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Porosity Analysis of Pliocene Limestone from the Mundu Formation Based on Core and Petrographic Analysis

Muh Ferdian Yusuf [1]*, Siti Umiyatun Choiriah[1], Wahyuni Annisa Humairoh[2], Samuel Antonio Gutteres[2], Kharisma Idea[2], Danang Faisal Amri[2]

[1] Department of Geological Engineering, Faculty of Mineral and Energy Technology, UPN "Veteran" Yogyakarta, Indonesia.
[2] Department of Geological Engineering, Faculty of Mineral and Energy Technology "Veteran" Yogyakarta, Indonesia.

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Corresponding Author:
Muh Ferdian Yusuf
muhammadferdian0326@gmail.com

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Abstract: This study analyzes the porosity characteristics of Pliocene limestone from the Mundu Formation in the Gunung Pegat area, Lamongan, East Java, which lies within the Rembang Zone and is considered a potential carbonate reservoir. The research involved geological field mapping, measurement of four stratigraphic profiles, and collection of thirteen rock samples. Laboratory methods included petrographic analysis to classify lithofacies, core analysis to determine porosity, calcimetry for carbonate content, and microfossil analysis for age and depositional environment. Petrographic results show dominant packstone and wackestone lithologies, with pore types consisting of interparticle, moldic, and vuggy pores formed through bioclast dissolution and diagenesis. Core analysis reveals porosity values ranging from 1.5% to 22.1%, averaging 13.6%. High-porosity zones (>20%) occur in the western and northwestern parts, associated with bioclast-rich facies and meteoric water dissolution, whereas low values (<10%) are concentrated in the southeastern part due to compaction and recrystallization. These findings indicate that lithofacies variation and diagenetic processes significantly control reservoir quality. Overall, the Mundu Formation demonstrates good potential as a carbonate reservoir, particularly within packstone facies with well-developed secondary porosity, providing a useful basis for hydrocarbon and groundwater exploration in the northern East Java Basin.

Keywords: Carbonate Reservoir; Diagenesis; Mundu Formation; Porosity

Introduction

This study was conducted in the Gunung Pegat area, Sambeng District, Lamongan Regency, East Java Province. The Gunung Pegat area in Lamongan, East Java, is located within the Rembang Zone, a tectonically active belt marked by strike-slip faults, folds, and fractures that have developed since the Neogene. These geological conditions provide a favorable setting for the development of secondary porosity in carbonate rocks (Janjuhah et al., 2021; Vásconez Garcia et al., 2024). Geomorphologically, the study site represents a transition between alluvial lowlands and gently rolling hills, where limestone outcrops of the Mundu Formation are widely exposed. Such conditions make the area highly suitable for examining the relationship between lithology, depositional environment, and pore system characteristics.

The Mundu Formation is composed of Pliocene-aged bioclastic limestone deposited in shallow marine environments with variable energy. Its lithology—dominated by micrite, sparite, and bioclastic components such as foraminifera and algae—supports the formation of both primary and secondary porosity.

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Despite its recognized potential as part of the petroleum system in northern Java (Doust & Noble, 2008; Koesoemadinata, 1980), most previous studies have focused on stratigraphy and paleontology (Affandi, 2020), leaving a gap in quantitative petrophysical evaluations. Detailed studies linking lithofacies, porosity, and diagenetic processes remain scarce, even though they are crucial for determining reservoir quality.

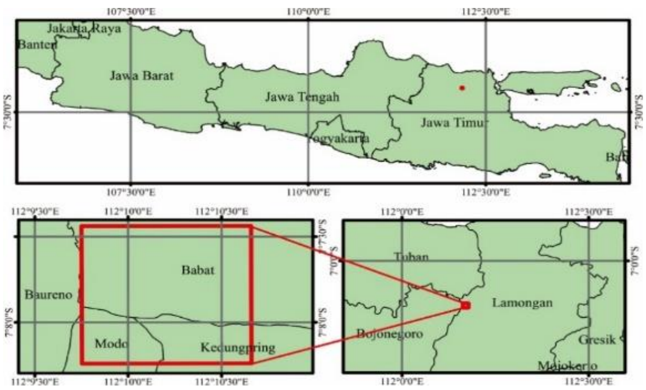

Figure 1. Location Index Map (Study area)

The novelty of this research lies in its integrated methodology. By combining field mapping with petrographic thin section analysis, core porosity measurements, and microfossil identification, this study provides a more comprehensive understanding of the Mundu Formation. This multi-approach strategy allows not only the identification of lithofacies types such as wackestone and packstone, but also the evaluation of how diagenetic processes—including dissolution, cementation, and recrystallization—control porosity both laterally and vertically. Such integration has not been systematically applied in previous studies of the Mundu Formation.

