Grain Maturity and Sedimentary Processes of the Early Miocene Semilir Formation, Ngoro-oro Gunungkidul, Yogyakarta

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Abstract

The texture of sedimentary rocks is a fundamental aspect of sedimentation, reflecting the physical properties of particles and their relationships. Understanding rock texture is essential for interpreting depositional mechanisms and environments. Grain maturity represents a key property within sedimentary textures. The Early Miocene Semilir Formation is characterized by turbidite deposits with tuffaceous lithologies; however, the transport mechanism remains unclear. This study aimed to analyze the sedimentation process of the Semilir Formation by observing grain maturity. Granulometric analysis was conducted on three rock samples from the Ngoro-oro area, Gunungkidul Regency, Yogyakarta. The samples were ground, separated into size fractions, and statistically evaluated to determine quartiles, median diameter, sorting coefficient, skewness, and kurtosis. The results showed that the Semilir Formation consisted of immature grain sedimentary rocks, indicating that the sediments were deposited under moderate to high energy conditions. These findings suggest that the deposits were derived from a nearby source and were strongly influenced by volcanic slopes and underwater volcanic activity.

Keywords: *Grain maturity; Granulometric analysis; Sedimentary process; Semilir formation*

1. Introduction

The main composition of sedimentary rocks consists of texture, mineral composition, and sedimentary structure. The texture of sedimentary rocks can determine how the sedimentation process occurred in the rock and how far the grains were transported from the original rock. The texture of sedimentary rocks consists of grain size, grain shape (roundness and sorting), and fabrics [1]. The erosion of the original rock produces sediment particles, which are then transported by water media and subsequently develop different grain sizes, textures, and distributions. These variations occur due to the influence of depositional location, current strength, and sediment supply [2].

The terminology of grain maturity refers to the clay mineral content, grain shape, and grain sorting in sedimentary rocks, which reflects the physical processes occurring during transportation and deposition [3]. Mature sedimentary rocks are characterized by relatively well-rounded grains and uniform sizes, indicating long transport distances. In contrast, immature sedimentary rocks consist of angular and poorly sorted grains, suggesting limited transportation and proximity to the source area.

The research area is located in the Ngoro-oro Area, Gunung Kidul Regency, which belongs to the Southern Mountains of Java Island (see Figure 1). The exposed stratigraphy consists of the Kebo-Butak Formation, Semilir Formation, and Nglanggran Formation, ranging from the Middle Oligocene to Late Miocene [4]. Bronto [5] stated that these three formations are closely related to volcanic activity. According to several researchers in Mulyaningsih [6], the Kebo-Butak Formation and Semilir Formation represent turbidite deposits formed in a deep-marine environment as distal turbidites. The lithological characteristics of the Semilir Formation include tuff sandstone, lapilli tuff, sandstone, tuff, polymic breccia, mudstone, siltstone, and shale. However, the exact volcanic source of the Semilir Formation has not yet been fully identified.

