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Density and Porosity Analysis of Limestone as a Groundwater Reservoir in Kayubulan Village, Gorontalo Regency

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ABSTRACT

This study examines the potential of limestone in Kayubulan Village, Batudaa Pantai District, Gorontalo Regency, to determine its suitability as a groundwater reservoir. The research focuses on understanding the relationship between rock density and porosity, which are key factors in water storage capacity. The methods employed include geological field mapping, specific gravity testing following SNI 1969:2008 standards, and petrographic analysis. Geological field mapping identified the distribution and characteristics of limestone facies, while specific gravity testing involved measuring dry weight (W_0) and saturated weight (W_w),which were incorporated into Giancoli's (2014) density formula. Petrographic analysis was conducted to examine the inverse relationship between density and porosity in various limestone facies and to identify porosity types.Five samples representing Wackestone, Packstone, Crystalline Carbonate, and Coralline Framestone facies were analyzed for density, porosity, and water absorption. Based on Koesoemadinata's (1980) classification, porosity values were as follows: Wackestone 4.49% (negligible), Packstone 8.4% (poor), Wackestone FAK 12 10.54% (fair), Crystalline Carbonate 12.69% (good), and Coralline Framestone 23.7% (very good). Variations in micrite and sparite composition also influenced porosity; Wackestone FAK 15 showed lower porosity than FAK 12 due to its higher sparite content.Coralline Framestone emerged as the most viable reservoir candidate, as high-porosity, low-density rocks generally exhibit superior water absorption capacities. These findings highlight the significance of porosity and density in groundwater management and offer valuable insights for optimizing Gorontalo's water resources.

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1. INTRODUCTION

The Batudaa Pantai district in Gorontalo holds significant geological potential due to its abundant limestone deposits. While these deposits are known for their use in construction and industry, their full potential, particularly as groundwater reservoirs, has yet to be explored (Eksan et al., 2019). Local communities rely heavily on groundwater, making it essential to understand the physical characteristics of this limestone specifically, its density and porosity to assess its water storage capacity. Limestone has applications in various construction projects, including house foundations, road pavements, and other physical structures (Sukandarrumidi, 2016).

Prior research conducted at Gorontalo, including (Permana & Eraku, 2020; Permana et al, 2023; Suarno, 2023), has used petrographic porosity analysis to provide fundamental insights into the internal structure of limestone. Nevertheless, despite their interrelated influence on groundwater storage potential, these studies frequently ignore the role of density in connection to porosity. Sandstone typically produces less mineralized water since it is primarily composed of quartz, which is chemically inert. Limestone, on the other hand, often leads to harder water due to the dissolution of calcium and magnesium carbonates. These factors suggest that sandstone may be more advantageous as a groundwater reservoir, particularly in regions where consistent and high-quality water supply is critical. However, since the greatest geological potential at the site lies in limestone deposits, researchers have decided to focus their study on limestone to better understand its groundwater storage capacity.

This disparity emphasizes the necessity of a thorough investigation that incorporates both factors. To meet this need, this study uses Koesoemadinata's (1980) classification of porosity as a framework to investigate the link between density and porosity in the limestone of Kayubulan Village. By examining the inverse relationship between these factors, this study intends to provide a more precise evaluation of limestone's suitability as a groundwater reservoir, which will be a useful guide for future resource use initiatives.

