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Facies and Depositional Environment Analysis of Limestone in Citeureup Area, West Java, Indonesia

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ABSTRACT

The Citeureup area in West Java Province hosts Middle Miocene limestone outcrops belonging to the Klapanunggal Formation, which has long been considered a promising source of raw material for Indonesia's cement industry. Despite its economic significance, detailed sedimentological studies and facies characterization of this formation remain limited. This study aims to identify the dominant lithofacies and reconstruct depositional environments to understand the formation's genesis and assess its resource potential. Thin-section petrographic analysis, enhanced with blue epoxy resin, was employed to identify porosity, fossil assemblages, and mineral composition. The investigation revealed three primary facies types: packstone, boundstone, and dolomitic grainstone. The packstone and dolomitic grainstone facies are interpreted to have formed in reef-flat settings, associated with shallow, high-energy marine conditions. The boundstone facies, in contrast, are linked to reef-crest environments subjected to more dynamic hydrodynamic regimes. These findings point to a depositional system characteristic of a carbonate platform shaped by variable energy conditions. The presence of abundant skeletal grains, well-developed porosity, and mature mineralogical features indicates the limestone's high potential as a quality raw material for cement production. Beyond its industrial relevance, the study enhances sedimentological insights into the Klapanunggal Formation and provides a scientific basis for informed resource evaluation and sustainable exploitation strategies in similar carbonate settings.

Keywords: Klapanunggal Formation, limestone facies, depositional environment, petrographic analysis, cement raw materials.

INTRODUCTION

Limestone is a sedimentary carbonate rock predominantly composed of calcium carbonate ($CaCO_3$), typically formed from the biogenic accumulation of calcareous organisms and the chemical precipitation of inorganic materials in marine environments [1]. Depositional settings and diagenetic processes strongly influence its formation and lithification over geological time [2]. In addition to calcium carbonate, most limestones contain varying amounts of magnesium, silicates, and other trace elements such as manganese, aluminium, and sulfur, affecting their physical and chemical properties. These mineralogical and textural variations are critical in determining the rock's suitability for industrial applications, particularly as raw material in cement production [3]. In Indonesia, limestone has long been utilized in cement manufacturing, yet comprehensive sedimentological and facies analyses of major deposits remain limited [4].

One such geologically significant unit is the Middle Miocene limestone of the Klapanunggal Formation, located in the

Citeureup area, West Java (Figure 1). This formation has been widely recognized for its potential as a source of cement raw material [5]. However, despite its industrial importance, detailed studies focusing on its depositional environment, facies architecture, and lithological variability are notably scarce. The lack of such investigations hinders the ability to evaluate the quality and distribution of limestone resources, which are essential for supporting sustainable exploitation and regional development.