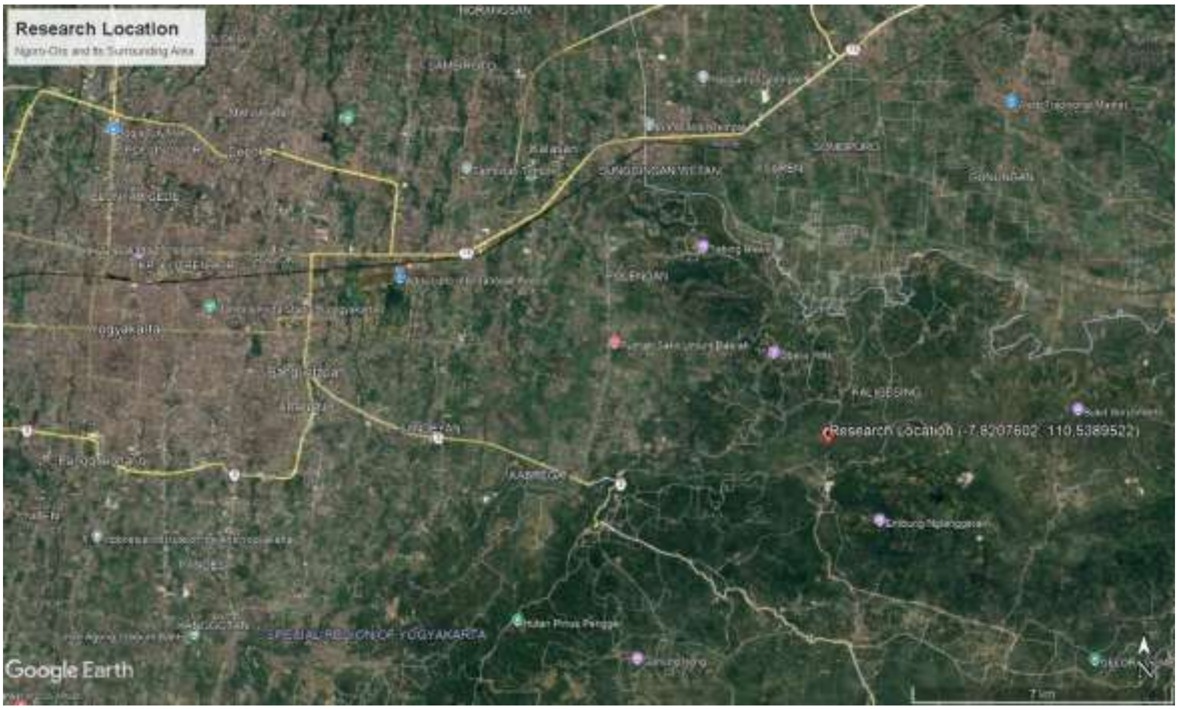

Figure 1. The location of the research area (marked by red pin).

Although many previous studies have described the stratigraphy and volcaniclastic nature of the Semilir Formation, detailed investigations focusing on grain maturity and textural statistics remain limited. The absence of such data makes it difficult to fully understand the transport mechanisms, sedimentary energy, and depositional settings of this unit within the broader context of the Southern Mountain Basin evolution. Therefore, this study provides a comprehensive granulometric analysis of the Semilir Formation to evaluate grain maturity and sedimentary processes. The choice of the Ngoro-oro area is significant because the outcrops are well-preserved and representative, allowing for detailed sampling and analysis. The role of structural control on volcaniclastic dispersal in the Semilir Formation may resemble cases where fault density and tectonic influences determined sedimentary pathways in Java [7][8]. The results are expected to contribute new insights into the depositional mechanism of volcaniclastic turbidites in Java, clarify the role of volcanic slopes and submarine processes, and strengthen the regional interpretation of sediment supply and basin evolution.

2. Method

This research builds on a qualitative and quantitative analysis method. Qualitative methods consist of megascopic lithology description. Quantitative methods are conducted by several statistical calculations through granulometry analysis in terms of providing sedimentary grain maturity. Granulometry analysis is conducted on compacted sedimentary rocks. Samples were collected from the Semilir Formation, with 1 sample representative from each location in 3 locations of the Ngoro-oro Area. The sample is converted into unconsolidated granules by grinding it until it forms a granular shape, then the sample is soaked with peroxide fluid to separate grains from the matrix and cement. Hereafter, the unconsolidated grains were split after measuring the weight. The samples are analyzed by the quartering method and sieved mechanically to obtain the representative grain size distribution. This research uses 7-grain distribution ranges, those are mesh 2.39 mm, mesh 1.19 mm, mesh 0.59 mm, mesh 0.297 mm, mesh 0.149 mm, mesh 0.074 mm, and the least sieve <0.074 mm. The result of the sieving measurement is utilized to build the statistical graphics, which present the skewness, kurtosis, sorting of the grain, percentile of the grain, and to interpret the grain maturity and sedimentary process mechanism.