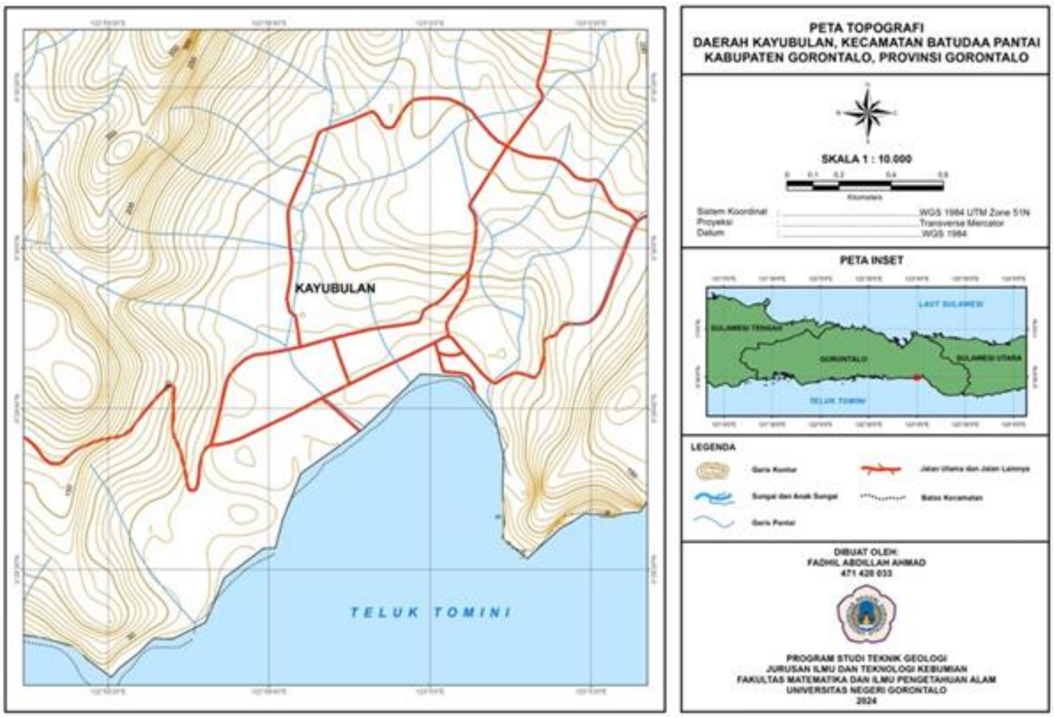

Figure 1. Map of the research location.

2. METHOD

2.1. Geological Mapping and Sampling Methods

The research location is in Kayubula Village, Batudaa Pantai District, Gorontalo Regency. This research focuses on limestone in the research area (Figure 1).This research employed two main methods: geological mapping and laboratory analysis. Field surveys focused on describing and interpreting limestone types and selecting suitable samples for laboratory testing (Permana et al, 2019; 2020; 2021; 2022; 2024a; 2024b; 2024c; Marfian et al, 2023; Mane et al, 2024; Damogalad et al, 2024; Mooduto et al, 2024; Robot et al, 2024; Sandi et el, 2024; Triyani et al, 2024; Wowiling et al, 2024; Suratinoyo et al, 2024; Panai et al, 2024). Laboratory analyses included specific gravity and petrographic tests. The study area's stratigraphy comprises pyroclastic breccia, diorite, and limestone. Researchers examined lithological features in the field, analyzed petrographic data, and compared the findings with prior studies. The research area is covered in the regional geologic map of Tilamuta by Bachri et al (1993). The stratigraphy consists of six units, from oldest to youngest:

Diorite, Pyroclastic Breccia, Packstone, Wackestone, Crystalline Carbonate, and Coralline Framestone.

2.2. Spesific Gravity Analysis

Specific gravity analysis is the ratio of an object's weight to its volume. Specific gravity analysis was conducted at the Soil Mechanics and Transportation and Highway Laboratories of the Civil Engineering Department, Universitas Negeri Gorontalo. To ensure a saturated surface-dry (SSD) condition, the sample is first dried in an oven at a temperature of 110 ± 5°C for 24 ± 4 hours, then cooled to room temperature and weighed to obtain the dry weight (W_0). Afterward, the sample is fully immersed in water for 24 ± 4 hours until no air bubbles remain. Once soaked, the sample is removed and gently blotted with a clean, absorbent cloth to remove surface water without reducing the water within the pores. This step is followed by a visual inspection to ensure no visible water remains on the surface. As soon as this condition is achieved, the sample is weighed to record the saturated surface-dry weight. The time and temperature were adjusted from the SNI 1969:2008 standards to ensure quality and accuracy in the measurements. Calculation of rock porosity using equation from Wiloso & Ratmy (2017):

$$Porosity\ (\%) = \frac{W_w - W_o}{W_w - W_s} \times 100\% \tag{1}$$

Where: W_w is the saturated weight of the sample after 24 hours (grams); W_o is the dry weight of the sample after 24 hours of oven drying (grams); W_s is the saturated weight of the sample suspended in water (grams). While the density value can be calculated using the formula from Giancoli (2014) :

$$Density = \frac{\rho_{fluida} \times m_o \times g}{W_o - W_w} \tag{2}$$

Where: ρ_fluida is the fluid volume of water (1000 kg/m^3); 〖 m〗 _o is the dry mass (kilograms); g is the gravitational acceleration (9.8 m/s^2); W_o is the dry weight of the sample (grams); W_w is the saturated weight of the sample (grams).