This research is important because porosity is a fundamental parameter in evaluating the suitability of carbonate rocks as reservoirs. The findings are directly relevant to hydrocarbon exploration, groundwater resource management, and geological risk mitigation in karst environments. By filling the gap in petrophysical data, this study strengthens the geological basis for identifying prospective reservoir zones in the northern East Java Basin and provides practical insights for future exploration and sustainable resource utilization.

The Mundu Formation, deposited during the Pliocene within the Rembang Zone, represents one of the most prominent shallow-marine carbonate units in northern East Java. Lithologically, this formation is dominated by bioclastic limestone composed of wackestone and packstone, containing abundant planktonic foraminifera, algae fragments, and other skeletal grains. Stratigraphically, the Mundu Formation overlies the Ledok Formation and is laterally intercalated with the Paciran Formation, reflecting a transition from deeper marine to shallower carbonate environments (Affandi, 2020). These facies variations record fluctuations in depositional energy that are important in controlling primary porosity development. At the same time, the tectonic reactivation of the Rembang Zone since the Neogene has generated strike-slip faults, folds, and fractures that strongly influence the formation of secondary porosity and reservoir heterogeneity (Fahrudin & Aribowo, 2024; Prasetyadi et al., 2011).

Regionally, the Mundu Formation is part of the petroleum system of the northern East Java Basin and has long been considered to possess potential as a carbonate reservoir (Doust & Noble, 2008). Earlier studies, however, have tended to focus more on its stratigraphic succession, paleontological content, and general depositional framework (Affandi, 2020; Haryanto et al., 2020). Only a limited number of works have investigated its petrophysical properties in detail. For example, Nur'aini (2020) reported porosity values ranging between 4% and 18% from limestone samples in Lamongan, while Alkatiri (2019) emphasized the role of structural control on reservoir development. More recent research by Kololu & Matakupan (2023); Rachman et al. (2025) has highlighted the importance of facies variation and diagenetic processes in governing carbonate reservoir quality in East Java. Nevertheless, integrated studies that combine lithofacies description, petrographic observation, and laboratory-based core analysis for the Mundu Formation remain rare.

In carbonate reservoir studies, porosity is a key petrophysical parameter that determines the fluid storage capacity of rocks. Porosity in carbonates can be classified into two origins: primary porosity, which forms during deposition such as interparticle and intragranular pores, and secondary porosity, which develops through post-depositional diagenetic processes including dissolution, cementation, recrystallization, and fracturing (Choquette & Pray, 1970; Lucia, 1995). Moldic and vuggy porosity are typical features in bioclastic limestones, commonly formed by the dissolution of fossil fragments and carbonate grains (Memon et al., 2023). These pore types significantly enhance reservoir potential when well connected, but their distribution is highly variable.

The development of porosity in the Mundu Formation is also strongly affected by diagenetic processes. Dissolution of bioclasts by meteoric water can generate moldic and vuggy pores, increasing effective porosity, while cementation and compaction commonly reduce pore space by occluding interparticle pores (Kargarpour, 2020; Rachman et al., 2025; Wijaya & Kusuma, 2022). Recrystallization may alter pore geometry by reducing pore size or restricting connectivity. In addition, several sedimentological factors influence porosity values, such as grain size, sorting, and packing. Well-sorted and rounded grains tend to produce higher porosity than poorly sorted or angular grains (Beard & Weyl, 1973; Dasgupta & Mukherjee, 2019), while grain packing in cubic arrangements generally preserves more pore space compared to rhombohedral packing (Boggs Jr, 2009). These factors, combined with the influence of diagenetic alterations and structural deformation, result in a highly heterogeneous porosity distribution within the Mundu limestone.

Considering these factors, there remains a clear research gap in systematically evaluating the relationship between lithofacies, diagenetic processes, and porosity heterogeneity of the Mundu Formation. The absence of detailed and integrated petrophysical data has created uncertainty in predicting the spatial variation of reservoir quality, which is important not only for hydrocarbon exploration but also for groundwater resource management and geological risk assessment (Yuwanto & Rosadi, 2023).

Therefore, this study focuses on analyzing porosity characteristics of the Mundu Formation limestone in the Gunung Pegat area, Lamongan, by integrating core analysis, petrographic description, and microfossil identification. The objective is to evaluate the correlation between lithofacies, pore types, and diagenetic processes, as well as to understand the spatial distribution of porosity across the study area. The findings are expected to enhance the understanding of reservoir heterogeneity in the Mundu Formation and provide a valuable reference for carbonate reservoir evaluation in the northern East Java Basin.

Method

This research was conducted using field mapping and sampling methods, along with laboratory analyses that included petrographic analysis, core analysis, and microfossil analysis.