3. Results and Discussion

3.1. Grain size statistic

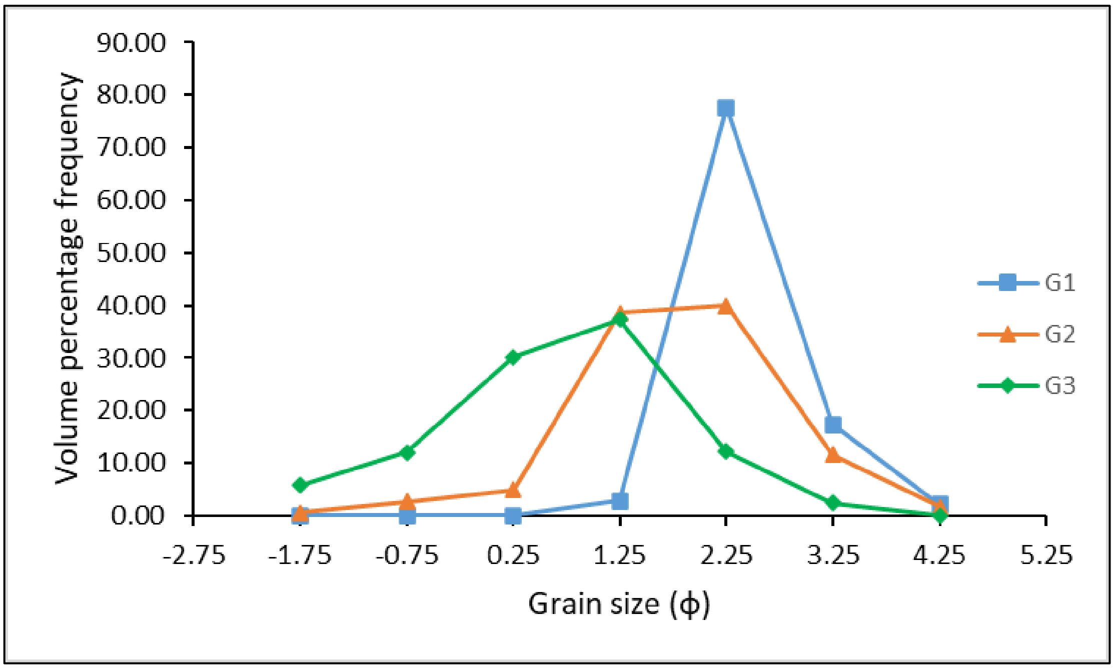

Figure 2. Curves of grain size frequency distribution from the Semilir Formation

The frequency distribution graph of grain sizes reveals that samples obtained from the Semilir Formation exhibit an unimodal characteristic, with the peak of the curve occurring at a grain size of 2.25ϕ for both G1 and G2 and 1.25ϕ for sample G3 (Figure 2). This observation indicates that, in general, sample G3 possesses coarser grain sizes in comparison to samples G1 and G2. The unimodal nature of all three samples implies a consistent sedimentation process throughout the deposition phase for each sample. The grain size distribution of sample G1 displays positive skewness (fine-skewed), suggesting an abundance of fine-sized materials within its depositional environment. In contrast, sample G3 exhibits negative skewness (coarse-skewed), indicating an abundance of coarse-sized materials. Meanwhile, sample G2 demonstrates a relatively symmetric distribution.

The statistical parameters for grain size, including mean, standard deviation, skewness, and kurtosis, are obtained from the grain size distribution graph through appropriate statistical calculations [9]. The parameters utilized to depict the particle size characteristics of the Semilir Formation samples can be observed in Table 1. At the same time, the result of the grain size parameter from Semilir Formation samples is shown in Table 2.

3.1.1. Graphic mean (Mz) is a parameter that provides an overall representation of the grain size of a sediment. It represents the average size of sediment particles and is expressed in ϕ units, which can depict the magnitude of energy during the sediment deposition process [10]. The calculated results indicate average grain sizes of 1.9ϕ (medium sand), 1.325ϕ (medium sand), and 0.2ϕ (coarse sand) for samples G1, G2, and G3, respectively. The average grain sizes in the samples suggest localized variations during the deposition of the Semilir Formation. Sample G3 was deposited under higher energy conditions than samples G1 and G2. Samples G1 and G2 share the same grain size terminology: medium sand. However, the average grain size in sample G1 is smaller than in sample G2, indicating that sample G1 was deposited under lower energy conditions than G2 and G3. Overall, all three samples from the Semilir Formation suggest a sedimentary environment with moderate to high energy levels.

