

GEOMORPHOLOGY, LITHOSTRATIGRAPHY, AND STRUCTURAL INFLUENCE ON KARST LANDSCAPE EVOLUTION IN THE SELASARI AREA, SOUTHERN WEST JAVA

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ABSTRACT

This study investigates the geomorphological characteristics and geological evolution of the Selasari area, Southern West Java, with emphasis on the interaction between lithostratigraphy, tectonic evolution, and karst landscape development. The objectives are to characterize the geomorphological and lithostratigraphic framework, analyze structural control on landscape development, and reconstruct the geological evolution of the area. An integrated approach combining morphographic, morphometric, morphogenetic, lithostratigraphic, and structural characterization from DEM-based interpretation and field observations was applied. The study area is characterized by karst low hills developed on carbonate-dominated lithologies deposited in a shallow marine environment during the Middle–Late Miocene. Structural analyses suggest a dominant NW–SE orientation that may influence drainage development and valley alignment, possibly associated with tectonic activity related to regional subduction processes along southern Java and subsequent uplift during the Plio–Pleistocene. The integration of geomorphological, lithostratigraphic, and structural evidence suggests that the geological evolution of the study area records a transition from shallow marine carbonate deposition to a tectonically uplifted karst terrain. These findings contribute to a better understanding of karst landscape evolution in the Southern Mountains of Java and highlight the importance of integrated geological approaches for understanding structurally controlled karst systems and supporting geological mapping.

Keywords: carbonate platform, karst landscape, Southern mountains, structural control, West Java

INTRODUCTION

Java Island was formed by the continuous subduction process between the Indo-Australian and the Eurasian Plate from the Late Cretaceous to Recent (Smyth et al., 2008). This process later forms crustal deformation, arc magmatism, and sedimentary basin development, resulting in a highly heterogeneous geological framework (Hall, 2017; Hall & Spakman, 2015).

The complex subduction process can be observed in the southern part of Java Island, namely the Southern Mountains Zone (van Bemmelen, 1949). It is characterized by folding and uplifted terrain that has undergone deformation since the Miocene. This area also developed the karst system that formed between the Middle to Late Miocene. These two characteristics indicate an interaction between the development of the carbonate

environment and regional structural controls, which is reflected in the tectonic uplift process of the Sunda Arc.

To better understand the interaction between tectonic control and the karst system, this research analyzes the influence of geomorphological processes. It includes the endogenic forces such as tectonics processes that drive faulting and joints, as well as exogenic forces such as chemical weathering (karstification) and erosion. Furthermore, this research also includes lithostratigraphic characteristics such as detailed rock physical properties, depositional environments, relative rock age, and stratigraphic relationships. By integrating all of this data from various sources, geological history reconstruction provides a more complete view of the evolution that occurred on Earth's surface.

Previous studies in the Selasari area predominantly addressed regional geological conditions at a general scale, with limited emphasis on detailed tectonic evolution that influenced geomorphological and lithological characteristics. Several studies have discussed geological evolution and tectonic development in southern Java, particularly within volcanic settings; however, studies integrating tectonics, geomorphology, and stratigraphy to reconstruct geological evolution in a karst context remain limited. In particular, the interaction between tectonic processes, karst geomorphology, and stratigraphic development in the study area from the Miocene to recent times has received limited attention.

Based on the introduction, this research aims to: (1) Characterize the geomorphological and

lithostratigraphic framework of the study area through morphographic, morphometric, morphogenetic, and lithological characterization, including depositional environments, relative ages, and stratigraphic relationships; (2) Analyze the influence of geological structures and tectonic evolution on the geological development of the study area; and (3) Reconstruct the geological evolution through the integration of geomorphological, stratigraphic, and structural data.

The study area is located in Parigi and Langkaplancar Districts, Pangandaran Regency, West Java Province, specifically within Selasari Village, and exhibits representative geological features of the processes shaping the region (Figure 1).

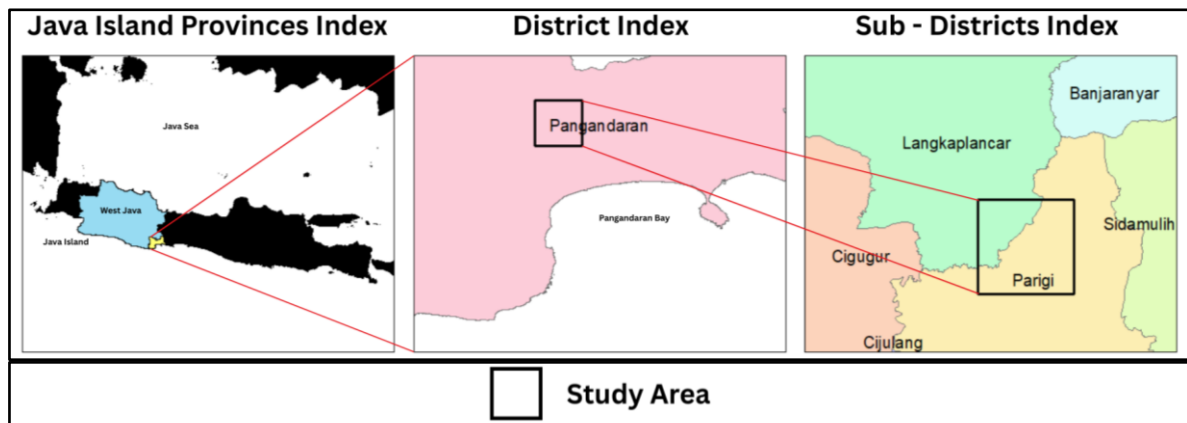


Figure 1. Study Area in Selasari Village, Parigi Sub - District

REGIONAL GEOLOGY

Stratigraphic Framework

The stratigraphic succession of the study area consists of rock units that exhibit relatively similar ages and depositional environments, dominated by the Pamutuan Formation (Tmpa) (Simandjuntak and Surono, 1992). The study area is composed of rock units ranging in age from the Middle to Late Miocene, consisting of sandstone, calcarenite, marl, tuff, claystone, and clastic limestone. Limestone occurrences generally occupy the margins of the Jampang volcanic hills and occur as isolated bodies in several locations (Haryanto, 2018). The depositional environment of the Pamutuan Formation corresponds to a shallow marine, neritic to open marine setting (Simandjuntak and Surono, 1992). These deposits represent the sedimentation processes in the carbonate environment with the influence of siliciclastic material, forming a stratigraphic succession that reflects depositional processes and environmental conditions.