Porosity calculations are compared with the qualitative classification proposed by Koesoemadinata (1980), as shown in Table 1.

2.3. Pethrographic Method

Table 1. Classification of Porosity Based on Koesoemadinata (1980)

Percent	**Porosity Value**
0%-5%	Negligible
5%-10%	Poor
10%-15%	Fair
15%-20%	Good
20%-25%	Very Good
>25%	Excellent

This phase involves identifying limestone porosity types through thin-section analysis and porosity calculations. Petrographic analysis provides insights into the micrite and carbonate mud content, which affect rock porosity. This process helps determine porosity type based on Koesoemadinata's classification (1980). The analysis is conducted at the Petrography Laboratory, Geological Engineering Department, Universitas Negeri Gorontalo. Rock samples are prepared using blocking techniques to create thin sections that absorb blue dye, facilitating lab analysis (Crabtree et al., 1984). Five samples will undergo petrographic analysis. The descriptive classification system for carbonate pore types developed by (Choquette & Pray, 1970) (Figure 2), covering primary and secondary pores, is widely applied in both academic and commercial domains.

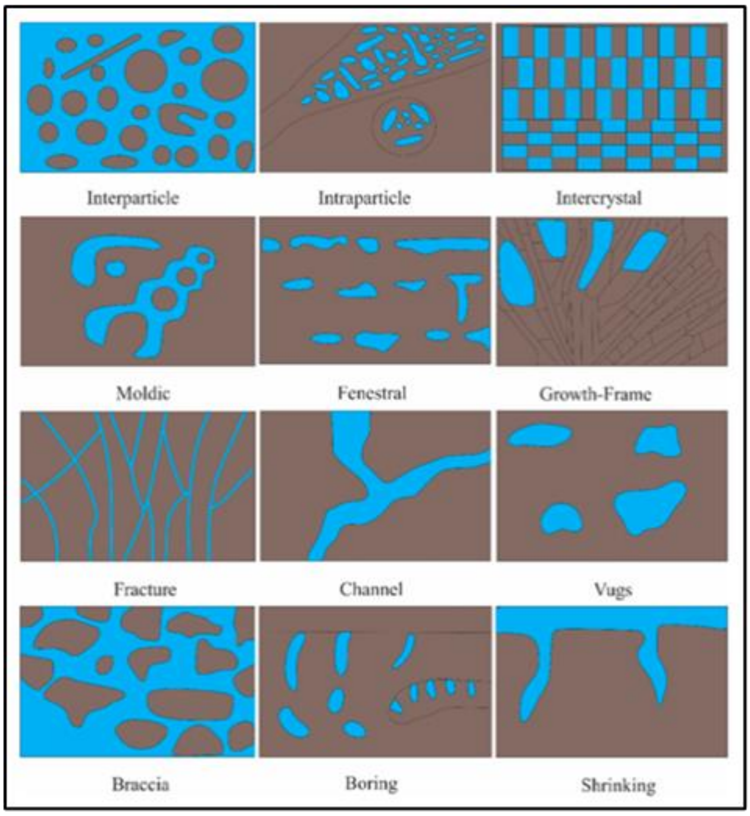

Figure 2. Porosity type based on Choquette & Pray (1970)

3. RESULTS AND DISCUSSION

3.1. Density and Porosity Analysis Based on Spesific Gravity Test

The density and porosity of limestone facies in the Kayubulan region of Batudaa Pantai District, Gorontalo Regency, are examined in this study. Five rock samples were observed to use specific gravity tests to measure their density and porosity (Table 2).