Table 1. Descriptive terminology of grain size parameter (after Blott and Pye [11])

Standard deviation (σ_1)	Descriptive terminology	Skewness (Sk_1)	Descriptive terminology	Kurtosis (KG)	Descriptive terminology
< 0.35	Very well sorted	+0.3 to +1.0	Very fine skewed	< 0.67	Very platykurtic
0.35 – 0.50	Well sorted	+0.1 to +0.3	Fine skewed	0.67 – 0.90	Platykurtic
0.50 – 0.70	Moderately well sorted	+0.1 to -0.1	Symmetrical	0.90 – 1.11	Mesokurtic
0.70 – 1.00	Moderately sorted	-0.1 to -0.3	Coarse skewed	1.11 – 1.50	Leptokurtic
1.00 – 2.00	Poorly sorted	-0.3 to -1.0	Very coarse skewed	1.50 – 3.00	Very leptokurtic
2.00 – 4.00	Very poorly sorted			> 3.00	Extremely leptokurtic
> 4.00	Extremely poorly sorted				

Table 2. Grain size parameter of Semilir Formation samples

Parameter	G1 Calculated	G1 Terminology	G2 Calculated	G2 Terminology	G3 Calculated	G3 Terminology
Mean	1.91	Medium sand	1.325	Medium sand	0.20	Coarse sand
Standard deviation	0.52	Moderately well sorted	0.95	Moderately sorted	1.13	Poorly sorted
Skewness	0.26	Fine skewed	-0.022	Symmetrical	-0.14	Coarse skewed
Kurtosis	1.16	Leptokurtic	1.09	Mesokurtic	1.12	Leptokurtic

3.1.2. Inclusive graphic standard deviation (σ1) is a metric conveying the degree of sorting or uniformity within a grain size distribution. This measure can provide insights into variations in hydrodynamic energy conditions within a given depositional environment [12]. The standard inclusive graphic values for the three Semilir Formation samples are moderate - moderately well sorted for samples G2 and G1, while sample G3 is poorly sorted (Table 2). The three samples showed different levels of item sorting, with the G1 sample having the best level of item sorting and the G3 sample being the worst. In marine depositional environments, sediments characterized by moderate sorting generally suggest either a segregation of grain sizes or an introduction of previously well-sorted sediments [13] [14] [15].

3.1.3. Inclusive graphic skewness (Sk1) is a measurement of particle size distribution used to assess the characteristics of particle size dispersion in the tail of the distribution. An asymmetric curve with an excess of fine particles exhibits a tail of fine particles. It depicts positive particle size values, while many coarse particles indicate negative particle size values. A symmetrical curve indicates a particle size value of 0ϕ. The skewness values in the three samples of the Semilir Formation vary, with a positive skewness value of 0.26ϕ for sample G1, symmetry (-0.02ϕ) for sample G2, and negative skewness (-0.14ϕ) for sample G3 (Tabel 2). The presence of symmetrical skewness and positive skewness indicates the onset of fine material deposition and the loss of coarse-grained sediment. Sediments with a particle size distribution approaching symmetry can indicate the absence of extreme conditions such as tidal fluctuations, wave erosion, and seasonal detrital sediment supply [16]. This condition is reflected in the skewness value for sample G2.

3.1.4. Graphic kurtosis (KG) represents the sharpness of the peak in the particle size distribution graph. A sharply peaked curve indicates better sorting in the central part of the particle size distribution compared to its tails, while a flat-topped curve suggests the opposite. The graphic kurtosis values of the Semilir Formation samples are categorized as leptokurtic for samples G1 and G3 and mesokurtic for sample G2 (Table 2). The variety in kurtosis values is attributed to changes in the characteristics of the flow fluid during sedimentation processes [15].

