DRAINAGE MORPHOMETRY CHARACTERIZING ACTIVE TECTONISM
IN WEST JAVA, INDONESIA

Febri Hirnawan* and Dicky Muslim*

Abstract

The Tertiary Halang Formation, composing predominantly sandstone beds with
claystone and breccia layers alternation, is of Upper Miocene to Middle Pliocene in age,
on which the Quaternary volcanic breccia unconformably overlies this formation.
Drainage morphometry of Cijolang River has been developing on the Halang Formation
in the northern part of the study area. On the other hand, the morphometry of Cimuntur
River is developing in the southern part, where the Quaternary volcanic breccia is
distributed.

To test the neotectonism in the study area, data of morphometry and lineations of
fractures were collected through topographic map and aerial photograph interpretation
methods.

Results of statistical analysis through tests of difference between two means of azimuth-
and morphometry variables from both river basins developing in the respective rock
units are not significantly different. Those variables are represented by lineament and
river-segment azimuths and also by bifurcation ratio ($R_b$) and drainage density ($D_d$). The
result suggests that the drainage basin development is not affected by kinds of rocks but
merely by the deformation pattern. This phenomenon indicates that the recent tectonism
is active. This neotectonism generated the similar joint patterns in both the Tertiary
Halang Formation and the overlying Quaternary volcanic breccia, which continuously
intersecting the unconformity between the rock units. This tectonic morphometry
phenomenon proved the active tectonism in a part of an active continental plate margin.

Keywords: morphometric development, neotectonism, tectonic morphometry, active
continental plate margin, bifurcation ratio, drainage density

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INTRODUCTION

The development of drainage basin morphology is affected by the geological factors, including fluvial processes, topography, sea-level changes, tectonism and other factor like climatic condition (Doornkamp, 1986). As the result of the dynamic condition of the basin and the climate in a region where the surface run off flows to the lowland into the sea following the pattern of geological weaknesses encompassing joints, faults, bedding planes and other discontinuities, such as unconformable surfaces, the characteristics of drainage pattern morphology of river basins are generated (Stewart and Hancock, 1994; Keller and Pinter, 1999). Active tectonism play an important role affecting the development of the river basin morphology. Surface fault and/or recent flexural deformations are good indicators to the surface movement characterizing the active tectonisms (Nakata, et al., 1996).

The study area is located in the eastern part of West Java, Indonesia (Fig. 1). It lays between the active NW-SE trending Baribis-Majenang Fault System in the north and the active Ciawi-Pangandaran Fault System with the same trend in the south. The entire area between both fault systems is about 200 kms long and more than 50 kms wide, and known as the hazardous area by mass-movement mainly in the rainy seasons (Hirnawan, 2000). The study Area, known as Panawangan Area, is about in the middle part of the entire area. Shallow earthquakes frequently happen, which give the impressions that those two fault systems are in motion at the present controlled by active tectonisms (Kastowo and Simandjuntak, 1979).

Majalengka earthquake, for example, which happened on July 6, 1990 had only magnitude M = 5.1 Richter scale, but the generated earthquake coefficient was large enough to cause houses and other structures damaged since the focus was shallow (about 33 km in depth). This earthquake was characterized by the occurrence of a new right-lateral slip fault of N300°E in direction. It dislocated the floors of many people’s houses, followed by a landslide of about 50 metres wide (Soehaimi, 1990). Besides, recent surface breakages being generated by reactivation of northwestern segments of the active Citanduy fault system and the Baribis fault system, such as the new surface ruptures ranging from N60°E to N120°E or from N240°E to N300°E in directions, are observed crossing roads on Quaternary volcanic breccia in the field. The damages of these roads in southern Panawangan area frequently happen. According to Nakata et al. (1996) surface ruptures are due to reactivation of buried pre-existing fault.

In this area, the Upper Miocene to Lower Pliocene Halang Formation consists of predominant sandstone beds intercalated with claystone beds and breccia layers, which is unconformably overlain by the Cijolang Formation and Old volcanic products (Quaternary volcanic breccia).