This formation comprises several members

that were deposited contemporaneously and developed in an interfingering relationship with one another, namely the Marly Tuff Member (Tmpt), which consists of marly tuff interbedded with sandstone, claystone, and limestone. And the second member is the Calcarenite Member (Tmpl), which consists of calcarenite and clastic limestone, interbedded with marl.

Structural Framework

There are three dominant structural lineament orientations recognized in Java Island, namely the Meratus Pattern (NE-SW), Sunda Pattern (N-S), and Java Pattern (W-E) (Pulunggono and Martodjojo, 1994). Within West Java, these regional structural trends are expressed by four dominant fault orientations, namely NE-SW, N-S, W-E, and NW-SE (Faisal Hilmi and Haryanto, 2008) (Figure 2). The NW-SE trending faults are not included in the Meratus, Sunda, or Java Patterns, but are referred to as the Sumatra Pattern, based on their orientation parallel to the long axis of Sumatra Island (Faisal Hilmi and Iyan Haryanto, 2008).

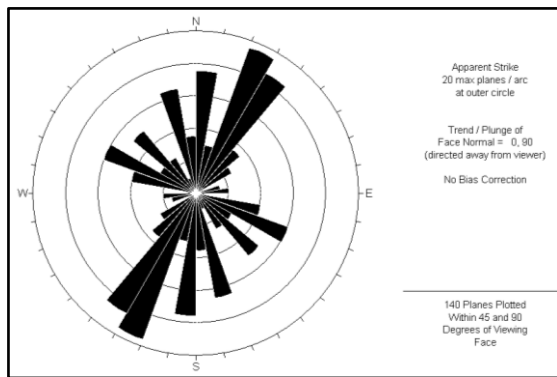


Figure 2. West Java stress pattern (Faisal Hilmi and Iyan Haryanto, 2008)

Regionally, the structures developed in the study area originated from three tectonic episodes, which are the Eocene, Oligocene–Miocene, and Pliocene–Pleistocene tectonic episodes. The study area first experienced a tectonic phase during the Eocene, when subduction activity was initially established. This subduction process continued to influence the area during the Oligocene–Miocene period as an extensional regime. The tectonic regime during this time reactivated pre-existing structures and initiated the early development of the Southern Mountains belt, which is currently exposed onshore to the south. Furthermore, the study area underwent continued deformation due to uplift associated with folding and faulting caused by compressional force, as a result of increasing tectonic intensity during the Pliocene–Pleistocene tectonic episode. This process ultimately contributed to the uplift of the Southern Mountains zone within the study area. The eastern to southeastern sector of the Southern Mountains is characterized by NW–SE and N–S trending normal faults that deform both Tertiary and Quaternary rock units. These regional fault systems continue toward Pangandaran and are referred to as the Citanduy Fault (Subagio, 2018). Previous fault-related studies using geophysical methods have also contributed to the presence of normal faults and an anticline structure indication within the study area (Adiltha et al., 2024). However, the anticline identified in the previous study was not observed in the present investigation.

RESEARCH METHOD

Data Gathering

This study consists of both primary and secondary geological data. Primary data follows standard geological mapping procedures that are usually applied in detailed surface geological investigations, consisting of direct field observations. It is focused on geomorphology, lithology, stratigraphy, and geological structures analysis. The methods

applied during field observation include terrain orientation, outcrop identification, structural measurements, field documentation and sketching, and rock sampling for further petrographic and paleontological analyses.

Secondary data was obtained by using the Digital Elevation Model (DEM) data obtained from the National Digital Elevation Model of Indonesia (DEMNAS) and Indonesian Topographic Maps (RBI) data obtained from the Indonesia Geoportal. The DEM data were processed in a raster format and projected in the national coordinate reference system (WGS 1984) for further analyses. A base map at a scale of 1:12,500 was generated through digitization of RBI topographic data and later used as the primary spatial framework for all data visualization.

Geomorphological Analysis

The morphographic map was generated using DEMNAS data processed with GIS software. Morphographic analysis was conducted by classifying landforms based on absolute elevation in the study area and later divided into four out of seven classes in the Van Zuidam (1985) classification. Morphographic analysis also includes valley shapes, and the classification of river drainage patterns.

Valley shapes were identified qualitatively through field observations, distinguishing between blunt U-shaped valleys, which are characterized by relatively flat valley floors where lateral erosion dominates and vertical erosion is minimal, and sharp V-shaped valleys, which are characterized by intense vertical erosion influenced by tectonic activity (Van Zuidam, 1985).

Drainage pattern classification was conducted based on analyzing the visual river pattern on RBI data, examining the incisions of intermittent and main river channels. These were later compared to the Howard (1967) in Van Zuidam (1985) classifications. The results were validated by comparing them to the RBI and adjusted to field conditions. Drainage orientations were measured based on the azimuth of stream segments derived from the drainage network and later compared with valley lineament orientations.

Morphometric characterization was conducted through DEM-based slope classification to characterize terrain steepness and its relation to geomorphological processes using a semi-quantitative geomorphological approach. Slope values were expressed in degrees and classified according to Van Zuidam (1985), which in this study area was classified into six classes, namely flat (0°–2°), gently slope (2°–4°), sloping (4°–8°), slightly steep (8°–16°), steep (16°–35°), and very steep (35°–55°).