3.2. Textural parameter inter-relationship

Comprehending the interconnections among textural parameters is vital in identifying sediment deposition mechanisms and differentiating between various depositional environments. The texture parameter of sediment grains is susceptible to change in different depositional environments and the processes occurring during sediment deposition [17][18]. Previous researchers have stated that binary or cross-plots of textural parameters of grain size are reliable data for differentiating the processes occurring during sediment deposition and can also be used to determine the depositional environment of sediment [18][19]. Combinations of several textural parameters represented in bivariant plots have been widely utilized to identify the depositional environment of sediment [19]. Bivariate plots rely on robust statistical parameters to depict variations in fluid flow mechanisms during sediment transport and deposition processes. Numerous previous researchers have demonstrated and documented that bivariant plots are reliable for identifying fluid flow mechanisms in different depositional environments [20][21][22]. Additionally, they have emphasized the significance of bivariate plots, considering them crucial and frequently employed tools in this context [9][19]. Bivariant plots, including skewness versus standard deviation, skewness versus mean, kurtosis versus skewness, and standard deviation versus mean, are used to identify the depositional environment of the Semilir Formation (Figure 3). The bivariate plot indicates the presence of coastal processes in samples from the Semilir Formation. Based on regional geological considerations, the Semilir Formation is primarily composed of turbidite deposits.

3.3. Visher diagram

Employing cumulative frequency graphs on a logarithmic scale to differentiate sediment transport mechanisms is suggested by [23]. The Visher diagram of Semilir Formation samples clearly shows double saltation populations with a single suspension population. Sample G1 exhibits a notably distinct curve trend compared to samples G2 and G3 (Figure 4). This disparity can be attributed to the fact that sample G1 possesses the finest average grain size among the three. The dominant sediment transport mechanism expected to occur in sample G1 is suspension, whereas in samples G2 and G3, the possibility of saltation mechanisms persists.

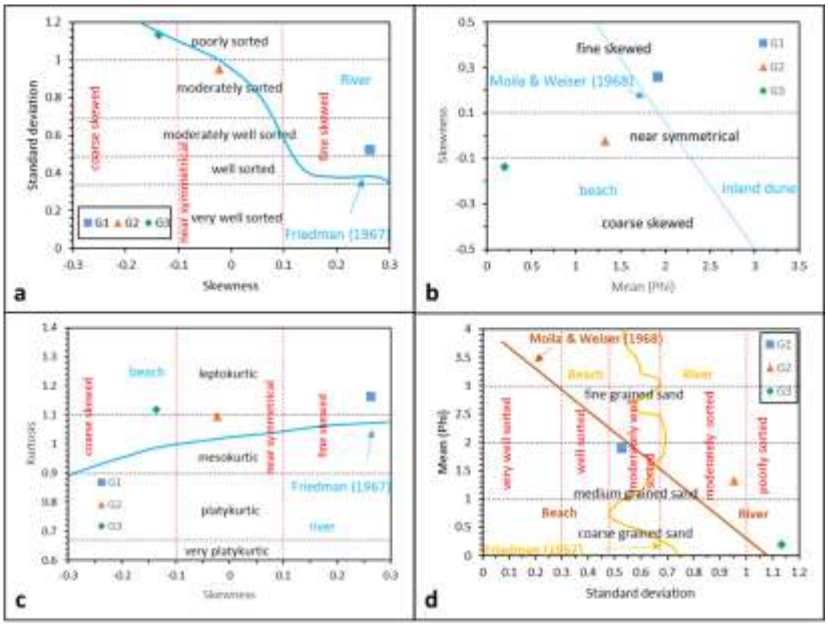

Figure 3. Bivariate plots with background map [23][24] of grain size parameters, showing (a) bivariate plot of standard deviation against skewness; (b) bivariate plot of skewness against mean; (c) bivariate plot of kurtosis against skewness; (d) bivariate plot of mean against standard deviation.