The objective of this study is to examine if morphological development of river basin on Quaternary volcanic breccia is governed by the recent deformation. If so, it would be the evidence of active tectonism. If the tectonisms is active, both the Quaternary volcanic breccia unconformably overlying the Tertiary
sediments and the sediments themselves should be deformed and may serve as the recent surface deformation, governing all the morphological developments of river basins, including those occurring on the youngest rock unit. The morphometry of the rivers on this Quaternary rock unit would resemble that on the Tertiary rock unit due to the neotectonic activity. In order to test this hypothesis, the authors attempt to compare those morphometric data using the statistical method. Statistical analysis has been used by many authors for geomorphological approach to the study of neotectonism before 1960s (Doornkamp, 1986).

Volcanic breccia of the Cijolang Formation (Middle Pliocene) and the Old Volcanic Product (Pliocene-Pleistocene) lie unconformably on the Halang Formation. These volcanic products mainly consist of monomictic breccia with tuffaceous matrix (Budhitrisna, 1986; Kastowo, 1975). River terrace deposits, distributed in Cikijing area, and Recent alluvium are made of loose sands, gravels, and boulder materials. Recent alluvium is distributed along the side wall and floors of rivers.

Outline of Stratigraphy and Lithology

Figure 2 illustrates the columnar section of the study area. The Halang Formation (Upper Miocene-Middle Pliocene) lies conformably on the Pemali Formation (Lower to Middle Miocene), which consists of mudstone and they serve as basement rock in the study area. The Halang Formation consists of sandstone and claystone beds. In the lower part, this formation also interfingers with the sedimentary breccia of Gunung Hurip Member (Budhitrisna, 1986).
Sandstone bed of the Halang Formation is characterized by well developed stratification, and fine to medium grain size, limy sandstone, sedimentary structures of graded bedding and parallel lamination are observed in several exposures. Claystone bed of the Halang Formation is characterized by well developed stratification, and grayish color. Limy and shaly claystones are commonly found in the field. Sedimentary structure especially parallel lamination is observed. In many other areas, outside the study area sandstone and claystone exposures of the Halang Formation indicate complete sedimentary structures of a, b, c, d, and e intervals belonging to the turbidite facies model (Bouma, 1976 in Simandjuntak, 1980).

Sedimentary breccia of Gunung Hurip Member is characterized by massive to poorly stratified beds, polymeric breccia, hard, dark brown color as a result of intensive oxidation, carbonaceous fine grain matrix, matrix supported (open fabric), poorly sorted clasts. The clasts consist of sandstone, claystone and andesitic fragments, and are predominantly subangular shaped and gravel to boulder in size.

The Quaternary volcanic breccia is massive poorly stratified bed, black grayish color, monomictic breccia, clasts supported and poorly sorted. The clasts are of igneous rock fragments, subrounded to angular shape and sand to boulder size. Matrix is tuffaceous and sandy. This volcanic breccia is the product of the Ciremai Mountain and Sawal Mountain near the study area (Budhitrisna, 1986; Asterlina, 1997).

Geological Structure

Baribis-Majenang and Ciawi-Pangandaran fault systems are active faults that related with the occurrence of subduction zone along the southern side of Java Island (Situmorang et al., 1976). These two fault systems, according to Martodjojo (1984) are thrust faults, which directly influence the geologic structure in the study area (Fig. 1).

The Cijolang fault is a major thrust fault in the study area and is the part of the Baribis-Majenang fault system. It runs along the Cijolang River from northwest to southeast in the study area. This fault is characterized by its steep dip of about 70°, with lineaments followed by the same trending flow direction of the Cijolang River. The other same thrust fault, namely Cicacaban fault, also occurs south of the Cijolang fault and is parallel to it. The occurrence of wrench faults in the Cijolang river basin intersecting these two thrust faults characterizes the intensive deformation of the river basin.

The result of statistical test of difference between two means of variables of morphometric features in Table 1 also suggests the morphological development of the Cijolang river basin being affected by the more intensive deformation compared to that of Cilutung and Cibantar upper river basins. The very significant difference of means of both $D_d$ (drainage density) and $R_b$ (bifurcation ratio) in the northern block (Cilutung and Cibantar upper drainage basins on the Tertiary Halang Formation, $D_d = 3.399$ km/sq.km and $R_b = 1.949$) with that in the southern block (Cijolang drainage basin on the same formation, $D_d = 4.232$ km/sq.km and $R_b = 3.923$) shows that the southern block is more strongly deformed.
Table 1. Tests of difference between two means of Bifurcation Ratio (Rb) from Cilutung and Cibantar upper river basins and Cijolang river basin, and Drainage Density (Dd) from the respective river basins; independent samples.