Field Mapping and Sample Collection

The field mapping activities aimed to identify outcrops of the Mundu Formation and to understand variations in lithology, stratigraphic sequences, and geological structures present in the study area. A total of 13 rock samples were collected from five measured stratigraphic sections. These samples were selected to represent a range of facies and diagenetic stages, thus providing a comprehensive overview of the lithological variability within the Mundu Formation.

Laboratory Analysis

Petrographic Analysis: Petrographic analysis was conducted on selected representative samples. These samples were cut and prepared into thin sections, which were then observed under a polarizing microscope. Observations focused on identifying texture, mineral composition, and pore types. Lithological classification was based on the identification of wackestone as the dominant facies, characterized by the presence of micrite and bioclasts that do not make contact with one another. In addition, observations were carried out to identify the effects of diagenetic processes such as dissolution, cementation, and recrystallization on pore system development.

Core Analysis: The core analysis aimed to determine the physical properties of the carbonate rocks, particularly porosity and density. The method used was conventional, employing a porosimeter in the core analysis laboratory. Each sample was analyzed to determine both total and effective porosity values, based on the ratio of pore volume to the total rock volume. This data was used to evaluate the fluid storage capacity of the Mundu Formation limestone.

Microfossil Analysis: Microfossil analysis was conducted to support age determination and depositional environment interpretation. The samples were processed using standard preparation methods and observed under a binocular microscope to identify fossil species. Age determination was based on the zonation classification by Gilinsky (1991), while the interpretation of the depositional environment referred to the classification proposed by Barker (2010).

Data Interpretation: Integration of field data and laboratory analysis results was used to interpret porosity variations within the Mundu Formation. The interpretation was carried out by considering the relationship between lithology types (particularly wackestone and packstone), pore types, and diagenetic processes.

Results and Discussion

Field Observations

Mapping results indicate that the Mundu Formation is extensively exposed in the central to western parts of the study area, with lithology dominantly composed of bioclastic limestone. The observation map shows four measured stratigraphic sections covering facies variations from east to west, along with the positions of 13 rock sampling points. The surface geological map indicates the distribution of the Mundu Formation and the presence of geological structures such as strike-slip faults and vertical joints cutting through the carbonate layers. These structures play an important role in the development of secondary porosity and delineate zones with higher reservoir potential.

The field observation map is equipped with a north arrow at the top to facilitate spatial orientation. Each stratigraphic section is displayed in a different color, while point symbols indicate the locations where rock samples were collected. The explanation of section line symbols and sampling points has been adjusted to match the legend on the map.

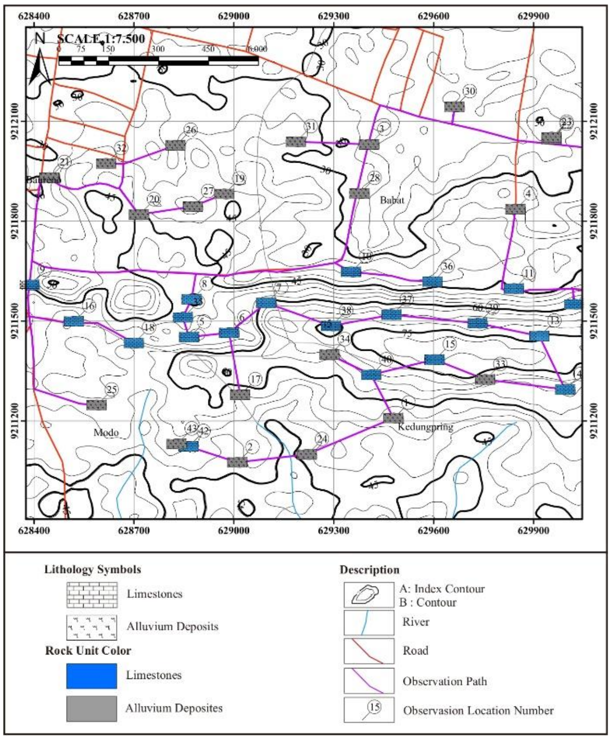

Figure 2. Observation Location Map

Based on Figure 2, the field observation locations display four main stratigraphic sections distributed from east to west across the study area, each marked with a different color. Each section represents variations in lithology and limestone facies of the Mundu Formation, observed systematically. Rock sampling points are clearly indicated on the map, showing a spatially distributed pattern suitable for laboratory analysis. The north arrow on the map aids in interpreting the orientation of local geological structures. This information provides an essential basis for understanding the lateral and vertical distribution of porosity characteristics, as well as the influence of geological structures on the pore system of the limestone.