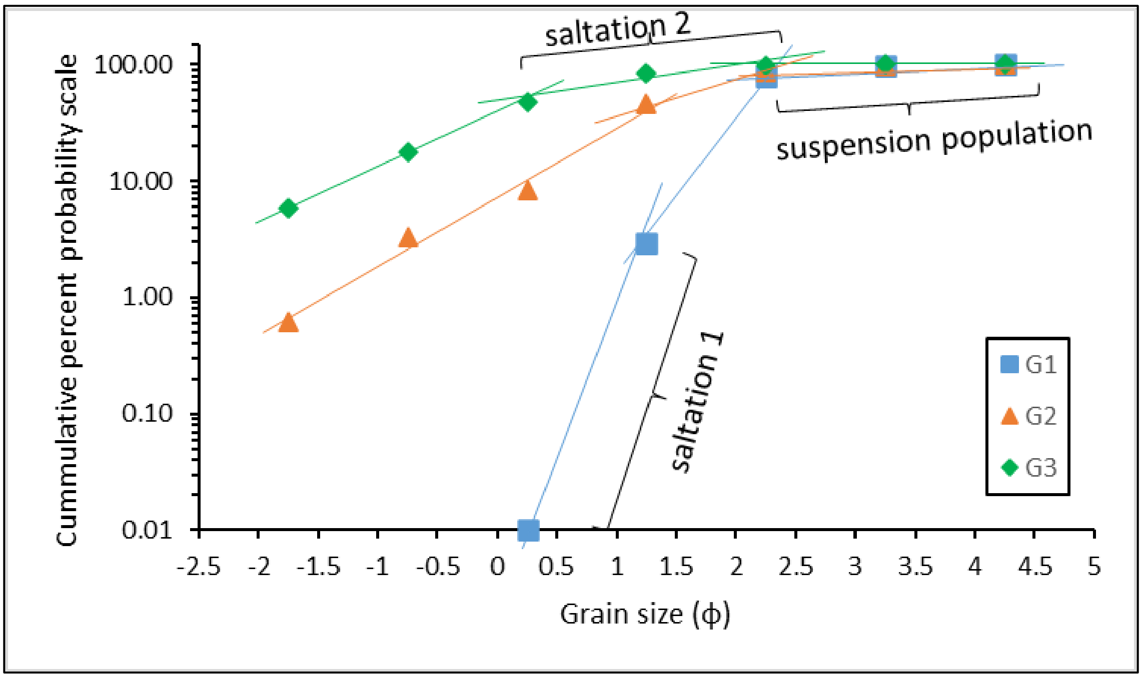

Figure 4. The probability curve of grain size cumulative frequency shows the double saltation populations and a single suspension population for G1, G2, and G3.

3.4. Linear discriminate function LDF and the C-M pattern (Passega diagram)

LDF is valuable for interpreting the energy changes and fluidity parameters throughout sediment deposition processes. The application of LDF exhibits a robust correlation with diverse sedimentation processes and their associated environmental conditions [12]. LDF employs mathematical expressions Y1, Y2, Y3, and Y4, which represent equations involving mean, standard deviation, skewness, and kurtosis. Figure 5 depicts the results of LDF on samples from the Semilir Formation. From the LDF graphs, it can be inferred that turbidity current mechanisms predominantly dominate the sedimentation processes in samples G1, G2, and G3. On the other hand, Passega diagrams are also employed for interpreting the hydrodynamic conditions occurring during the sedimentation process [10]. C-M represents a bivariate plot that illustrates the relationship between the median value (M) in microns and the grain size value in microns at the 1st percentile. Figure 6 reveals that the coarser nature of samples G2 and G3 results from the deposition process of gradually suspended sediment under high turbulence conditions, while sample G1 is formed by mixing sediment suspensions.