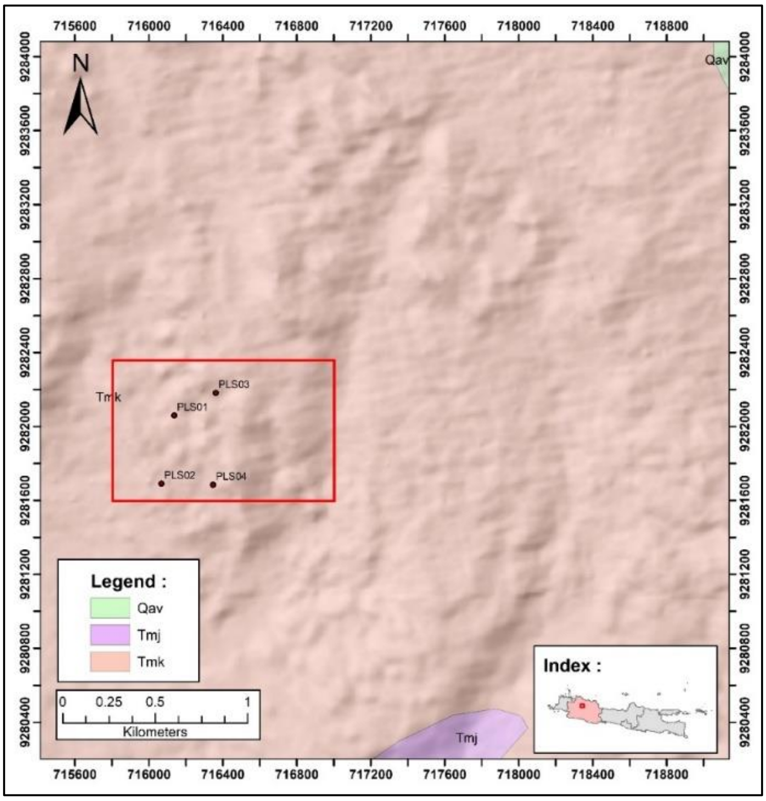

Figure 1. Regional geological map of the Citeureup Area

This study aims to classify and characterize the primary lithofacies within the Middle Miocene limestone of the Klapanunggal Formation, interpret the depositional environments, and assess their implications for its industrial application. Understanding these sedimentological features is crucial for evaluating the limestone's potential as a raw material for cement production, as facies and depositional environments significantly influence its texture, porosity, and mineral composition [6]. These factors directly impact its performance in industrial processes such as cement manufacturing [7].

Understanding this formation's depositional environments and lithofacies is crucial for evaluating its genesis and material quality. Facies analysis allows researchers to reconstruct past environmental conditions and assess sedimentary processes' impact on porosity, fossil content, and mineral composition—factors that directly influence their performance in cement production [8]. This study addresses this gap by examining the limestone of the Klapanunggal Formation through detailed petrographic analysis using blue epoxy-impregnated thin sections to enhance visibility of pore structures and micro-fossils.

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By focusing on the Klapanunggal Formation, this research provides a more detailed understanding of its sedimentological framework, which can contribute to more informed decision-making regarding the sustainable management and efficient exploitation of carbonate resources [9]. This knowledge is essential for ensuring the quality and consistency of raw materials used in the cement industry and promoting long-term sustainability in the mining and resource extraction sectors [10].

Moreover, the findings of this study offer a scientific foundation for evaluating limestone deposits in other geologically similar regions [11]. The petrographic and facies analysis methods used in this research provide a transferable framework that can be applied to other limestone formations, enhancing the ability to assess their industrial potential and contributing to the broader discourse on resource management in sedimentary geology.

METHODOLOGY

This study adopts a descriptive and analytical research design to characterize limestone's lithofacies and depositional environments from the Klapanunggal Formation and evaluate its industrial potential as a cement raw material. The methodology covers four main stages: geological mapping and sampling, petrographic analysis, facies interpretation, and quality assessment. The framework is illustrated as a mind map (Figure 2), demonstrating the interconnected steps from field data acquisition to laboratory-based interpretation and analysis.

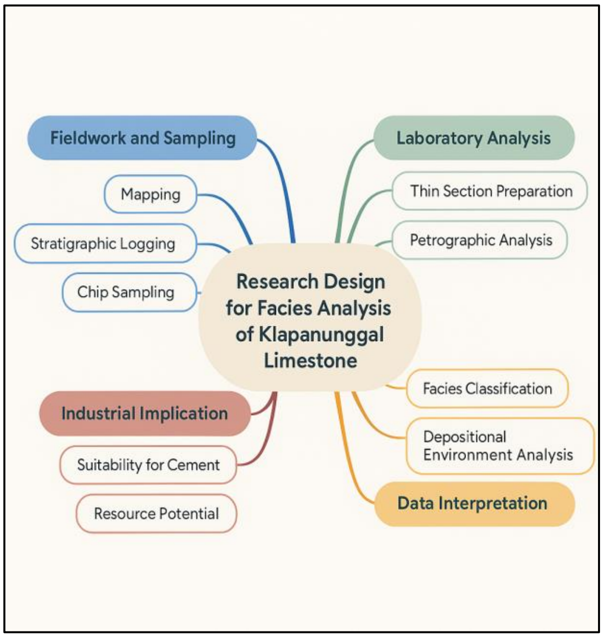

Figure 2. Illustration of the research mind map

Geological Setting and Sampling Strategy

The research was conducted in the Citeureup area, which geologically belongs to the Klapanunggal Formation within the Bogor Basin and is dated to the Middle Miocene epoch. This formation is typified by reefal limestone that exhibits distinct fossil porosity and is interpreted to have been deposited in a shallow marine environment with warm, clear waters [12]. The formation shows a unique hill morphology compared to surrounding units, often associated with transgressive-regressive sequences that influence facies distribution [13].

