vf (Figures 2 and 3). The development of en-echelon folds in this research area has been attributed to tectonic deformations 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 show a relatively low Dd in most of the sub-basin. The low 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 having formed underground cave streams that make the surface flows have a rough texture.

The IAT analysis showed 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 area 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, some of which are considered active faults and have the potential to induce earthquakes as sources, with magnitude Mmax 6.5 and Mw 7.0 (Soehaimi, Sopyan, Ma'mur, & Agustin, 2021).

Field observations show that tectonics and weathering play the major roles in shaping the landform in Watuputih hills, as shown by several pieces of evidence found in the field. Weathering is associated with rock strength and has relevance in a morphometric study (Topal, 2019). Rock strength in the research area is mainly moderate based on the rock strength classification for geomorphology studies (Selby, 1980). The exposure of the oldest rock in the research area, which is limestone in Tawun formation in the axial surfaces of Ngiono, Pakel and Brama anticlines, shows that weathering has shaped the landform. The limestone bearing formations like Paciran and Bulu also show a moderate degree of chemical weathering with the development of solution holes, caves, sinkholes and stalactites – stalagmites (Figure 6C, D).

Figure 6. A. Faulting indication in clastic limestone from Paciran Fm., B. intense joint limestone from Bulu Fm., C. solution holes in limestone from chemical weathering, and D. a sinkhole formed into a cave named Manuk cave in Gunem

Some sedimentary rocks also show signs of deformation, such as intense joints and faults (Figure 6A, B).

5. Conclusions

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

Acknowledgements

The authors express their appreciation and gratitude to the Head of Geological Survey Center of The Ministry of Energy and Mineral Resources and other parties for their support in this research.

References

Buczek, K., & Górnik, M. (2020). Evaluation of tectonic activity using morphometric indices: case study of the Tatra Mts. (Western Carpathians, Poland). *Environmental Earth Sciences*, *79*. doi:10.1007/s12665-020-08912-9

Bull, W. B. (1984). Tectonic geomorphology. *Journal of Geological Education*, *32*(5), 310–324. doi: 10.5408/0022-1368-32.5.310

Bull, W. B., & McFadden, L. D. (1977). Tectonic geomorphology north and south of the Garlock fault, California. *Geomorphology in arid regions* (pp. 115–138). Oxfordshire, England: Routledge.

Campbell, J. D. (1958). En echelon folding. *Economic Geology*, *53*(4), 448–472. doi:10.2113/gsecongeo. 53.4.448

Das, J. D., Saraf, A. K., & Shujat, Y. (2010). A remote sensing technique for identifying geometry and geomorphological features of the Indo-Burman frontal fold belt. *International Journal of Remote Sensing*, *31*(16), 4481–4503. doi:10.1080/014311 60903154366

Delcaillau, B., Graveleau, F., Carlier, D. saint, Rao, G., le Béon, M., Charreau, J., & Nexer, M. (2022). Geomorphic analysis of active fold growth and landscape evolution in the central Qiulitage fold belt, southern Tian Shan, China. *Geomorphology*, *398*, 108063. doi:10.1016/J.GEOMORPH.2021.108 063

el Hamdouni, R., Irigaray, C., Fernández, T., Chacón, J., & Keller, E. A. (2008). Assessment of relative active tectonics, southwest border of the Sierra Nevada (southern Spain). *Geomorphology*, *96*(1–2), 150–173. doi:10.1016/j.geomorph.2007.08.004

Faturrakhman, M. L., & Kusumah, K. D. (2017). *Remote sensing geological map of Jatirogo sheet, Java scale 1 : 50.000*. Geological Survey Center.

Hall, R. (2014). The origin of Sundaland. *Proceedings of Sundaland Resources 2014 MGEI Annual Convention*. Retrieved from http://searg.rhul.ac.uk/ pubs/hall_2014 Sundaland origin.pdf

Hidayat, E., Muslim, D., Zakaria, Z., Permana, H., & Wibowo, D. A. (2021). Tectonic geomorphology of the Karangsambung area, Central Java, Indonesia. *Rudarsko-Geološko-Naftni Zbornik*, *36*(4), 85–105. doi:10.17794/rgn.2021.4.8

Husein, S., Kret, kakda, & Aditya, H. (2015). En Echelon folds mechanism in northern parts of Rembang anticlinorium. *Seminar Nasional Kebumian Ke-8 Jurusan Teknik Geologi FT UGM*. doi:10.13140/ RG.2.1.2276.9362

Husein, S., Sakur, M., & Setianto, A. (2016). En echelon distribution in Rembang anticlinorium. *Prosiding Seminar Nasional Kebumian Ke-9 Jurusan Teknik Geologi Fakultas Teknik Universitas Gadjah Mada*, 70–82.

Keller, E. A., & Pinter, N. (1996). *Active tectonics: Earthquakes, uplift and landscape* (Vol. 338). Hoboken, NJ: Prentice Hall.