Generally, the relationship between porosity and density in all samples shows a consistent pattern. The higher the porosity, the lower the density, as more pore space causes the mass per unit volume to decrease. This is also directly related to the absorption value, where samples with higher porosity show a greater absorption rate.

Table 1. Classification of Porosity Based on Koesoemadinata (1980)

Code Sample	Porosity Based on Specific Gravity Test	Density	Water absorption
FAK 15	4.88%	24.67 kg/m^3	2.04%
FAK 9	12.71%	24.86 kg/m^3	5.78%
FAK 12	16.6%	22.10 kg/m^3	8.89%
FAK 2	20.5%	21.85 kg/m^3	11.77%
FAK 21	28.13%	21.16 kg/m^3	18.74%

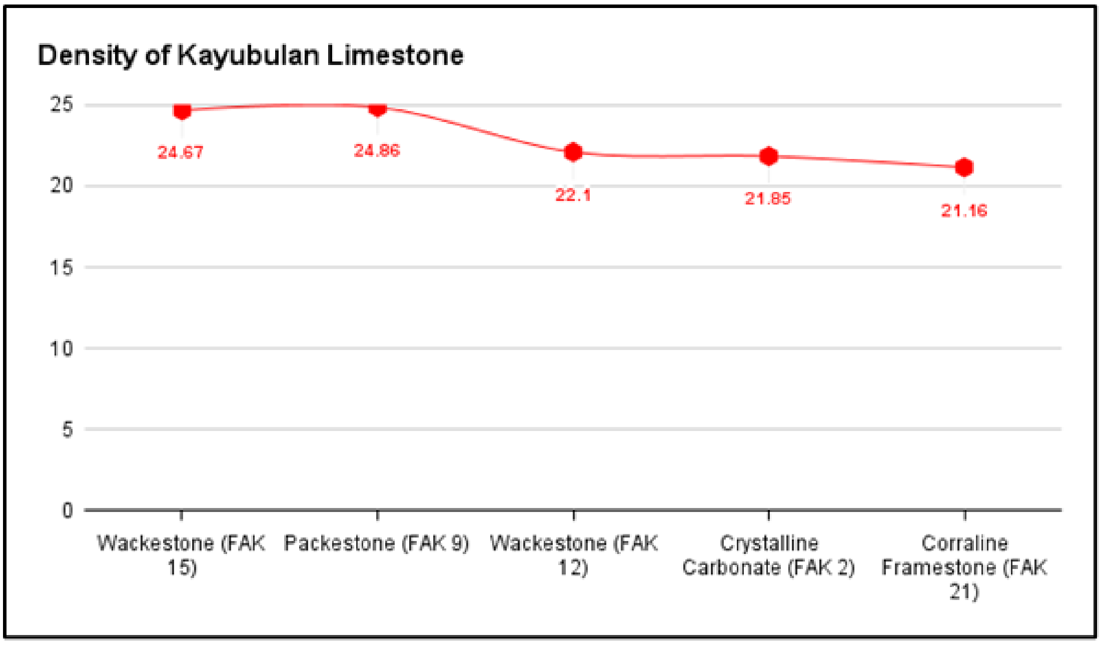

Figure 3. Density of Kayubulan limestone

Based on the graph above (Figure 3), it can be explained that:

a. **FAK 2**: This sample has a high porosity (20.50%), consistent with the relatively low density (21.85 kg/m³). The high porosity leads to a high water absorption value of 11.77%, indicating that many pore spaces can absorb water.
b. **FAK 9:** This sample has a lower porosity (12.71%), contributing to its higher density (24.86 kg/m³). The water absorption is lower (5.78%), which indicates that the pore space inside this sample is relatively less, leading to its higher density.
c. **FAK 12:** This sample had a fairly high porosity (16.60%), contributing to a slightly lower density (22.10 kg/m³) when compared to FAK 9. The water absorption value was 8.89%, indicating a still significant water absorption capacity.
d. **FAK 15:** With the lowest porosity among all samples (4.88%), FAK 15 has a high density (24.67 kg/m³) and the lowest water absorption (2.04%). This indicates that this sample is very dense with little pore space, which reduces the ability to absorb water.
e. **FAK 21:** This sample had the highest porosity (28.13%), which led to the lowest density (21.16 kg/m³) and highest water absorption (18.74%). This indicates that this sample has a large pore space, allowing for much water absorption.