Limestone samples were collected using chip sampling at various accessible outcrops representing different lithofacies within the study area. A total of 15 representative samples were obtained from stratigraphic sections selected based on field observations of lithologic variability, fossil content, and structural features. Sampling was carried out using a systematic approach to ensure spatial coverage across the formation.

All sampling and fieldwork were conducted with appropriate permissions from local authorities and landowners. No endangered geological or paleontological features were disturbed during the sampling process. The research adhered to institutional and environmental ethics standards in geological data collection and laboratory handling. Safety protocols were observed during field activities and laboratory work to minimize risks to personnel and the environment.

Data Collection and Thin Section Preparation

After collection, the limestone samples were prepared for petrographic analysis by cutting and grinding them into standard thin sections of approximately 0.03 mm in thickness. Cover glasses were affixed to each thin section to facilitate observation under a polarising microscope using transmitted light. This process enabled detailed examination of mineral textures, fossil presence, pore structures, and types of cement present within the rock matrix.

Alizarin Red S (ARS) dye was applied to thin sections to distinguish between calcite and dolomite. Calcite-rich areas reacted with the dye, turning pink, while dolomite remained unstained or appeared transparent. Additionally, blue-dyed epoxy resin was introduced during sample preparation to highlight porosity. This resin filled voids within the rock, making them easily visible under the microscope and aiding in quantitative porosity estimation.

Analytical Approach

Petrographic analysis was conducted to identify textural and mineralogical features, including grain size, grain contact, recrystallization, fossil types, micritic or sparitic matrix, and diagenetic alterations. Facies classification followed established carbonate sedimentology models [14], categorizing samples into distinct lithofacies based on compositional and structural characteristics. These classifications were then interpreted in depositional environments using facies models for reef, lagoonal, and slope settings [15].

Integrating petrographic observations with field-based data facilitated the reconstruction of depositional settings. It allowed for evaluation of the limestone's quality for cement manufacturing, focusing on parameters such as purity (mineral composition), porosity, and fossil assemblage [16].

RESULTS

Outcrop Observation and Lithological Classification

Megascopic observations were conducted on exposed limestone outcrops in the Citeureup area to identify lithological variations and classify carbonate facies based on field characteristics. The physical properties assessed included color (fresh and weathered), hardness, fossil content, and texture. Field classification focuses on grain support, fossil dominance, and the presence of matrix or cement [17], [18].

The appearance of the surface sampling locations is depicted in Figure 3. Sample PLS01 (Figure 3a) displays a blackish-gray fresh color and a blackish weathered surface, with a moderately hard, slightly chalky texture. The fossil content exceeds 10%, with large bioclasts, classifying the rock as a rudstone. Sample PLS02 (Figure 3b) shows a brownish-white fresh surface with slightly consolidated blackish weathering. It has a lower fossil abundance (<10%) consisting of foraminifera and mollusk shells, and is

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classified as floatstone. A reddish-brown weathered surface with a massive structure characterizes sample PLS03 (Figure 3c). Fossils are sparsely distributed (<10%), predominantly mollusks, and the rock is also categorized as floatstone, supported by calcite-dominated mineralogy. Sample PLS04 presents a brownish-white to blackish-gray weathered surface with high fossil content (>10%) dominated by corals, algae, and foraminifera. Based on its dense fossil framework and minor matrix content, it is classified as framestone.