The geological map displays the distribution of the Mundu Formation lithologies, fault structures, and local topography. A north arrow is located at the top of the map for orientation reference. Fault symbols are represented by dashed lines, while formation boundaries are marked with solid thick lines; all symbols conform to standard geological map legend conventions, although not explicitly shown in the Figure 3.

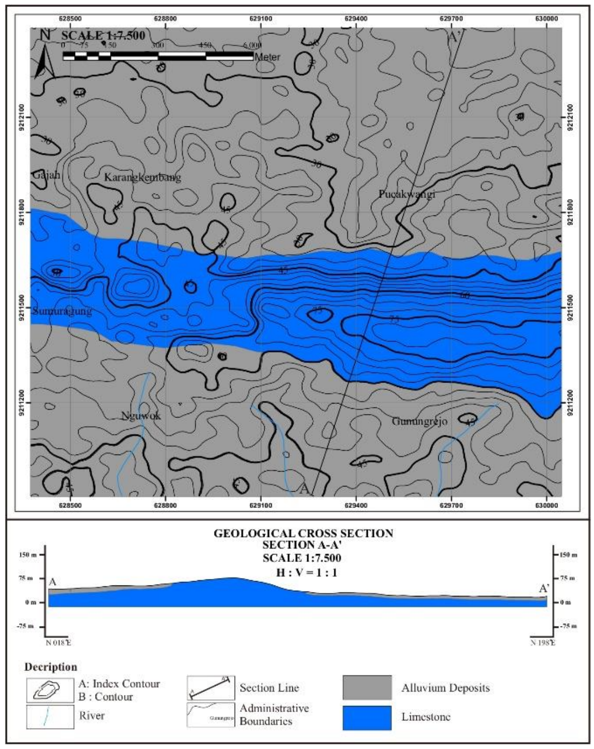

Figure 3. Geological Map

Based on Figure 3, the geological map of the study area shows that the bioclastic limestone of the Mundu Formation is predominantly exposed in the central to western parts of the study area. The lithological distribution pattern indicates a transitional zone from low-energy to moderate-energy facies, which corresponds with field observations. Topographic information on the map also supports the interpretation of the relationship between elevation and porosity potential, where areas with higher elevation generally exhibit more porous rock characteristics.

Laboratory Analysis

Petrographic Analysis:

A total of 13 thin sections of limestone from the Mundu Formation were microscopically analyzed to evaluate their textures, structures, and mineral compositions. The analysis was performed using a polarizing microscope under both plane-polarized light (PPL) and cross-polarized light (XPL). The classification of carbonate lithofacies follows the system proposed by Embry & Klovan (1971), which distinguishes types of limestone based on the abundance and dominance of bioclastic components (allochems) and the presence of carbonate matrix.

In this classification system, wackestone is defined as limestone containing more than 10% carbonate grains dispersed in a micritic matrix, without grain-to-grain contact. In contrast, packstone contains a higher abundance of bioclasts and exhibits grain-supported textures, although micrite still exists as a matrix that fills the pore spaces.

Based on the analysis results, out of the 13 samples examined, four samples were classified as packstone and nine as wackestone (Table 1). Samples with a packstone texture are dominated by fossil fragments and calcite grains with tight packing, reflecting a moderate- to high-energy depositional environment and a good potential for interparticle porosity development. In contrast, the wackestone samples are dominated by micritic matrix with scattered bioclastic grains, indicating a low-energy environment such as a lagoon, with more limited porosity.

In general, the observed porosity ranges from 1% to 2%, consisting of primary pores and, to some extent, secondary pores resulting from localized dissolution. The textural differences between wackestone and packstone reflect the variation of carbonate facies within the Mundu Formation and serve as an important basis for evaluating reservoir potential. Zones with packstone lithofacies demonstrate a better prospect as reservoir rocks compared to those with wackestone.

Table 1. Carbonate Rock Classification

Sample Code	Rock Classification
LP 5 middle	Packstone
LP 7	Wackestone
LP 10	Packstone
LP 11	Packstone
LP 14 middle	Wackestone
LP 14 top	Wackestone
LP 16	Wackestone
LP 17	Packstone
LP 18 bottom	Wackestone
LP 18 middle	Wackestone
LP 19 middle	Wackestone
LP 19 middle	Wackestone
LP 21	Wackestone

Wackestone samples, such as LP 7 through LP 21, are dominated by micrite with sparse, non-touching grains, reflecting a low-energy environment such as a lagoon. In contrast, packstone samples (LP 5 middle, LP 10, LP 11, LP 17) contain abundant grains in contact with one another, indicating deposition in a higher-energy environment, such as a mid-ramp setting. Packstone tends to exhibit better porosity and pore connectivity, whereas wackestone has reservoir potential primarily through the development of secondary porosity resulting from dissolution.