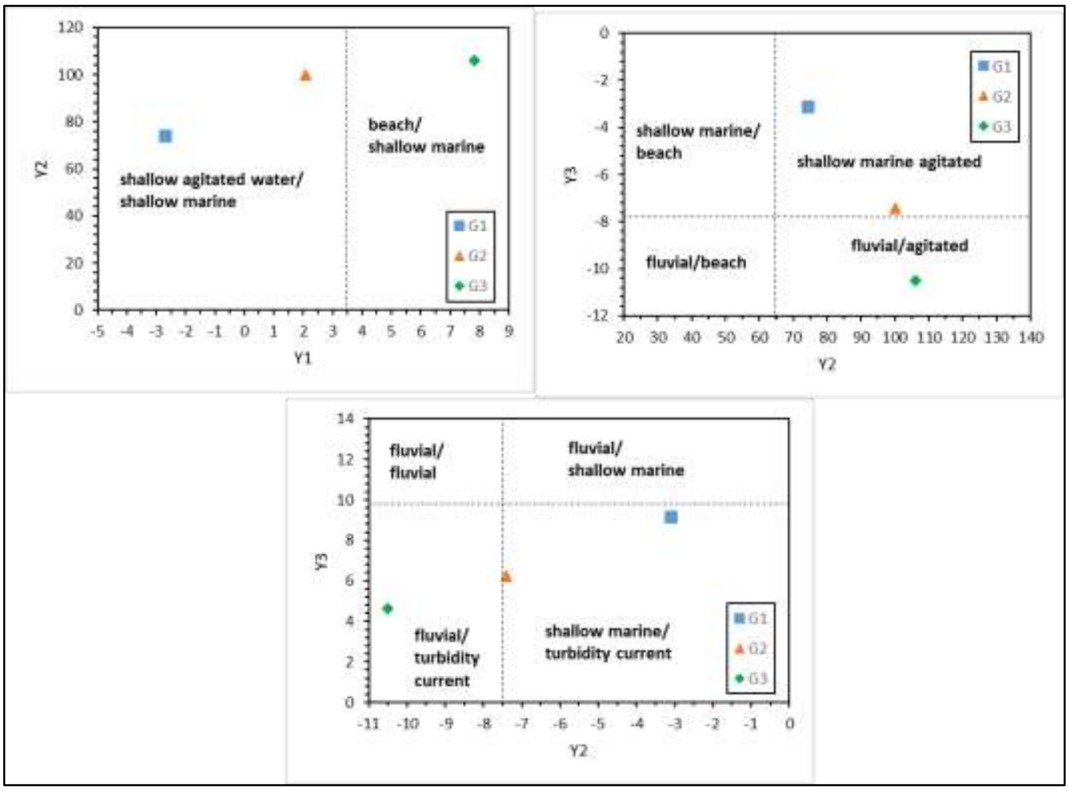

Figure 5. LDF graph of Semilir Formation samples using the linear discriminate function (after Sahu [24])