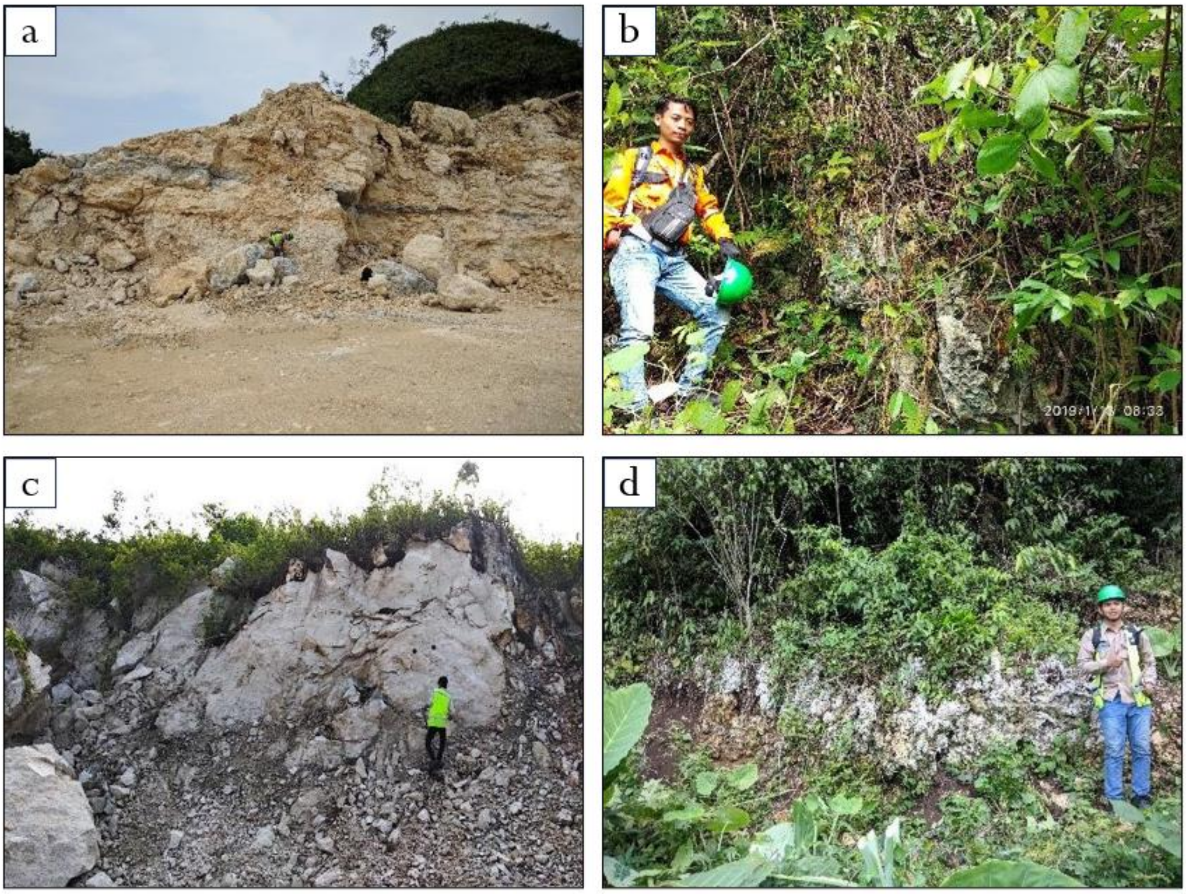

Figure 3. Appearance of surface sampling at locations PLS01 (a), PLS02 (b), PLS03 (c), and PLS04 (d)

Facies Interpretation and Industrial Implications

Field analysis indicates that floatstone and framestone facies are predominant within the study area. Floatstone represents a facies type where grains larger than 2 mm are supported within a matrix, suggesting deposition in moderate-energy environments such as the lower fore-reef or lagoonal settings. This facies is commonly associated with reworked bioclasts and reduced hydrodynamic conditions, allowing for matrix accumulation. In contrast, framestone is composed of autochthonous, in-situ fossil frameworks with minimal matrix, reflecting deposition in high-energy reef crest or fore-reef zones, where bioconstructors such as corals and calcareous algae are abundant [19].

The presence of these facies types has direct implications for the limestone's potential as a cement raw material. Framestones, with their high fossil content and cementation, often exhibit superior mechanical properties, while matrix-supported floatstones may exhibit higher porosity and reactivity in clinker production. Therefore, identifying and characterizing these facies is crucial for resource assessment, quality control, and optimizing extraction strategies for cement-grade limestone.