Mulyadi, D., Solihin, Permana, H., & Yuniati, M. D. (2019). Petrography and XRD mineral dolomites, Paciran formation, district of Lamongan, East Java. *Journal of Physics: Conference Series*, *1280*(2), 022075. doi:10.1088/1742-6596/1280/2/022075

Novita, D., Sanjaya, I., Margono, U., Rijani, S., & Mawardi, S. (2017). *Remote sensing geological map of Blora sheet, Java scale 1: 50.000*. Geological Survey Center.

Selby, M. J. (1980). A rock mass strength classification for geomorphic purposes: with tests from Antarctica and New Zealand. *Zeitschrift Für Geomorphologie*. doi:10.1127/zfg/24/1984/31

Setiawan, T., Syah Alam, B. Y. C. S. S., & Haryono, E. (2020). Hydrochemical and environmental isotopes analysis for characterizing a complex karst hydrogeological system of Watuputih area, Rembang, Central Java, Indonesia. *Hydrogeology Journal*, *28*(5), 1635–1659. doi:10.1007/s10040-020-02164-4

Singh, A. P., Arya, A. K., & Singh, D. sen. (2020). Morphometric analysis of Ghaghara River Basin, India, using SRTM data and GIS. *Journal of the Geological Society of India*, *95*(2), 169–178. doi:10.1007/s12594-020-1406-3

Sissakian, V. K., Kadhim, T. H., & Jab'bar, M. F. A. (2014). Geomorphology of the high folded zone. *Iraqi Bulletin of Geology and Mining*, *6*, 7–51.

Soehaimi, A., Sopyan, Y., Ma'mur, & Agustin, F. (2021). *Active faults map of Indonesia scale 1: 5.000.000*. Geological Survey Center.

Strahler, A. N. (1964). *Quantitative geomorphology of drainage basin and channel networks*. New York, NY: McGraw-Hill.

Sukiyah, E. (2009). *Erosion model of quaternary volcanic landscapes in the Southern Bandung basin* (Master's dissertation, Padjadjaran University, Bandung, Indonesia)

Sukiyah, E. (2017). *Geographic information system: Concepts and applications in quantitative geomorphological analysis.* West Java, Indonesia: Unpad Press.

Sukiyah, E., Sunardi, E., Sulaksana, N., & Raditya Rendra, P. P. (2018). Tectonic geomorphology of upper Cimanuk drainage basin, West Java, Indonesia. *International Journal on Advanced Science, Engineering and Information Technology*, *8*, 863–869. doi:10.18517/ijaseit.8.3.5441

Surjono, S. S., Setyowiyoto, J., & Sugai, Y. (2017). Facies and reservoir characteristics of the Ngrayong sandstone in the Rembang area, Northeast Java (Indonesia). *Open Journal of Geology*, *7*(05), 608. doi:10.4236/ojg.2017.75042

Topal, S. (2019). Evaluation of relative tectonic activity along the Priene-Sazlı Fault (Söke Basin, southwest Anatolia): Insights from geomorphic indices and drainage analysis. *Journal of Mountain Science*, *16*(4), 909–923. doi:10.1007/s11629-018-5274-x

Topal, S., Keller, E., Bufe, A., & Koçyiğit, A. (2016). Tectonic geomorphology of a large normal fault: Akşehir fault, SW Turkey. *Geomorphology*, *259*, 55–69. doi:10.1016/j.geomorph.2016.01.014

Topal, S., & Özkul, M. (2018). Determination of relative tectonic activity of the Honaz fault (SW Turkey) using geomorphic indices. *Pamukkale University Journal of Engineering Sciences*, *24*. doi:10. 5505/pajes.2017.18199

van Bemmelen, R. W. (1949). *General geology of Indonesia*. The Hague, The Netherlands: Martinus Nijhoff.

Winarti, W., Sukiyah, E., Syafri, I., & Nur, A. A. (2022). Tectonic control of the Nanggulan formation based on morphometric analysis in Kulon Progo, Indonesia. *Indonesian Journal on Geoscience*, *9*(2), 147–157. doi: 10.17014/ijog.9.2.147-157

Winarto, J. B., Sukiyah, E., Haryanto, A. D., & Haryanto, I. (2019). Sub surface active fault identification on quaternary and tertiary rocks using geoelectric method in Cilaki drainage basin, southern part of West Java, Indonesia. *International Journal on Advanced Science, Engineering and Information Technology*, *9*(5), 1563–1569. doi:10.18517/ijaseit.9.5.8111

Zetra, Y., Burhan, R. Y. P., Firdaus, A. W., Nugrahaeni, Z. v., & Gunawan, T. (2021). Characteristics of Cepu block oil, Wonocolo formation, East Java Indonesia: Study of aliphatic biomarkers. *AIP Conference Proceedings 2349(1):020040*. doi:10.1063/5.0052284