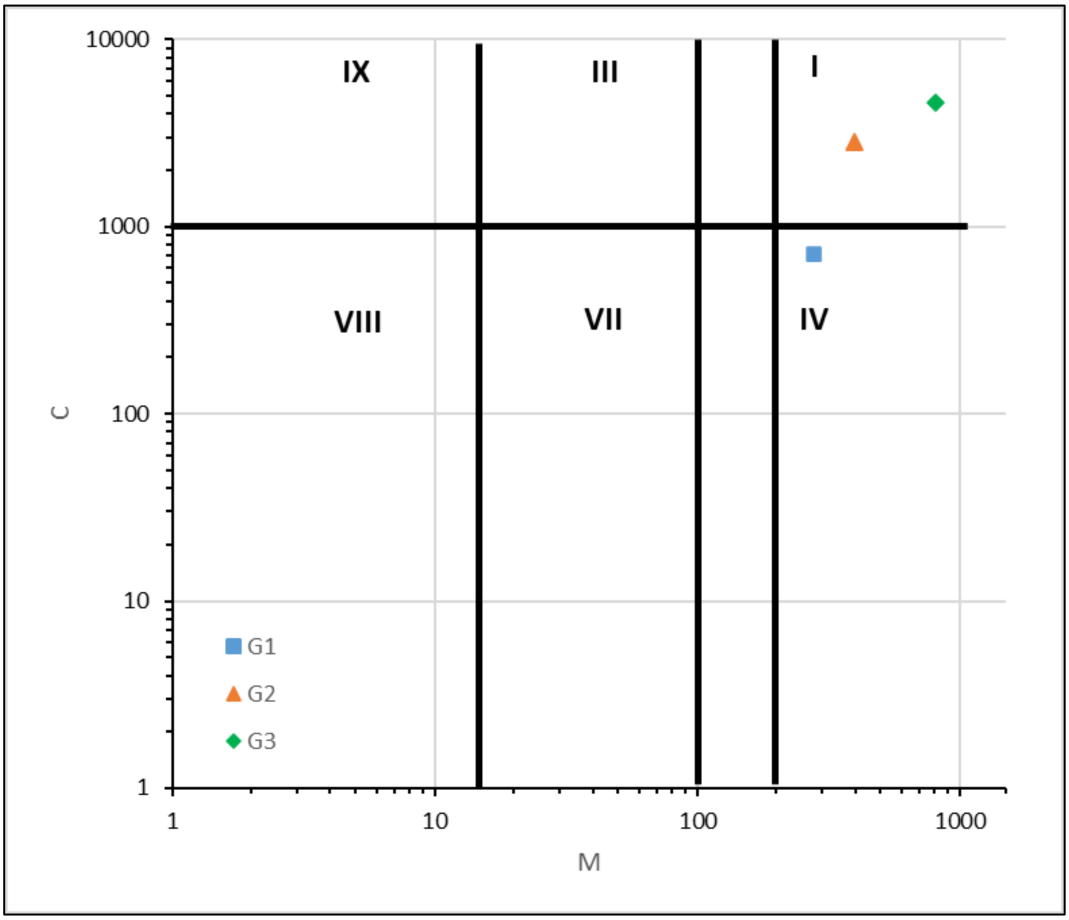

Figure 6. The Passega Diagram shows that G2 and G3 are in block I while G1 is in block IV (after Passega [25]).

3.5. Grain Maturity and Depositional Processes

The Early Miocene Semilir Formation at Ngoro-oro comprises sand-dominated volcaniclastic turbidites that exhibit low textural maturity. Grain-size statistics show medium to coarse sands with poor to moderate sorting and variable skewness, indicating rapid emplacement under high-energy conditions. These attributes, together with leptokurtic or platykurtic kurtosis, imply deposition from turbulent density currents rather than prolonged reworking. The Visher and Passega plots place most samples within suspension–saltation fields, supporting deposition by gravity-driven flows on a submarine fan. Slightly better sorting and near-symmetrical skewness in a few samples may reflect minor nearshore reworking, but they do not outweigh the overall immature textures and dominance of graded bedding and parallel lamination.

Regional analogues reinforce this interpretation. In the Late Miocene Kerek Formation of East Java, thick volcaniclastic turbidites derived from volcanic eruptions along the median line of Java were deposited contemporaneously with marl, highlighting how explosive volcanism feeds deep-marine fans [25][26]. The Semilir turbidites show similar provenance and depositional mechanisms. The immaturity and sorting trends identified here could be further contextualized by comparison with other facies-based studies in Indonesian basins. Comparisons with other Indonesian volcaniclastic systems show that coarse, angular turbidites commonly occur where pyroclastic debris is rapidly reworked into deep-marine basins [27][28]. In East Java, marl deposition in the Kalibeng Formation was contemporaneous with the emplacement of volcaniclastic turbidites, underscoring the interplay between volcanic input and basin filling [25]. Meanwhile, hydrogeologic studies of the Gunungkidul karst reveal that karst terrains have high groundwater vulnerability because thin or absent soil cover and highly permeable carbonate rocks allow rapid infiltration [29]. Given its location in Gunungkidul, the depositional and post-depositional processes of the Semilir Formation could be linked to broader hydrogeological systems, similar to karst and geothermal studies in the region [30][31].

In summary, the Semilir Formation at Ngoro-oro represents immature volcaniclastic turbidites deposited on a deep-marine fan under high-energy conditions, with only minor coastal reworking. Structural control, regional analogues such as the Kerek Formation, and insights from karst hydrogeology provide a broader framework for interpreting these deposits. Future research should integrate detailed structural mapping and high-resolution stratigraphic analysis to clarify how tectonics, volcanism and sedimentation interacted in this part of Java.

4. Conclussion

Integrated analysis indicate that the Early Miocene Semilir Formation at Ngoro-oro is an immature volcaniclastic succession deposited on a submarine fan. The sandstones are medium to coarse grained, poorly to moderately sorted and display variable skewness and kurtosis, pointing to rapid sediment input with limited reworking. Bivariate plots (Visher, Passega) and LDF curves consistently place the samples within the suspension–saltation fields, confirming deposition from high-energy density currents rather than long-shore or nearshore processes. This interpretation is reinforced by the dominance of graded bedding, parallel lamination and the absence of tidal or wave-generated structures.

Minor deviations in sorting and skewness suggest that some beds experienced limited reworking during waning flow or brief interaction with shallow-marine conditions. Nevertheless, the overall textural immaturity and facies architecture support a depositional model dominated by turbidity currents sourced from an active volcanic arc and delivered across a steep submarine slope. Regional analogues, such as the Late Miocene Kerek Formation, demonstrate that volcaniclastic turbidites derived from arc volcanism commonly interfinger with hemipelagic marl, highlighting the broader geodynamic context in which the Semilir turbidites formed.

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