In hydrocarbon and groundwater exploration, porosity and density are very important in determining the ability of rocks to act as reservoirs. Samples with low density and high porosity (e.g., FAK 21) show greater reservoir potential because the large pore spaces can store fluids such as oil, gas, or water. Conversely, samples with high density and low porosity (e.g., FAK 15) tend to be less effective as reservoirs due to their limited pore space. High density indicates a denser rock that is less permeable to fluids.

3.2. Porosity Analysis Based on Petrographic (Thin Section)

A detailed calculation of porosity values was done by observing five petrographic fields of view. The values obtained from each field of view were then averaged for more precise results. The measurement scale used was 24 mm².

3.2.1. Facies Crystalline Carbonate (Dunham, 1962)

Observations (Table 3) indicate porosity values for the five fields of view as 6.99%, 3.50%, 5.21%, 4.27%, and 4.41%. Averaging these values, the porosity for the Crystalline Carbonate facies is calculated to be 4.88%. Petrographic analysis indicates that this facies has vuggy porosity formed by limestone and intercrystalline porosity due to carbonate dissolution.

Table 3. Porosity values of Crystalline Carbonate Facies (FAK 2) based on petrographic analysis

MP	MP Area (24 mm²)	Porosity (%)	Average (%)
1	1.68	6.99	
2	0.84	3.50	
3	1.25	5.21	4.88%
4	1.03	4.27	
5	1.06	4.41	

This process creates voids between grains, potentially increasing total porosity if well-connected. However, in sample FAK 2, sparite infilling and other diagenetic processes limit the contribution of intercrystalline porosity, resulting in relatively low total porosity. Figure 4 shows minimal porosity, as indicated by the blue color in the thin petrographic section.

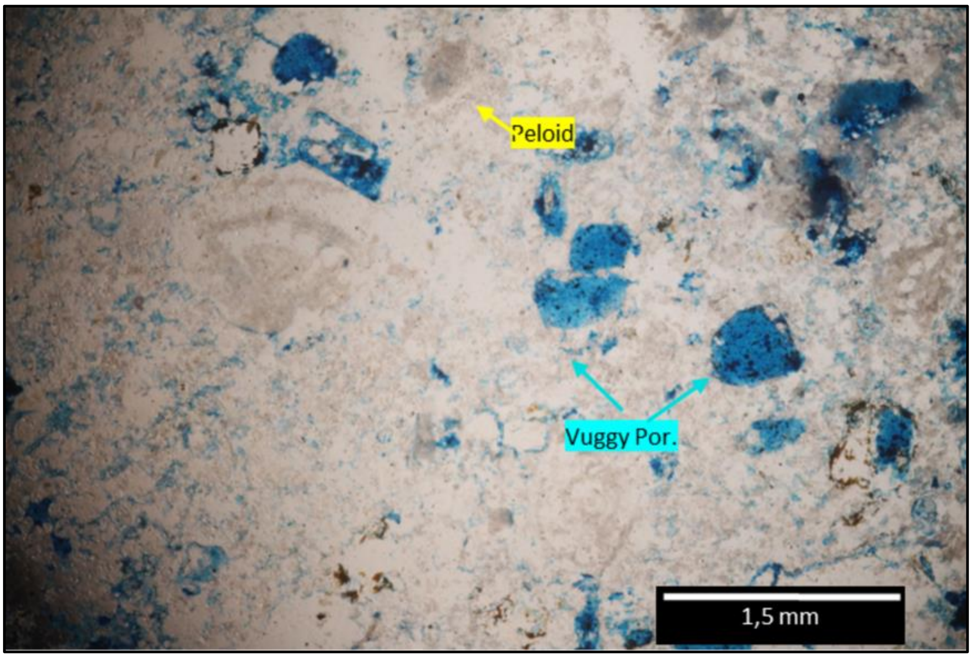

Figure 2. The results of petrographic analysis of Crystalline Carbonate (PPL), blue color indicates the presence of porosity

3.2.2. Facies Packestone (Embry & Klovan, 1971)

Observations (Table 4) show porosity values for the five fields of view as 3.30%, 3.73%, 5.43%, 5.24%, and 2.81%. The average of these values indicates a porosity of 4.10% for the Packestone facies.