<table>
<thead>
<tr>
<th>Variable Tested</th>
<th>Variable means</th>
<th>n1/n2</th>
<th>tcalc</th>
<th>t.05</th>
<th>t.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bifurcation Ratio, $R_b$</td>
<td>X (Cibantar-Ciujung)</td>
<td>1.949</td>
<td>3.923</td>
<td>9/36</td>
<td>-6.998**</td>
</tr>
<tr>
<td>Drainage Density; $D_d$</td>
<td>Y(Cijolang)</td>
<td>3.399</td>
<td>4.232</td>
<td>9/36</td>
<td>-3.790**</td>
</tr>
</tbody>
</table>

Note: ** difference very significant

A couple of anticlines and synclines develop on the Halang Formation in the study area. Their directions, which run northwest-southeast, are mainly parallel to the major Cijolang and Cicacaban thrust faults. These structures have the sedimentary rocks deformed almost vertically (steep dip).

Several strike-slip (wrench) faults as mentioned in the foregoing, namely the Cibatuhrip, the Cibali, and the Palasari faults, are observed in the study area. These strike-slip faults mainly belong to first order of the wrench fault tectonic system according to Moody and Hill (1956). The Cibali and the Palasari faults intersect the
major Cijolang and Cicacaban thrust faults.

The Cibatuhurip sinistral fault lies in the northwestern part of the study area. It runs southwest-northeast as long as about 3 kms along the Cibatuhurip River. The Cibali sinistral fault extending along the Cibali River in the central part of the study area is about parallel to the Cibatuhurip fault and runs as long as about 4 kms. While, the Palasari dextral fault is in the southeastern part and it clearly marks the sharp morphologic bending of a Cijolang River-segment. This dextral fault extends more than 5 kms, which direction from the southern to the northern part.

River segments and topographic lineaments may reflect the effect of geologic structure on the earth surface. These two types of discontinuities exhibit the strengths and weaknesses of rock bodies. The authors attempt to analyze the effect of geologic structure on the river basin by drawing a drainage pattern map and compare the values of $R_b$ and $D_d$ of two main rivers, whose basins are developed on the rock bodies of different age.

**METHOD, ANALYSIS, AND RESULT**

Geological structures, such as folds, faults, and joints appear to control the drainage networks or drainage patterns. Morphometry concerns the measurement of drainage network or the form characteristics of rivers, lakes, etc. and their basins (Splitz and Schumm, 1997). Drainage basins are the entire area drained by a river system, which contains the rivers and all of its tributaries.

The morphological features of Cijolang and Cimuntur drainage basins were developed under the control of tectonic activity in the study area. The analysis was done to verify whether the tectonism in the study area is significantly active or not. The verification of the analysis should also be able to explain how far is the effect of tectonic activity on the development of the morphology of the respective rivers. For the purpose of the verification, the following data were analyzed using the rose-diagram and the statistical tests, known as the tests of differences between two means or T-tests, and the regression – correlation analysis.

**Lineament and River-segment**

Two pair of the samples of lineament azimuths and the river-segment azimuths were randomly taken along the Cijolang and Cimuntur Rivers. Lineament azimuths of the river basin were obtained from aerial-photo interpretation. River-segment azimuths were measured from topographic map and observed in the field. Every lineament together with the nearest river-segment was taken as a pair of the sample member. The number of the pair samples from the Cijolang and Cimuntur Rivers are 39 and 44 respectively.

The Cijolang and Cimuntur drainage basins were composed of folded, jointed and faulted Tertiary Sediments of the Halang Formation, and jointed Quaternary volcanic breccia respectively. The geological structures developing in the Tertiary Formation have already been discussed in the foregoing.

In order to analyse how is the effect of the deformation pattern (lineament azimuths) due to active tectonism on the river morphology (river-segment azimuths), the rose
diagrams were employed and then the relation was confirmed by the statistical tests as follows.