Facies Analysis Based on Thin Section Petrography

A qualitative petrographic analysis was conducted on thin sections obtained from surface limestone samples using a trinocular polarizing microscope. The objective was to identify fossil assemblages, matrix composition, cement characteristics, and pore types based on Dunham's classification scheme [20]. Each thin section measured 2.5 × 2.5 cm, and observations were conducted at 5x magnification. Representative photomicrographs are presented in Figures 4–7, where the observed thin section areas visually estimated mineral components and porosity percentages.

Sample PLS01 (Figure 4) is dominated by fragmented red algae (30%) and gastropods (15%), with characteristic ring-like sections from transverse cuts. The matrix (20%) consists of micrite with fine, cloudy, brown to blackish-gray crystals (see C3). Cement (15%) appears coarse sparite, observable through birefringence under cross-polarized light (F4). Porosity (15%) is primarily in the form of channel pores (D1), contributing to a moderately porous texture. This composition supports classification as a packstone, characterized by grain-supported textures with micritic infill.

Sample PLS02 (Figure 5) contains intact red algae (25%), partially cemented by sparite and micrite (E1 and B7). Minor constituents include pelecypods (5%), brachiopods (5%), and mollusks (5%) in both uniserial and biserial forms. The matrix (30%) is composed of micrite that fills intergranular spaces (A3). The fossil framework, largely preserved, suggests biologically bound components. Based on Dunham's classification, this sample is identified as a boundstone, formed in situ by organisms that have built a rigid framework, typically algae and corals.

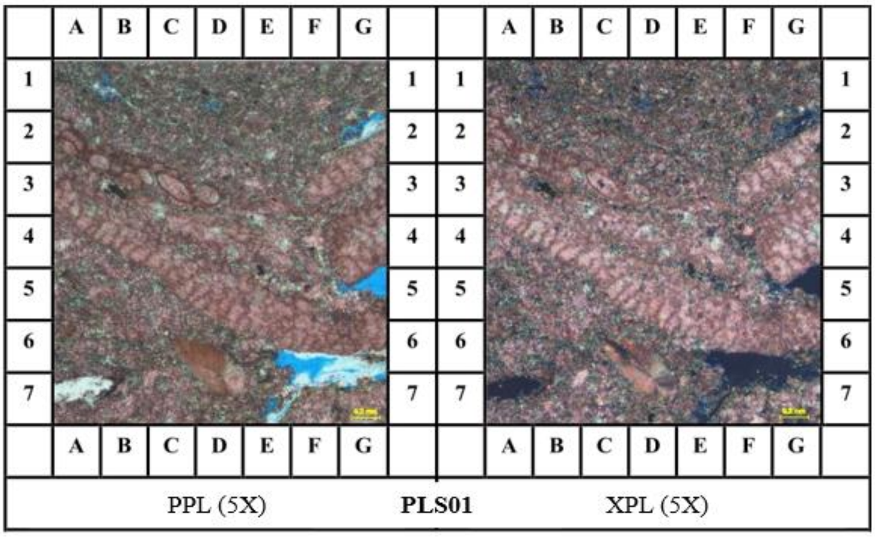

Figure 4. Photomicrograph of thin sections of sample PLS01 with 5x magnification

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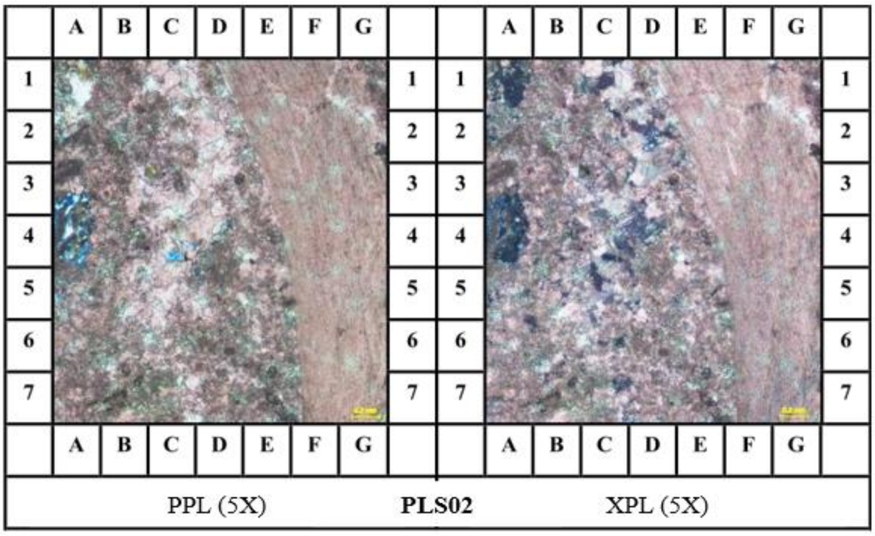