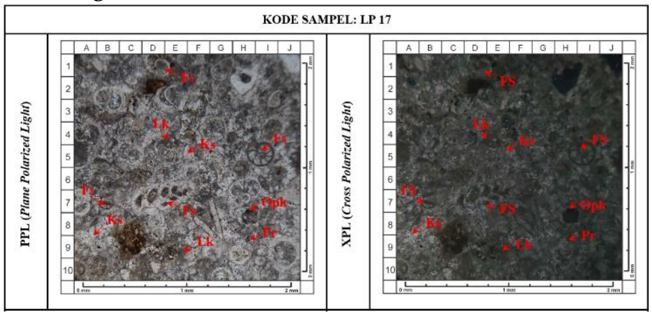

Figure 4. Thin Section Photomicrograph of Sample LP-17

Sample LP-17 (Wackestone)

The thin section of sample LP-17 exhibits a wackestone lithofacies characterized by a dark-colored micritic matrix that surrounds the carbonate grains. Bioclastic components such as foraminifera and algal fragments are scattered and do not make contact with one another. This feature indicates that the rock was formed in a low-energy depositional environment, such as a lagoon. The developed porosity is generally low, predominantly consisting of poorly connected intermatrix pores. Evidence of further cementation and compaction processes can be observed, which restrict the intergranular pore spaces.

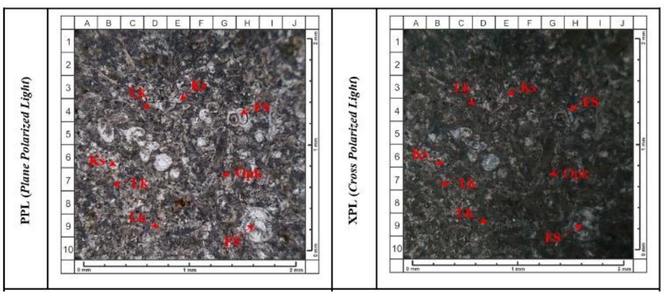

Figure 5. Thin Section Photomicrograph of Sample LP-21

Sample LP-21 (Packstone)

The packstone observed in the thin section of sample LP-21 is characterized by carbonate grains (bioclasts) in mutual contact, indicating well-developed grain support. Micritic matrix is still present, filling the spaces between grains, but in much smaller amounts compared to LP-17. Moldic porosity begins to develop, particularly in areas where partial dissolution of bioclasts has occurred. This sample reflects a higher-energy depositional environment compared to wackestone, such as a mid-ramp or a back-reef transitional zone, and exhibits better reservoir potential. The packstone sample displays a tightly packed grain structure with preserved intergranular pores. Although the absolute porosity value ranges from 1–2%, it is considered significant in the context of limestone, which typically undergoes porosity reduction due to diagenesis. The presence of secondary porosity, especially from bioclast dissolution, contributes to increased fluid accumulation capacity, thereby enhancing the reservoir potential of the rock.

Wackestone tends to be dominated by micritic matrix, which inhibits the development of effective porosity. This variation in rock types reflects changes in depositional energy within a shallow marine environment and results in lateral reservoir heterogeneity—one of the defining characteristics of carbonate systems. Based on this analysis, it can be concluded that the Mundu Formation, as a whole, still holds potential to be developed as a carbonate reservoir; however, its utilization requires further verification through quantitative petrophysical data and hydrodynamic testing.

Porosity Analysis

Porosity is a crucial parameter in evaluating reservoir quality, particularly in the limestone of the Mundu Formation, which exhibits a combination of primary and secondary porosity. The types of porosity observed include interparticle, moldic, vuggy, and fracture porosity, formed through diagenetic processes such as dissolution and recrystallization. Laboratory measurements indicate that total porosity ranges from 2% to 12%, with the following classification:
<5% → Very poor (non-reservoir zone),
5–10% → Fair,
>10% → Very good to prospective.

Packstone samples such as LP-7 and LP-18 Bottom recorded porosity values exceeding 10%, indicating significant potential as fluid accumulation zones. On the other hand, wackestone samples such as LP-13 and LP-11 exhibit lower porosity (<5%) due to micrite dominance and advanced cementation.

This map in Figure 6 is equipped with a north arrow at the top to facilitate orientation within the study area. A color scale is used to indicate porosity zoning, with a gradient ranging from green (low porosity) to red (high porosity). Contour lines represent isoporosity—lines of equal porosity values—helping to identify lateral trends in pore distribution. All map symbols follow the legend provided in the lower right corner of the image.
The porosity distribution map illustrates lateral variations that reflect the heterogeneity of reservoir quality in the limestone of the Mundu Formation. The highest porosity values (>25%) are found in the western to northwestern areas, particularly around Tremon Hamlet, influenced by secondary porosity types such as moldic and vuggy pores. In contrast, the southeastern zone near Kedungpring Village exhibits very low porosity (<10%) due to well-cemented and compacted rock. The central and southwestern regions show moderate porosity (10–20%) and are interpreted as transitional zones. This pattern aligns with geological and topographic conditions, where higher elevations tend to have better porosity and may serve as promising exploration targets.