Morphogenetic is classified into endogenic processes (volcanism and tectonics) and exogenic processes (weathering and erosion), based on lithology and geological structures from the field observations. This interpretation was supported by the analyses of structural features and lineaments to assess tectonic influence, as well as dissolution features, cave systems, and multibasinal drainage patterns to indicate karstification. These processes were then integrated with morphographic and morphometric aspects to interpret landform development according to the Van Zuidam (1985) classification.

Geological Structure Analysis

The geological structure of the study area was first analyzed through the interpretation of DEM imagery to determine the orientation of valley and ridge lineaments. The lineaments were interpreted visually based on morphological contrasts, hillshade patterns, topographic alignment, and abrupt river deflection. Each identified lineament was then measured for its azimuth and classified into specific angular intervals. The orientation data were then visualized and quantitatively analyzed using rosette diagrams to determine the dominant lineament directions, as a support for the interpretation of geological structure data obtained from field observations.

In direct field observations, the identification of faults is indicated by the presence of fault planes, displacement of bedding (offset), and minor structural features such as slickensides containing slicken lines. Structural data in the form of slickensides can be used to determine the type of fault based on the classification of Rickard (1972). The parameters required for fault type determination include strike, dip, pitch, and sense of movement determined from the orientation of slicken lines. Joint data can be used to predict the occurrence of fault structures in the study area, based on the Anderson (1951) fault classification. These data were subsequently input into Dips, ArcGIS, and Win-Tensor software to interpret fault geometry and determine the orientation and type of faults from the maximum principal stress (σ_1) estimation.

Stratigraphic Analysis

Stratigraphic analysis was conducted by constructing a measured stratigraphic section and stratigraphic profile to identify the sedimentation processes that occurred. This identification is based on sedimentary structures, lithological thickness, and contacts between lithologies. In the lithology classification, an informal lithostratigraphic framework based on the Indonesian Stratigraphic Code (1996) is applied. It is used

differences in physical characteristics such as rock color, grain size, grain shape, roundness, sorting, fabric, hardness, and sedimentary structures observable at the megascopic scale, as well as lithological uniformity and stratigraphic position between lithologies as the basis for distinction. These classifications are then correlated with formal nomenclature established by previous studies to support the determination of rock units.

Based on these considerations, unit boundaries are delineated by considering topographic conditions, strike patterns, cross-sections, lithology, and lithological uniformity. The boundary lines between units are interpreted surfaces and are therefore considered arbitrary boundaries. The nomenclature is then arranged based on depositional age which is determined through fossil analysis and the correlation with the regional geology to establish the stratigraphic relationships.

The depositional environment analysis follows the reef zonation classification of Pomar (2004), particularly for units composed of limestone (Figure 3). This depositional model is primarily used to describe clastic limestone systems, particularly within ramp or reef-type carbonate platforms controlled by marine energy dynamics and biotic distribution. This classification incorporates carbonate rock textures and biotic components as indicators of depositional environments, which are interpreted based on their position from the littoral to inner neritic zones (0–50 m depth).

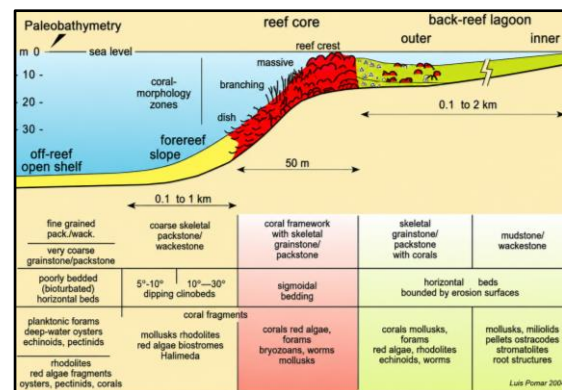


Figure 3. Carbonate depositional environment model (Pomar, 2004)

Laboratory Analysis

Paleontological analysis is conducted to identify fossil content, with a focus on planktonic and benthic foraminifera, in order to determine fossil distribution, age, and depositional environment (bathymetric zones). The analysis is carried out using microscopic examination following sample preparation stages, including mechanical disaggregation, chemical treatment using

NaOH and hydrogen peroxide, sieving, and drying, followed by fossil picking and taxonomic identification.

Petrographic analysis includes the description of mineral composition, relationships, and formation processes at the microscopic scale. This analysis is conducted using a polarizing microscope on thin section samples to classify the rocks in detail. The classifications applied include sedimentary rocks based on Pettijohn (1987) and limestones based on Dunham (1962).

RESULT AND DISCUSSION

MORPHOGRAPHY

Morphographic analysis reveals variations in landforms and drainage patterns that reflect lithological and structural control.

Landforms

The study area is divided into four landform classes distinguished by elevation values ranging from 50 to 200 m above sea level (Van Zuidam, 1985). The lowland (< 50 m) and inland lowland (50–100 m) classes are limited to the southeastern part of the study area. The low hills class (100–200 m) is the dominant class, occupying the central part and being evenly distributed, while the hills class (200–500 m) occupies only a small part of the southwestern area (Figure 5a).

Drainage Pattern

The multibasinal drainage patterns development is influenced by erosion and weathering of limestone lithology. These patterns form through the dissolution of calcium carbonate (CaCO_3) by meteoric water, representing the dominant chemical weathering process in the area. This dissolution creates subsurface pathways that allow surface streamflow to infiltrate underground cave systems or bedrock fractures.

The sub-dendritic drainage pattern is accompanied by numerous tributaries that join the main channel at obtuse and acute angles (Figure 5b). The drainage network exhibits a branching pattern with flow directions that indicate minor structural controls. This interpretation is supported by observations that some streams show deflections attributable to structural features.