1. General Pattern of River-segments

The lineament azimuths rose diagram in the Halang Formation with the river-segment azimuths rose diagram of the Cijolang River occurring on this formation indicates the same eastward direction vector means. The resultant vector gives the west-east direction. This gives a conclusion that the river segment corresponds clearly to the lineament. In other word, the river and the tributaries (drainage pattern) developed following the pattern of lineament in its drainage basin.

The same result is also shown by comparison of such rose diagrams which represent the data from the Cimuntur River Basin. The result suggests that the development of the river system (drainage pattern), occurring in the area of Quaternary volcanic breccia, is corresponding to the lineament pattern.

2. Difference between Lineament and River-segment

The result of statistical tests confirms the relation drawn from the above-mentioned result of the rose-diagram comparison. Directional differences between two mean values of lineament and river-segment azimuths for both Cijolang and Cimuntur Rivers are not significant (Table 2). These tests verify the same pattern of lineament and river-segment azimuths, suggesting that the morphological development is governed by the lineament patterns in the respective river basins. For confirming the neotectonic activity, the test of difference between two means of lineament azimuths from the Cijolang and Cimuntur Rivers was done, as well as the test for river-segment azimuths from both rivers (Table 3).

Table 2. Tests of difference between two means of lineament and river-segment azimuths; pair samples

<table>
<thead>
<tr>
<th>Variable Tested</th>
<th>Variable means</th>
<th>n1/n2</th>
<th>tcalc</th>
<th>t .05</th>
<th>t .01</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X (Cijolang)</td>
<td>Y(Cimuntur)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lineament</td>
<td>85.282</td>
<td>91.045</td>
<td>39/44</td>
<td>0.508ns</td>
<td>1.990</td>
</tr>
<tr>
<td>River segment</td>
<td>83.000</td>
<td>90.227</td>
<td>39/44</td>
<td>0.651ns</td>
<td>1.990</td>
</tr>
</tbody>
</table>

Note: *ns*) difference not significant

Table 3. Tests of difference between two means of lineament azimuths from Cijolang and Cimuntur Rivers, and river-segment azimuths from the respective rivers; independent samples

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Variable means</th>
<th>df</th>
<th>tcalc</th>
<th>t .05</th>
<th>t .01</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X (lineament)</td>
<td>Y (river-segment)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cijolang River Basin</td>
<td>85.282</td>
<td>83.000</td>
<td>38</td>
<td>1.965ns</td>
<td>2.022</td>
</tr>
<tr>
<td></td>
<td>91.045</td>
<td>90.227</td>
<td>43</td>
<td>0.845ns</td>
<td>2.010</td>
</tr>
</tbody>
</table>

Note: *ns*) difference not significant
The results indicate both the means of lineament patterns and the river-segment patterns from the respective rivers are not significantly different. These confirm that the tectonic controls all the lineament patterns from different distribution areas of Tertiary and Quaternary sediments, separated by an unconformity. The lineament pattern in the Cimuntur river basin is generated by recent surface deformation in Quaternary volcanic breccia due to active tectonism. Again, all the river-segment patterns representing the morphological development of the river systems in their respective basins are governed by the active tectonism until the present time. This suggests that the tectonic movement may be active since the Tertiary.

3. Relationship of Lineament and River-segment

The result of regression-correlation analysis indicates a significant relationship between the two above-mentioned variables (Fig. 3a). The result of the regression-correlation analysis verifies how close is the relation between lineament pattern and the river-segment pattern for the Cijolang River. The correlation coefficient \( r \) is 0.989 and large. The linear regression formula constructed from the analysis is:

\[
Y = -0.187 + 0.975 \times X, \text{ and} \quad r = 0.989.
\]

The result of analysis for the Cimuntur River basin also indicates the same phenomenon (Fig. 3b). The constructed linear formula is:

\[
Y = 2.155 + 0.967 \times X, \text{ and} \quad r = 0.993.
\]

The diagrams in Figure 3a and 3b show that the straight lines indicate the constants of proportion of nearly 1. The lines clearly explain that every plotted point on the diagrams represents the almost same value of the lineament and the river-segment azimuths on X-axis and Y-axis respectively.