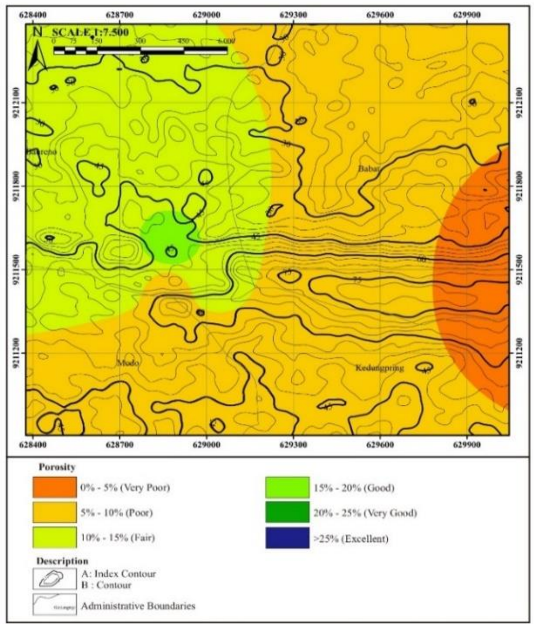

Figure 6. Porosity Value Distribution Map

Porosity analysis was conducted not only laterally but also vertically, to understand the variation in pore values with depth within the Mundu Formation limestone. This approach is essential given that carbonate reservoirs are stratigraphically heterogeneous due to the influences of lithology, diagenesis, and geological structures. Vertical data were obtained through laboratory measurements of samples collected from various outcrop points.

This map in Figure 7 illustrates vertical variations in porosity values based on core analysis data. A north arrow is included for consistent orientation. Color symbols represent porosity categories (high, moderate, low) in a stratigraphic context, while elevation contour lines indicate topographic changes that may influence the distribution of lithofacies and diagenetic processes. The color legend and units are adapted to standard geological and petrophysical mapping conventions.

The porosity distribution in the limestone of the Mundu Formation displays lateral variation that reflects spatial reservoir heterogeneity. Zones with high porosity (>20%) are concentrated in the western to northwestern part of the study area and are associated with bioclast-rich packstone lithofacies and meteoric water dissolution, resulting in secondary porosity such as moldic and vuggy types. In contrast, areas with low porosity (<10%) are located in the southeastern and northeastern regions, likely affected by diagenetic processes such as compaction and recrystallization, which reduce pore space. The central zone exhibits moderate porosity values (10–20%), representing a lithological transition between packstone and wackestone. This distribution pattern indicates that lithofacies, geological structures, and diagenesis play key roles in the development and distribution of porosity, and serve as an essential basis for identifying prospective reservoir zones within the Mundu Formation carbonate system.

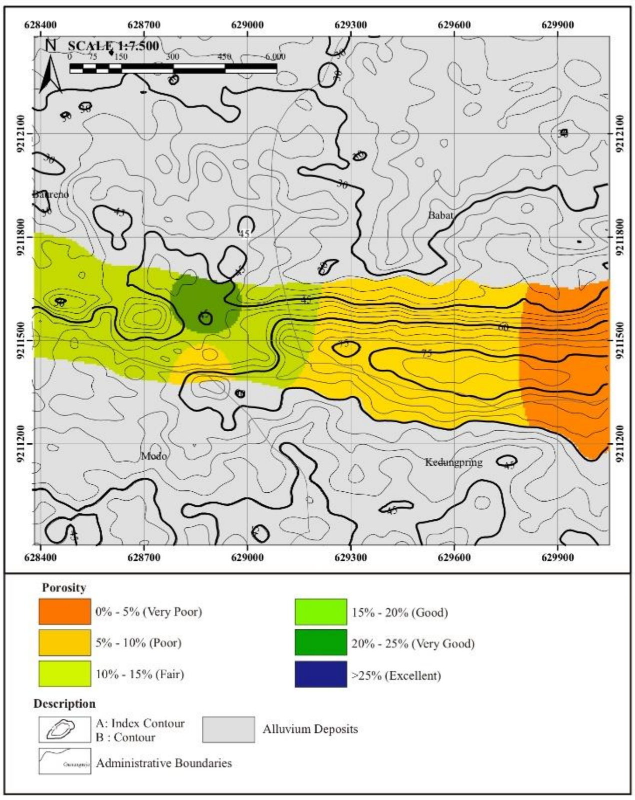

Figure 7. Porosity Distribution Map (vertical)