Table 4. Porosity Values of Packestone Facies (FAK 9) Based on Petrographic Analysis

MP	MP Area (24 mm²)	Porosity (%)	Average (%)
1	0.79	3.30	
2	0.89	3.73	
3	1.30	5.43	4.10%
4	1.26	5.24	
5	0.67	2.81	

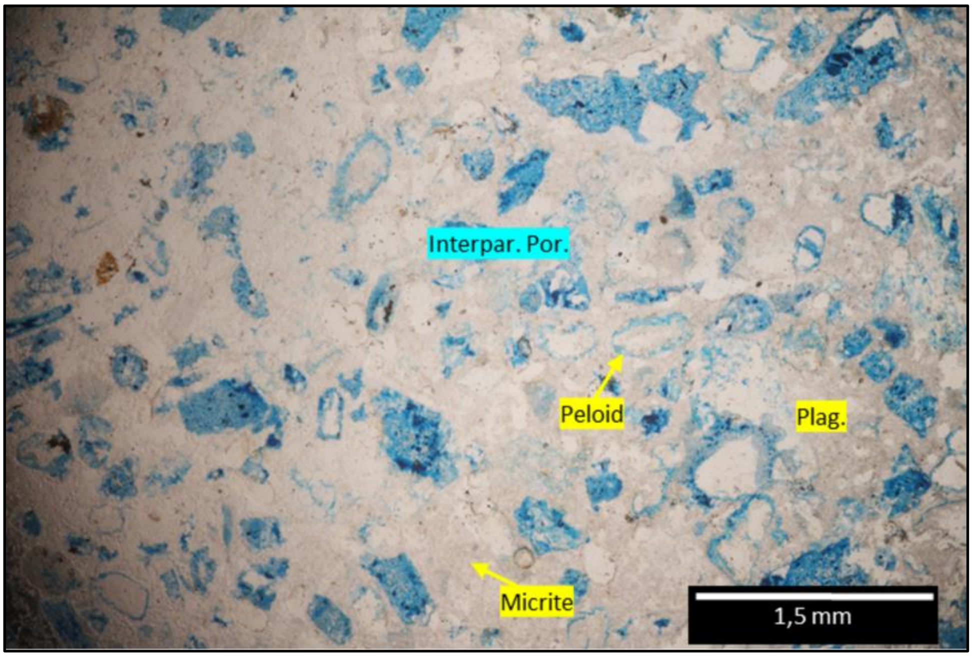

Figure 5. The results of petrographic analysis of Packestone (PPL), blue color indicates the presence of porosity

Petrographic analysis of sample FAK 9 reveals interparticle porosity, with voids occurring between particles. The rock exhibits a clast-supported texture with grain sizes ranging from 0.5 to 1 mm. Major components include peloids, plagioclase, rock fragments, and micrite matrix. This porosity primarily forms through diagenetic processes, particularly dissolution, leading to intercrystalline porosity. Minor porosity also developed after micrite recrystallized into blocky calcite, and coral fragments transformed into calcite and filled with micrite through micritization (Figure 5).

3.2.3. Facies Wackestone (Embry & Klovan, 1971)

Based on observations at Station FAK 12 (Table 5), porosity measurements were recorded as 2.86% in the first field of view, 4.85% in the second, 6.42% in the third, 4.22% in the fourth, and 4.12% in the fifth. The average porosity for the Wackestone facies across these fields of view is calculated at 4.49%. The observed porosity type is vuggy, resulting from the dissolution of limestone. This limestone exhibits low to moderate porosity, primarily due to intercrystalline porosity from minor dissolution. The composition is mainly micrite (30%) and sparite (35%), with foraminifera and peloids as grains, indicating a marine organic origin. Recrystallization and micritization processes reduce primary porosity but allow limited circulation in the intercrystalline spaces (Figure 6).