**Drainage Density and Bifurcation Ratio**

Bifurcation ratio \( \left( R_b \right) \) and drainage density \( \left( D_d \right) \) of sub-basins of the above-mentioned river basins were obtained for the samples randomly taken from drainage networks prepared from compilation of topographic map and aerial photo interpretation. The numbers of the samples from the respective rivers are 36 and 32.

Drainage density \( D_d \) is ratio of the total length of all rivers within a drainage basin \( L \) to the area of that basin \( A \) and \( D_d = L / A \). Bifurcation ratio \( R_b \) is ratio of total number of rivers of order \( u \) to the number of rivers of order \( u+1 \), \( R_b = N_u / N_{(u+1)} \) (Strahler, 1975).

The purpose of multivariate analysis of the difference between two means in Table 4 is to confirm the morphological development of the Cijolang and Cimuntur river basins as a result of active tectonism. The result of this simultaneous difference test between the mean values of \( R_b \) and \( D_d \) representing Cijolang River on one side and those variables means from the Cimuntur River on the other side is not significant.
Figure 6. Scattered-point diagrams representing relation of lineament azimuths and river-segment azimuths of (a) Cijolang river, and (b) Cimuntur river.

Table 4. Multivariate test of difference between morphometric variable means of Cijolang river basin and the variable means of Cimuntur river basin

<table>
<thead>
<tr>
<th>No</th>
<th>Variables</th>
<th>Cijolang river basin Mean value</th>
<th>Cimuntur river basin Mean value</th>
<th>$T^2_{.10}$</th>
<th>$T^2_{calc.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bifurcation ratio, $R_b$</td>
<td>3.9228</td>
<td>3.8350</td>
<td>4.458</td>
<td>2.639$^{ns}$</td>
</tr>
<tr>
<td>2</td>
<td>Drainage density, $D_d$</td>
<td>4.2319</td>
<td>3.8732</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: $^{ns}$ difference not significant

The result of the test suggests that the morphology of the Cimuntur River, developing on the Quaternary volcanic breccia, is the same with the Cijolang River morphology on Tertiary Halang Formation which is affected by the active tectonisms. Since the tectonisms is active, the recent deformation pattern in both Quaternary and Tertiary rock units is the same. As a result of the neotectonic activity, the morphology of those river basins having been governed by the deformation pattern should be the same.

CONCLUSION

Neotectonic activity related to the regional framework of the region between Baribis-Majenang Faults System and Ciawi-Pangandaran Faults System and the morphometric features of the region can be concluded as follows. The results of all the statistical tests in the foregoing, namely tests of difference between two means and the regression-correlation analyses, indicate the tectonisms is active until the present time.

Both the means of lineament azimuths and river-segment azimuths obtained from the Cijolang and Cimuntur River basins are not significantly different. These tests verify that morphology development of Cimuntur River on Quaternary volcanic breccia is governed by lineament pattern in the river basin, which is the same as that on the Tertiary sediment due to active tectonisms, even being
separated by an unconformity. This tectonic morphometry phenomenon has been verified as the effect of active tectonism on drainage networks development.

Furthermore, the regression-correlation analyses has identified and indicated that the directional relationships of the lineament and river-segment for both Cijolang and Cimuntur Rivers are very significant. This result of the analyses gives a conclusion that the river-segment orientation of both the rivers significantly depends on the direction of the lineament. This conclusion is also supported by the value of the coefficient of proportion almost equal to 1 in the regression formulae as it means that the direction of every river-segment is the same with (is governed by) the direction of the nearest lineament.

The development of river-segment pattern of mainly the Cimuntur River is governed by generated recent deformation pattern in the Quaternary volcanic breccia, which is the same with the deformation pattern in the Tertiary sediments due to the neotectonic activity.

At last, the result of multivariate analysis of difference between two means of morphometric variables $R_b$ and $D_d$ of both the above-mentioned rivers also suggests that the morphology of the Cimuntur River, developing on the Quaternary volcanic breccia, is the same with the Cijolang River morphology on the Tertiary Halang Formation, and both are governed by the recent deformation pattern under the active tectonic control.

The results of all the foregoing statistical analyses give the conclusion that recent deformation patterns in both Quaternary and Tertiary rock units are generated by the neotectonic activity, which causes the same morphometric features of the river basins occurring in the respective rock units separated by the unconformity.

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*) in Indonesian with English Abstract