Based on Figure 8, the Porosity Distribution Bar Chart clearly illustrates the variation in porosity values among limestone samples from the Mundu Formation. The highest porosity is recorded in sample "Profile 2 LP 5 MID," with a value approaching 20%, followed by "Profile 2 LP 5 Bottom" and "Profile 1 LP 1 Top," which also show high porosity values exceeding 15%. These samples represent zones with greater fluid storage capacity, likely influenced by favorable conditions such as good grain packing, minimal cementation, or the presence of secondary porosity formed through dissolution. Such conditions are typically found in high-energy depositional environments or areas affected by diagenetic processes that enhance pore development. Conversely, samples such as "Profile 6 LP 18 Top" and "Profile 7 LP 9 Bottom" display very low porosity, indicating that the rocks are more compacted or have undergone extensive cementation, thus reducing the available pore space. The overall variation in porosity values reflects the heterogeneity within the Mundu Formation, influenced by differences in lithofacies, diagenetic alterations, and structural features such as fractures or folds. These factors significantly impact reservoir quality, making it essential to analyze porosity both laterally and vertically in order to identify productive zones and improve reservoir characterization.

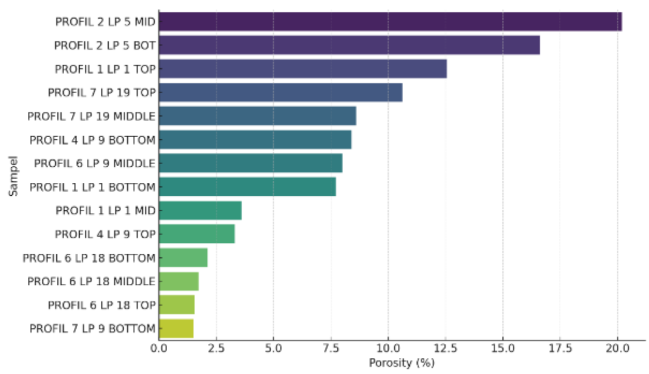

Figure 8. Porosity Distribution Bar Chart

Core Analysis

Core analysis of 13 limestone samples from the Mundu Formation was conducted to determine the physical properties of the rocks that directly relate to their reservoir potential. The analyzed parameters include porosity (%), density (g/cm³), and permeability (mD), all measured through laboratory testing. The results show porosity values ranging from 1.50% to 20.20%. The highest porosity values were recorded in samples LP 5 MID (20.20%) and LP 5 Bottom (16.61%), while the lowest were observed in LP 9 Bottom (1.50%) and LP 18 Top (1.53%).

These porosity values indicate that certain limestone zones possess good fluid storage capacity, particularly within the packstone intervals that are more susceptible to dissolution. Rock density ranges from 1.64 to 2.04 g/cm³. The lowest density is found in sample LP 5 MID (1.64 g/cm³), consistent with its high porosity value. In contrast, LP 18 MIDDLE (2.04 g/cm^3) and LP 18 Bottom (2.02 g/cm^3) exhibit high densities, indicating strong compaction and cementation and thus low porosity. A negative correlation between density and porosity is consistently observed across most samples.

In general, a combination of high porosity, low density, and high permeability is found in specific intervals of the Mundu Formation, particularly in sample LP 5, which demonstrates excellent reservoir characteristics. Meanwhile, other zones such as LP 18 and LP 9 Bottom show poor reservoir quality and may act as baffle zones or lateral seals. These findings highlight the importance of evaluating the internal heterogeneity of the Mundu Formation in planning for hydrocarbon exploration or carbonate aquifer modeling.

Microfossil Analysis

Microfossil analysis of the Mundu Formation limestone reveals a dominance of planktonic foraminifera such as *Globorotalia menardii* and *Orbulina universa*, indicating an Early to Middle Pliocene age and an open marine depositional environment. The presence of these fossils contributes to the development of primary porosity through the accumulation of skeletal shells, while their subsequent dissolution generates secondary porosity, such as moldic and vugular types—particularly observed in packstone samples. In contrast, wackestone generally exhibits lower porosity due to higher levels of cementation. Laboratory porosity values range from 4.3% to 22.1%, with an average of 13.6%, highlighting the significant role of microfossils and diagenesis in controlling pore network quality. Therefore, beyond serving as age indicators, microfossils also support depositional environment interpretations and porosity potential, reinforcing the Mundu Formation's prospect as a carbonate reservoir rock.