Figure 5. Photomicrograph of thin sections of sample PLS02 with 5x magnification

Sample PLS03 (Figure 6) consists predominantly of dolomite crystals (45%) and calcite (35%). Calcite appears in pink hues (C3), while dolomite is presented as fine, white crystals (A3). Dolomitization is evident, with vuggy and intercrystalline porosity (20%) distributed throughout the crystal mass (D2). Micritic zones are still present but subordinate. Given the abundance of dolomite and grain-supported texture with low matrix, the sample is classified as dolomitic grainstone.

Sample PLS04 (Figure 7) contains a diverse fossil assemblage including bryozoans (5%), mollusks (5%), large foraminifera (12%), and branching red algae (10%). Fossils are generally intact and filled with micrite. The matrix (15%) comprises micrite with cloudy textures (A3), while the cement (25%) is pink sparite with coarse crystalline structure (G7). Porosity (10%) is present in vuggy forms. The grain-supported structure and fossil content above 10% indicate a packstone facies classification.

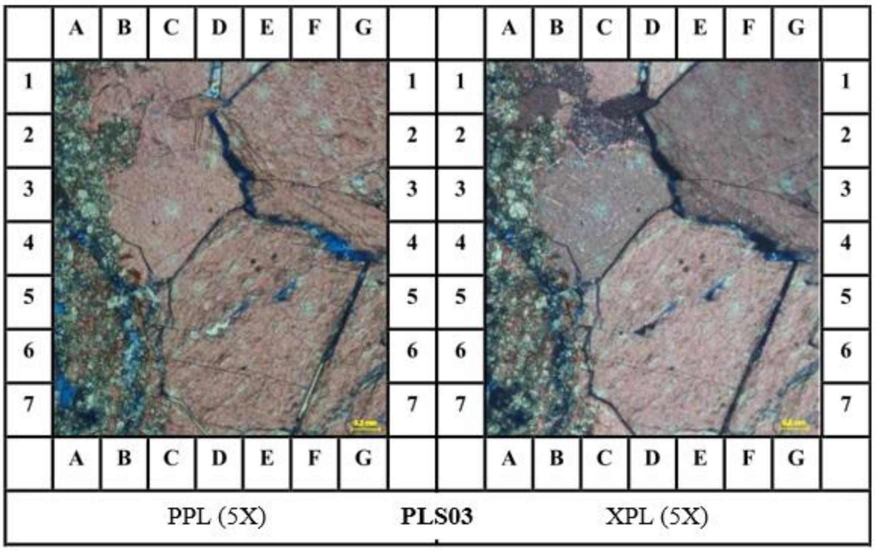

Figure 6. Photomicrograph of thin sections of sample PLS03 with 5x magnification

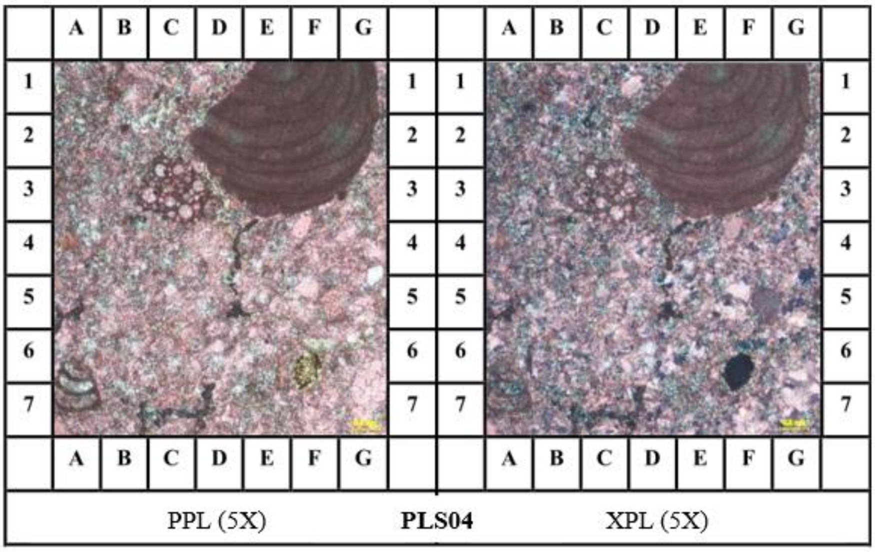

Figure 7. Photomicrograph of thin sections of sample PLS04 with 5x magnification

Depositional Environment Analysis

The depositional environment of the limestone facies has been interpreted using the carbonate platform zonation model modified from Scholl et al. [21]. Thin-section data, along with fossil content, matrix composition, and diagenetic features, were used to infer the environmental setting of each facies. The samples were then plotted within the environmental framework in Figure 8 to visually represent their spatial relationships and paleoenvironmental significance.