The parallel drainage in the study area is not dominant, as indicated by stream channels flowing relatively in parallel directions, following slope gradients and terrain linearity (Figure 5b).

Drainage patterns in the study area indicate a geological structure involvement reflected in the drainage system, where river channels

show azimuth deflections and flow alignments that are oriented in the NW–SE directions. This trend ranges from 110° to 140° , and the valley lineaments range from 120° to 160° (Figure 4). This similarity suggests that river channels preferentially follow the zones of structural weakness, such as valley and ridge formation.

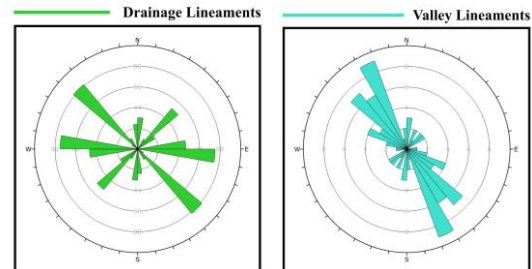


Figure 4. Comparison between valley lineament and river orientation

MORPHOMETRY

Slope gradient provides an overview of topographic steepness and its relationship with exogenic processes. Based on slope gradient values, the study area was classified into six classes, namely flat, gently sloping, sloping, slightly steep, steep, and very steep (Van Zuidam, 1985) (Figure 5a).

Slope Class Distribution

The study area contains very limited coverage of flat (0° – 2°) and gently sloping (2° – 4°) classes, which covers the southern and northeastern area, while the sloping class (4° – 8°) is the most dominant and evenly distributed. The slightly steep (8° – 16°), steep (16° – 35°), and very steep (35° – 55°) slope classes are also evenly distributed (Figure 5a). Similar slope characteristics have also been observed in previous studies in the southeastern part of the study area, where the average slopes found are categorized as very steep because they have a slope between 35° and even more than 55° (Hermanto et al., 2020). These steeper slope classes generally follow valley forms in the northwestern and southeastern parts of the area, as well as karst hills in the central part of the area. This slope distribution reflects the dominance of karst low hill morphology, where moderate slopes are controlled by limestone dissolution processes and structural influences.

MORPHOGENESIS

The development of the Selasari landscape is the result of dynamic interactions between endogenic and exogenic processes.

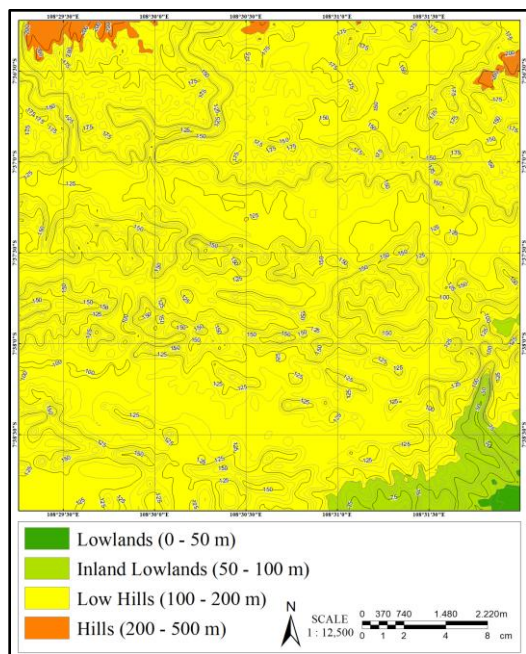
Endogenic Processes

The main endogenic processes are tectonic activity. Tectonic activity is expressed by geological structure features, whose presence

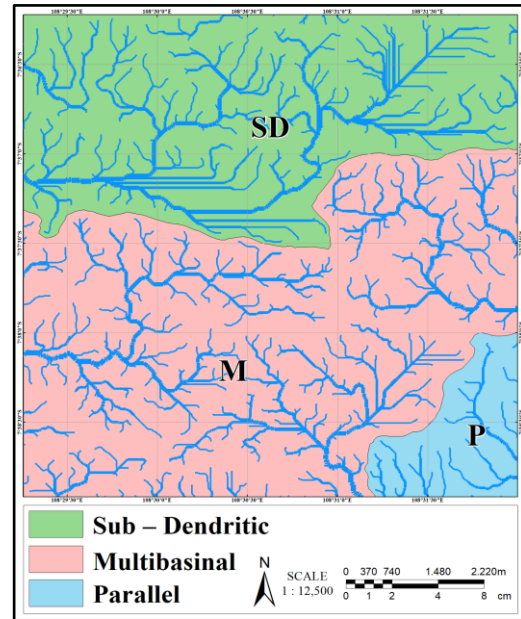
indicates tectonic control on surface morphology. This is supported by the dominant NW–SE drainage lineaments trend, which is indicated to be associated with the uplift of the Southern Mountains initiated by subduction processes during the Pliocene–Pleistocene. This uplift increases surface relief and slope gradients, enhancing surface runoff and limestone dissolution, which enhances karstification under structural control. Faults and joints provide pathways for water infiltration, accelerating dissolution and promoting karst features such as caves and multibasinal drainage systems. The interaction between uplift and weathering suggests that the karst landscape is dynamically evolving, with tectonic activity influencing geomorphic processes.