Discussion

The results of this study reinforce the understanding that the Mundu Formation, particularly in the Gunung Pegat area, holds significant potential as a carbonate reservoir rock. Based on petrographic analysis, core porosity data, and microfossil evidence, it was found that porosity distribution is intricately influenced by lithofacies, diagenetic processes, and geological structures. These findings are consistent with and expand upon previous research conducted in similar or nearby areas.

A study by Affandi (2020) in the Babat region, East Java, revealed that the Mundu Formation predominantly consists of bioclastic limestone deposited in shallow marine to transitional environments. This is in line with the findings of this study, where wackestone and packstone facies were identified, representing a shift in depositional energy from lagoon to mid-ramp settings. The presence of planktonic fossils such as *Globorotalia menardii* also supports the assignment of a Pliocene age and open marine environment, in accordance with micropaleontological interpretations by Haryanto et al. (2020).

In terms of petrophysical characteristics, Al Afif & Firsandi (2018) reported porosity values ranging from 4% to 18% for limestone in the Mundu Formation in Lamongan, which closely corresponds to the porosity range observed in this study (1.5%–22.1%). Laboratory results indicate that packstone intervals exhibit higher porosity and permeability values compared to wackestone, reinforcing the conclusion that lithofacies plays a central role in reservoir quality, as emphasized by Choquette & Pray (1970); Lucia (1995) in their classification of carbonate pore fabrics.

Furthermore, diagenesis is confirmed to be a crucial factor in the development of secondary porosity, such as the dissolution of bioclasts resulting in moldic and vuggy porosity. These findings align with the study by Wijaya & Kusuma (2022), which highlighted the significant influence of selective dissolution and recrystallization in forming pore networks within Mundu Formation limestone. Zones with high porosity values, especially in the western and northwestern parts of the study area, can be associated with the influence of meteoric water infiltration along fractures and faults, as discussed by Doust & Noble (2008) regarding tectonic evolution and reactivation in the East Java Basin.

From a structural geological perspective, this study confirms the importance of strike-slip faults and vertical joints as controlling agents of reservoir heterogeneity. This supports the findings of Alkatiri (2019), who stated that geological structures within the Rembang Zone directly influence fracturing, dissolution, and pore quality in the Mundu Formation. In this context, zones with low density and high porosity such as LP-5 MID and LP-5 bottom can be considered sweet spots for hydrocarbon or carbonate aquifer exploration.

The importance of integrating geological and petrophysical data is also emphasized in this study, as proposed by Yuwanto & Rosadi (2023). The integration of stratigraphic, microfossil, lithofacies, and petrophysical parameters provides a more comprehensive understanding of reservoir heterogeneity. Transitional zones between packstone and wackestone, for instance, show potential as baffles or semi-barriers, which have implications for fluid migration pathways within the reservoir system.

Thus, the findings of this study enhance previous research on the Mundu Formation by providing a more detailed mapping of lateral and vertical porosity variations, along with their close relationship to lithology and geological structures. The main contribution of this research lies in its integrated approach, combining core analysis, petrography, and microfossil data, which establishes a robust foundation for carbonate reservoir evaluation—not only in the Mundu Formation but also for analogous carbonate systems within the northern East Java Basin.

Conclusion

This study concludes that limestone of the Mundu Formation in the Gunung Pegat area exhibits porosity values ranging from 1.5% to 22.1%, with an average of 13.6%. The highest porosity (>20%) is associated with packstone lithofacies, which are characterized by open grain packing, intensive bioclast dissolution, and low micrite content. In contrast, wackestone lithofacies display lower porosity (<10%) due to micrite dominance, compaction, and cementation. Petrographic observations reveal that pore types consist of interparticle, moldic, vuggy pores, and micro-fractures, all of which formed through dissolution and recrystallization processes. Core analysis further indicates that density ranges between 1.64–2.04 g/cm^3 and permeability varies from 6.14 mD to 361.09 mD. The combination of high porosity and permeability in certain samples (e.g., LP 5 MID and LP 5 bottom) suggests the presence of highly prospective reservoir zones, whereas other samples such as LP 18 and LP 9 bottom reflect poor reservoir quality and may function as flow barriers. In general, the Mundu Formation demonstrates reservoir potential that varies from marginal to good, with the best prospects localized in packstone facies enriched in secondary porosity. These findings not only fill the gap in petrophysical data for the Rembang Zone but also provide broader implications: they highlight the critical role of lithofacies and diagenetic processes in controlling reservoir quality in carbonate systems. Practically, the results can be applied in hydrocarbon exploration to identify sweet spots in carbonate reservoirs and may also serve as a reference for groundwater resource evaluation and geological risk assessment in the northern East Java Basin and other comparable carbonate provinces.

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Conflict of Interest
The authors declare no conflict of interest regarding the publication of this paper.

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