Samples PLS01 and PLS03 are interpreted to represent the reef flat depositional environment. This interpretation is supported by the dominance of bioclastic grains (e.g., fragmented red algae, mollusks) embedded in micritic or dolomitized matrices, as well as moderate porosity and evidence of early marine cementation. The reef flat zone is typically characterized by relatively low to moderate energy conditions in shallow water settings, facilitating the deposition of fragmented skeletal materials mixed with carbonate mud.

Sample PLS02 is categorized within the reef crest environment. This evidence is supported by intact coral and red algae frameworks that exhibit limited transport and in situ growth features. Reef crest zones are typically the highest-energy part of the reef system, where constant wave action promotes the growth of robust, framework-building organisms such as branching corals and calcareous algae. The presence of cementation by sparite and micrite further indicates active seawater circulation, facilitating early lithification processes.

Sample PLS04, on the other hand, is interpreted to belong to the reef front environment. This interpretation is based on more delicate biota (e.g., foraminifera, mollusks, and bryozoans) and a relatively higher micrite content, suggesting deposition under calmer conditions than the reef crest. The reef front typically features a steeper slope and receives a moderate energy input from wave refraction and downslope transport of finer materials.

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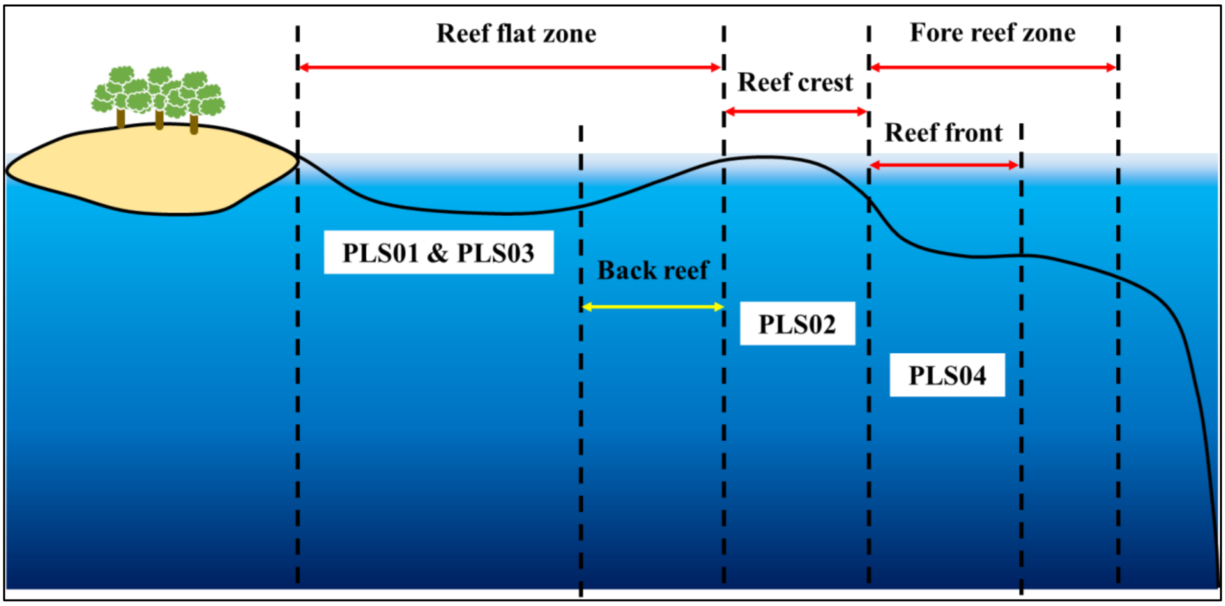