Exogenic Processes

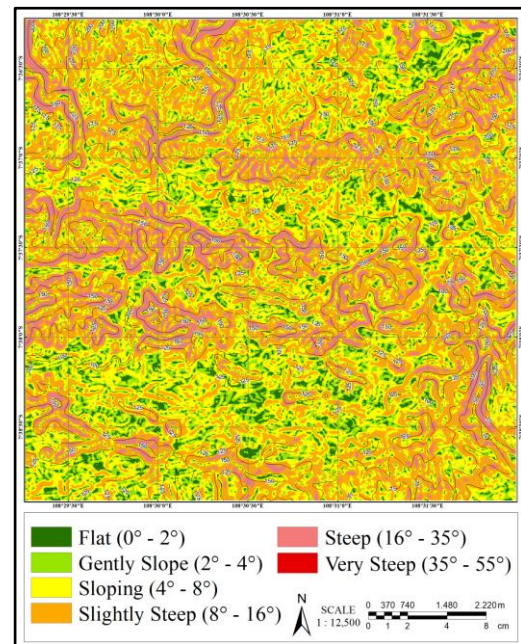
In the study area, the main exogenic processes are influenced by the lithology of the constituent rocks, consisting of weathered reef limestone fragments that have undergone erosion and redeposition. This sequence reflects an erosional phase. Subsequently, the limestone experienced chemical weathering in the form of karstification. It is intensely developed along river courses, forming sharp V-shaped valleys and multibasinal drainage patterns. This interpretation is supported by the presence of cave systems formed by intensive limestone dissolution, producing karst landscapes and exposed limestone hills.



(a)



(b)



(c)

Figure 5. (a) Landform map; (b) Drainage pattern map; (c) Slope gradient map of the study area

GEOMORPHOLOGICAL UNITS

The geomorphological units of the study area can be classified into three units, namely Sloping Karst Low Hills, and Slightly Steep Karst Low Hills, Slightly Steep Structural Low Hills (Figure 6a). This was carried out by analyzing geomorphological aspects followed by zoning based on the dominance of each aspect within the study area.

The primary diagnostic criteria for the Sloping Karst Low Hills and Slightly Steep Karst Low

Hills unit classification are lithological control and dominant geomorphological processes. These units were formed through uplift processes, as reflected by the uplifted carbonate platform that developed into low hilly landforms. These karst units are characterized by massive limestone lithology, chemical dissolution features such as caves, and multibasinal drainage patterns, indicating dominant karstification processes controlling the area. These units are distinguished by slope gradients and valley shape as shown in the geomorphological table (Table 1).

The Slightly Steep Structural Low Hills unit covers approximately 9% of the study area and is located in the northwestern area (Figure 6). It is classified by lithological control, dominant geomorphological processes, and structural influence. It is distinguished based on its genetic characteristics. This unit classification as a structural unit is based on sandstone-dominated lithology, faults and joints that control landforms, and drainage patterns influenced by minor structural features.

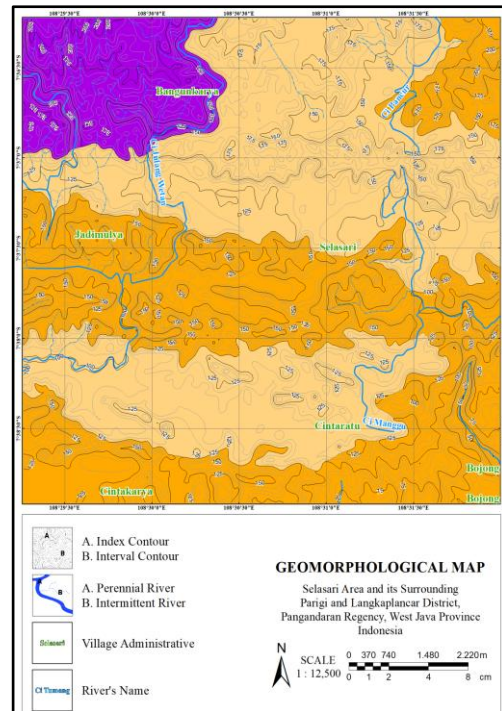


Figure 6. Geomorphological Map of the study area

Table 1. Geomorphological units of the study area and the explanations

No	Geomorphological Unit	Symbol	Geomorphological Aspects							
			Morphography			Morphometry		Morphogenetic		Constituent Lithology
			Landform and Elevation (m)	Valley Shape	Drainage Pattern	Slope Class (°)	Endogenous	Exogenous		
1	Sloping Karst Low Hills		Low Hills (50-175)	Blunt V	Sub-Dendritic - Multibasinal	Sloping (4-8)	Tectonism		Packstone and Wackestone	
2	Slightly Steep Karst Low Hills		Low Hills (50-150)	Sharp V	Multibasinal - Parallel	Slightly Steep (8-16)	Tectonism	Erosion & Weathering	Packstone, Wackestone, and Sandstone	
3	Slightly Steep Structural Low Hills		Low Hills (125-200)	Sharp V	Sub-Dendritic	Slightly Steep (8-16)	Tectonism & Volcanism		Sandstone and Tuffaceous Sandstone	

These geomorphological conditions indicate that geomorphic processes in the study area are controlled by the interaction between endogenic and exogenic processes, where tectonic uplift enhances surface gradients and structural control, while chemical weathering and erosion continue to modify the landscape. This interaction results in a dynamic geomorphological system, reflecting continuous landscape evolution in the Southern Java karst region.

LITHOSTRATIGRAPHY

Based on field observations and laboratory analyses, the stratigraphy of the study area can be divided into three informal lithostratigraphic units (Figure 7), arranged from the oldest to the youngest as follows.

Sandstone Unit (Tmbpk)

This unit is dominantly composed of

sandstone, with localized occurrences of tuffaceous sandstone containing volcanic tuff material. Megascopically, grain sizes ranged from fine sand (0.125–0.25 mm) to coarse sand (0.5–1 mm). This unit reacts when treated with 0.1 N HCl solution, indicating its carbonate nature and suggesting a marine depositional environment. This unit displays sedimentary structures such as ripple marks, indicating deposition under low to moderate energy conditions. Petrographic analysis shows sub-rounded grain shapes, moderate sorting, and a matrix-supported texture, with the matrix dominantly composed of clay minerals and carbonate cement. Based on these characteristics, the unit is classified as lithic greywacke sandstone (Pettijohn, 1975). Planktonic foraminifera, including *Globigerina bilobata*, *Globigerinoides bollii*, *G. subquadratus*, *G. ruber*, *Trilobatus trilobus*, and *G. italicus*, indicate a Middle Miocene age (N9–N13) (Blow, 1969).

Packstone Unit (Tmbgp)

This unit consists of clastic limestone derived from the accumulation of reworked carbonate fragments. Packstone type is relatively dominant, with minor occurrences of wackestone and sandstone. Megascopically, it is characterized by calcarenite-sized grains (2 mm), composed of organic remains such as coral and reef debris. This unit is massive and laterally extensive, forming karst hills in the study area. Petrographic analysis reveals the presence of skeletal fragments, including larger foraminifera and accumulations of microfossil shells, as well as non-skeletal grains such as ooids. This unit is composed of carbonate and minor oxide minerals. The matrix consists of micrite (microcrystalline carbonate) formed from the deposition and breakdown of carbonate material and microfossil debris, while sparite cement reflects diagenetic recrystallization of carbonate (calcite). Depositional texture is preserved, with grains not bound to each other and containing carbonate mud; however, the texture is grain-dominated. Based on its depositional characteristics, this unit is classified as packstone (Dunham, 1962). It is interpreted as allochthonous, indicated by fragmented grains and components reflecting transport processes. No planktonic foraminifera were identified; thus, the age is constrained by larger foraminifera analysis (*Amphistegina* sp., *Heterostegina* sp., and *Palaeonummulites* sp.), supported by regional correlation

(Simandjuntak and Surono, 1992), indicating a Middle Miocene age.

Wackestone Unit (Tmbgw)

This unit is dominated by wackestone, with minor occurrences of packstone. Megascopically, it is characterized by calcarenite-sized grains (2 mm), occurring as massive and laterally continuous deposits. Microscopically, the grains consist of skeletal fragments, including larger foraminifera and accumulations of microfossil shells, along with carbonate and minor opaque minerals. The matrix is dominated by micrite in significant amounts, with sparite cement. Depositional texture is preserved, with unbound components and mud-supported fabric, although grain content exceeds 10%. Based on these depositional characteristics, the rock is classified as wackestone (Dunham, 1962). The unit is interpreted as allochthonous, indicated by calcarenite-sized grains and fragmented biogenic components. Larger foraminifera such as *Discocyclus* sp. and *Heterostegina* sp., supported by regional correlation (Simandjuntak and Surono, 1992), indicate a Middle Miocene age.

The source of reworked carbonate material forming the clastic limestone in the study area may have originated from solitary boundstone to grainstone limestones developed in a patch reef environment (Haryanto, 2018). However, these limestone types were not identified within the study area.

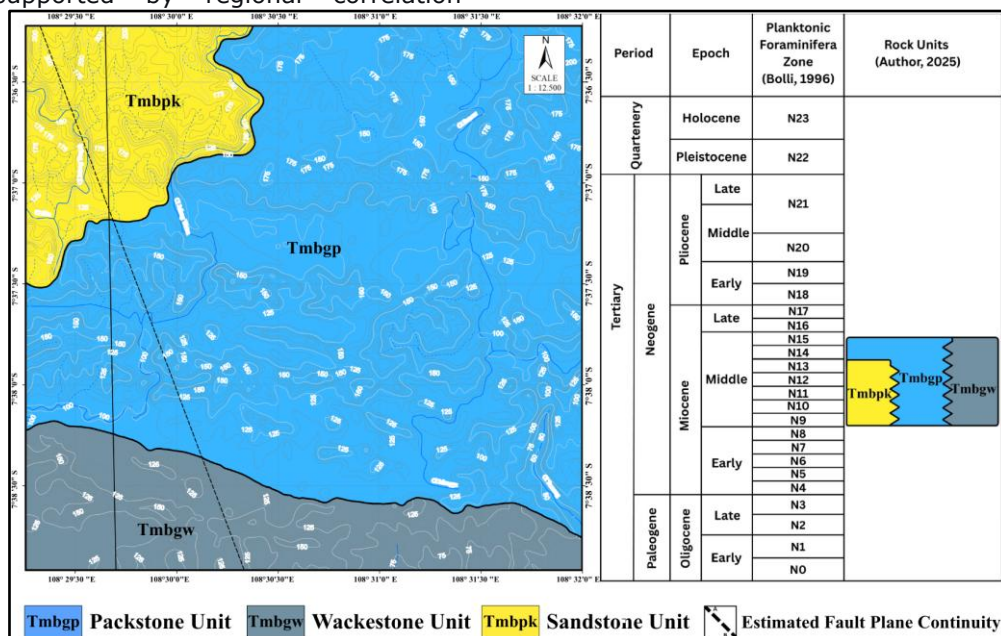


Figure 7. Geological map and lithostratigraphic column of the study area

Depositional Environment

The depositional environment of the sandstone unit is interpreted based on the

presence of benthic foraminifera such as *Operculina* sp. and *Triloculina tricarinata*, which indicate a middle to outer neritic setting (50–150 m depth). It is supported by

analyzing ripple mark structures that were found. This sedimentary structure indicates oscillatory (back-and-forth) flow conditions, typically generated by wave action in shallow marine environments or nearshore settings. The presence of locally distributed volcanic material (tuff) indicates that the depositional environment was influenced by shallow marine volcanic activity during the Oligocene to Miocene volcanic events, associated with the massive volcanic rocks formation (Jampang Formation) on the Southern Mountains belt, due to subduction activity along the southern margin of Java Island.

On the other hand, based on megascopic, microscopic, and fossil analyses, the packstone unit is interpreted to have been deposited in a reef-related setting, specifically within the reef core to outer back-reef transition zone (Pomar, 2004). This interpretation is supported by its grain-supported texture (55–60% grains), the presence of ooids, high amounts of skeletal fragments (including larger foraminifera and coralline algae), and its massive structure. The coexistence of micritic matrix and sparite cement indicates moderate to relatively high-energy conditions without strong directional currents, while the allochthonous nature of the components suggests transport from adjacent reef environments.