Figure 8. Illustration of the depositional environment at the research location (modified from [12])

DISCUSSIONS

Synthesis of Petrographic and Facies Findings

The integration of petrographic analysis and facies classification reveals a heterogeneous composition of carbonate rocks in the study area, reflecting variable depositional settings across the reef system. Based on the classification of Embry & Klovan [17] and Dunham [20], samples PLS01 and PLS04 are categorized as packstone, dominated by bioclastic grains such as foraminifera, mollusks, and red algae. These facies are interpreted to originate from reef flat zones, characterized by moderate energy conditions and significant carbonate mud content, suggesting sedimentation in shallow marine environments with intermittent wave action.

Sample PLS02, classified as boundstone, represents the reef crest environment, a high-energy, wave-exposed zone where encrusting organisms such as red algae and corals form a rigid framework. The intact skeletal remains and minimal matrix content support interpreting a wave-resistant structure, commonly associated with reefal carbonate build-ups in the tropics.

In contrast, PLS03, identified as dolomitic grainstone, indicates a reef front depositional environment. The presence of intercrystalline and vuggy porosity, along with a high proportion of dolomite crystals replacing original calcite, suggests that this facies underwent significant diagenetic alteration, likely associated with early dolomitization processes in a platform margin setting. This transformation implies fluctuations in salinity, fluid flow, and potentially fault-influenced hydrothermal circulation [22].

Relationship To Research Objectives And Depositional Model

The findings align with the study's objective of delineating the facies architecture and depositional environments of Miocene carbonates in the region, providing evidence of a well-developed reefal system consisting of back reef, reef flat, reef crest, and fore reef zones. The plotted samples (see figure 8) substantiate this zonation, highlighting the lateral facies variability typical of carbonate platform systems.

According to a sequence stratigraphic perspective, facies distribution suggests a transgressive to highstand systems tract, marked by vertical facies transitions from packstone and boundstone to dolomitized grainstone [23]. This vertical stacking pattern is essential for interpreting reservoir quality and continuity, especially in carbonate-hosted resource assessments [24].

Implications for Cement Raw Material Potential

The carbonate rocks in the study area, particularly those associated with packstone and dolomitized grainstone, exhibit promising characteristics as raw materials for cement manufacturing. High carbonate purity, moderate to high porosity, and stable mineral phases like sparite and dolomite favour clinker formation. Depending on cement quality specifications, dolomitized units (e.g., PLS03) may require beneficiation to reduce MgO content [25].

Furthermore, the spatial association of reef facies with high-energy depositional environments implies good accessibility and lateral continuity of carbonate units—factors critical for economic quarrying operations. The proximity to the Java Sea and regional infrastructure could further enhance the feasibility of future cement industry development.

CONCLUSION

The carbonate rocks in the Citeureup area belong to the Klapanunggal Formation and mainly consist of framestone and floatstone limestones. Petrographic analysis reveals packstone, boundstone, and dolomitic grainstone, which are found in different parts of a reef system: the reef flat, crest, and front. The reef flat has packstone and dolomitic grainstone, formed in moderate to high energy settings. In contrast, the reef crest has boundstone, showing strong biological activity, and the reef front has packstone, indicating lower energy. Evidence of dolomitization in the reef flat suggests changes due to fluids moving through the rock after it formed, creating more porous dolomitic grainstone. The rocks are rich in calcite from corals, algae, and fossils, making them high-quality materials, especially useful for cement production. Overall, this study improves the understanding of Miocene reef systems in Southeast Asia and shows their value for geological research and industrial use.

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