The wackestone unit is interpreted to have been deposited in an inner back-reef lagoon setting. This is supported by its mud-supported texture, the dominance of micritic matrix (50%), and the presence of microfossil fragments and also larger foraminifera such as *Discocyclusina* sp. and *Heterostegina* sp. These organisms require a good amount of sunlight and low turbidity, implying that the depositional setting is shallow, low-energy, and connected within a carbonate platform system.

The differences in depositional environments between the sandstone and limestone lithologies in the study area can also be explained by variations in foraminiferal abundance. As marine environments become deeper, the abundance of foraminifera generally decreases. In contrast, shallower depositional environments are characterized by higher foraminiferal abundances. (Winantris et al., 2024). This relationship explains why the limestone in the study area contains high amounts of skeletal fragments.

Stratigraphic Relationship

Based on relative age, cross-section reconstruction, and lithological contacts and distribution, this unit exhibits an interfinger stratigraphic relationship with the packstone unit. The sandstone unit, dated to the Middle

Miocene (N9–N13), was deposited contemporaneously with the packstone and wackestone units (Figure 7). However, its deposition ceased earlier, while carbonate sedimentation continued. Consequently, the sandstone unit is conformably overlain by the packstone unit, as supported by lithological contacts indicating its lower stratigraphic position.

The packstone and wackestone units exhibit an interfinger relationship. This is supported by their similar depositional age, both assigned to the Middle Miocene. Lithological distribution further indicates that these units intercalate and laterally transition into one another, reflecting lateral facies variations within the same carbonate depositional system, without significant temporal breaks in sedimentation. This stratigraphic relationship is consistent with the interpretation that the Pamutuan Formation comprises several members deposited contemporaneously and exhibiting interfingering relationships (Simandjuntak and Surono, 1992).

GEOLOGICAL STRUCTURE

The geological structure interpretation was initiated through remote sensing analyses using DEM data. Field observations were then conducted to examine structural features, including slickensides and other indicative structures. The results reveal the presence of lineament patterns, fault planes and slickensides, as well as joints, which collectively provide insights into the structural history of the study area.

Lineament Pattern

Based on DEM data interpretation, ridge features within the study area are identified with dominant lineament orientations of NW–SE to W–E (Figure 8a). These ridges are likely associated with having formed under compressional tectonic forces during the Pliocene–Pleistocene tectonic period. It is linear with the regional tectonic regime of the Pliocene–Pleistocene, which is characterized by predominantly compressional stress with a NE–SW orientation, resulting from the re-acceleration of subduction along the southern margin of Java Island during the Late Miocene after a prior decrease in velocity during the Oligocene.

This increase in subduction rate, reaching approximately 5–6.5 cm/year, led to intensified compressional tectonics that culminated during the Pliocene–Pleistocene. This compressional regime can be correlated with the Java structural pattern, which is characterized by dominant W–E-trending faults formed during the same period under a similar stress orientation. This compressional

tectonic phase may indicate the reactivating of the pre-existing faults in the study area and resulted in the uplift of shallow marine environments into terrestrial settings, driven by intense uplift and folding processes during that time.

The structural relationship between tectonic forces, lineament patterns, and the resulting structures can be explained using the pure shear deformation model (Moody and Hill, 1956). This model suggests that compressional stress may generate extensional structures, and vice versa, where extensional features tend to develop perpendicular to the principal compressive direction. Accordingly, the NW–SE orientation of lineaments in the study area is interpreted as a possible extensional response to regional NE–SW compressional stress during the tectonic period. This stress regime may have influenced the development of ridge and valley patterns that are also expressed by a dominant NW–SE orientation.

Fault Analysis

Based on the achieved field data, the plunge of σ_1 represents the most dominant stress controlling fault development in the study area. The high pitch values indicate relatively vertical movement along the fault plane, which is consistent with the maximum principal stress showing a steep dip of up to 84° , while the minimum stress remains relatively horizontal. The vertical orientation of σ_1 suggests that the dominant force is extensional, driven by gravitational processes (Figure 8b).

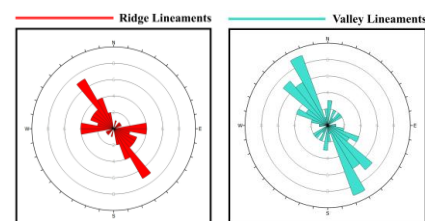
The direction of this extensional regime follows the minimum principal stress (σ_3), which is oriented NE–SW (246°), resulting in fault development perpendicular to this direction (NW–SE). Based on their geometry and kinematic characteristics, the faults are classified as normal-slip faults (Rickard, 1972). The stereonet analysis further suggests that faulting in the study area is controlled by a NE–SW-oriented stress regime. However, the continuity of this fault is not indicated by any other aspect except for this fault plane.

The normal-slip faults in the study area are shown to have a NW–SE trend, controlled by an extensional stress regime oriented NE–SW (Figure 8b). This suggests that it is possibly associated with the faulting developed during an extensional tectonic phase spanning the Oligocene to Miocene. This extensional regime is associated with the Sunda tectonic pattern (Eocene–Oligocene), which generated dominant N–S structural trends. The Sunda pattern is closely related to subduction along the southern margin of Java Island,

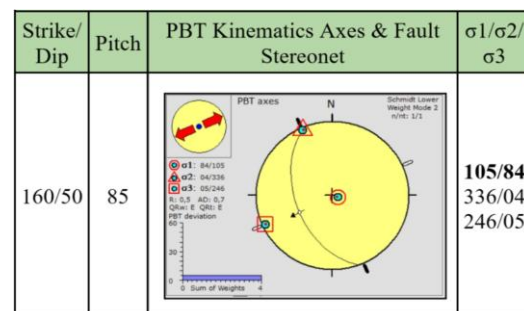
characterized by a convergence direction of approximately $N10^\circ E-N30^\circ E$ and an estimated rate of 18 cm/year. Towards the late Oligocene, the subduction rate decreased to around 3–4 cm/year while maintaining a similar direction, marking the onset of possibly the sedimentation and subsequent loading of Miocene-aged units in the study area. Therefore, it is potentially indicated that the faults in the study area were influenced by the Sunda tectonic regime and likely initiated during the Oligocene.

Joint Analysis

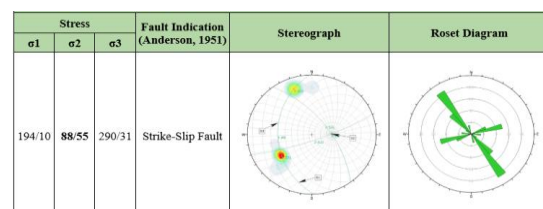
A total of 50 joint measurements were collected from the sandstone unit using the window scan method. Based on field data processed using Dips, σ_2 is interpreted as the dominant principal stress in the study area. The results indicate that σ_1 and σ_3 are relatively horizontal, whereas σ_2 tends to be vertical. These stress conditions are consistent with the development of strike-slip fault structures (Anderson, 1951) (Figure 8c).



(a)



(b)



(c)

Figure 8. (a) Lineament pattern showing ridges and valleys caused by stress orientation; (b) PBT axes showing fault type and stress orientations; (c) Fault indication based on joint data

Rose diagram analysis showed that the joints were formed under a dominant stress orientation of NE–SW, followed by NW–SE (Figure 8a). The clustered distribution of joint orientations on the stereonet supports regional stress control on joint formation. However, these results are not consistent with the fault patterns observed in the study area. This may reflect that the joints did not form simultaneously with, nor were they directly influenced by the existing faults. Instead, the joints could be linked to be controlled by the regional stress regime associated with the Java tectonic pattern during the Pliocene–Pleistocene. This assumption is supported by the fact that this tectonic phase commonly produces strike-slip faults trending NW–SE (Faisal Hilmi and Iyan Haryanto, 2008).

Geological History Reconstruction

Subduction along the southern margin of Java Island began in the Late Eocene, marked by a southward shift of the subduction zone. This tectonic activity subsequently led to the formation of a series of shallow marine volcanic arcs in southern Java. Subsequent volcanic activity produced the Jampang Formation, initiated during the Oligocene–Miocene.

During this period, the tectonic regime was dominantly extensional, with a stress orientation trending NE–SW, characterized by a convergence direction of approximately N10°E–N30°E. As a result, faults in the study area began to develop with a NW–SE trend, perpendicular to the extensional stress direction. Toward the Late Oligocene, the subduction rate decreased, allowing the study area to undergo sedimentation and loading processes within a shallow marine environment. These sedimentary processes are represented by units correlated with the Pamutuan Formation, including sandstone, packstone, and wackestone units. The presence of volcanic (tuffaceous) material within the sandstone unit reflects exposure to shallow marine volcanic activity associated with the formation of the Jampang Formation during the same period.

The deposition of carbonate and sandstone units indicates that during the Miocene, the study area was part of a shallow marine system, ranging from an inner back-reef lagoon environment (represented by the wackestone unit) to middle–outer neritic settings (represented by the sandstone unit). These three units are interpreted to have an interfinger stratigraphic relationship, characterized by lateral facies variations deposited within the same time interval (Miocene) and showing intercalation as well as lateral transitions between units. This entire

depositional sequence occurred during a period of relatively reduced tectonic activity, spanning from the Oligocene to the Late Miocene.

During the Pliocene–Pleistocene, tectonic activity intensified again, marking the onset of a compressional regime. This increase in tectonic intensity was driven by a rise in subduction rate to approximately 5–6.5 cm/year, while maintaining a similar stress orientation to the earlier extensional phase. The ridges and joints observed in the study area are products of this tectonic phase and are expressed perpendicular to the acting tectonic stress. This compressional activity ultimately uplifted the shallow marine depositional environment into a terrestrial setting and contributed to the formation of the Southern Mountains zone of West Java.

This tectono-stratigraphic evolution is evidenced by the present-day Southern Mountains, which consist of volcanic, clastic sedimentary, and carbonate rocks of the Oligocene–Miocene age. These processes were subsequently followed by erosion and the development of alluvial deposits during the Holocene.

CONCLUSION

This study demonstrates that the geomorphological and lithostratigraphic framework of the Selasari area is likely to be controlled by the interaction between tectonic activity and karst processes. Morphographic, morphometric, and morphogenetic characterization indicate that the landscape is dominated by karst low hills with sub-dendritic to locally parallel drainage patterns, while lithostratigraphic analysis shows that the study area consists of carbonate-dominated units deposited in a shallow marine environment during the Middle to Late Miocene.

The influence of geological structures and tectonic evolution is reflected in the dominant NW–SE structural trend, which controls drainage orientation and valley development. This structural pattern is associated with regional tectonic activity related to subduction processes along southern Java, followed by uplift of the Southern Mountains during the Pliocene–Pleistocene. This tectonic evolution has increased surface relief and facilitated structural pathways that enhance karstification processes.

The integration of geomorphological, stratigraphic, and structural data indicates that the geological evolution of the study area can be interpreted as a transition from marine carbonate deposition to tectonically uplifted karst terrain. This is potentially related to the

evolution of the study area, where continuous interaction between tectonic uplift and surface processes had an impact on the development of karst landforms. These discussions contribute to a better understanding of the indication of structurally controlled karst systems and highlight the importance of integrated analyses in geological mapping and its potential application in karst management and geological hazard assessment.

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