Table 4. Porosity Values of Packestone Facies (FAK 12) Based on Petrographic Analysis

MP	MP Area (24 mm^2)	Porosity (%)	Average (%)
1	0.69	2.86	4.49%
2	1.16	4.85	
3	1.54	6.42	
4	1.01	4.22	
5	0.99	4.12	

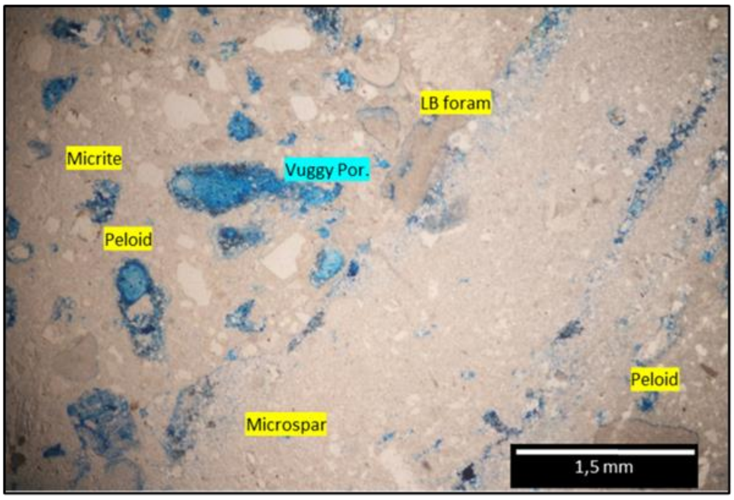

Figure 6. The results of petrographic analysis of Wackestone FAK 12 (PPL), blue color indicates the presence of porosity

A similar analysis was conducted on another Wackestone sample at station FAK 15. Observations show porosity values across five fields of view: 5.41% in the first, 2.90% in the second, 3.68% in the third, 7.73% in the fourth, and 0.83% in the fifth. The average porosity for this Wackestone facies is calculated to be 4.11%.

Table 6. Porosity Values of Wackestone Facies (FAK 15) Based on Petrographic Analysis

MP	MP Area ($24\ mm^2$)	Porosity (%)	Average (%)
1	1.30	5.41	4.11%
2	0.70	2.90	
3	0.88	3.68	
4	1.86	7.73	
5	0.20	0.83	

Sample FAK 15 exhibits a mud-supported texture, predominantly composed of peloids (15%), micrite (35%), and sparite (50%). The observed porosity is vuggy, formed by minor dissolution, resulting in irregular pore spaces. Although micrite has undergone recrystallization to microspar through neomorphism, this diagenetic process does not indicate the rock's diagenetic environment (Figure 7).

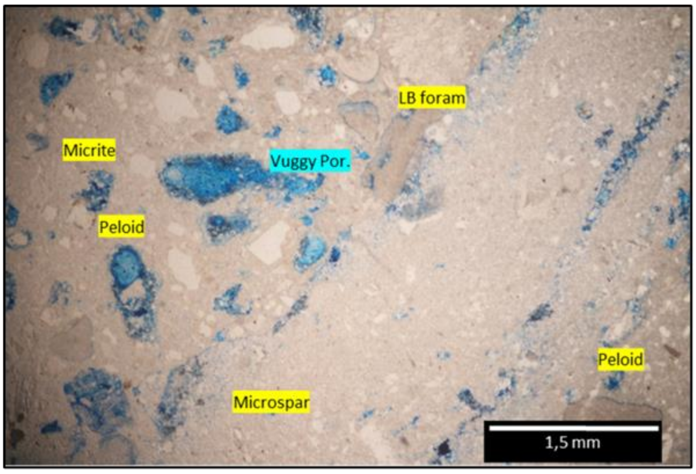

Figure 7. The results of petrographic analysis of Wackestone FAK 15 (PPL), blue color indicates the presence of porosity

3.2.4. Facies Carraline Framestone (Embry & Klovan, 1971)

Observations from five fields of view show varying porosity values: 20.22% in the first, 18.21% in the second, 18.58% in the third, 20.50% in the fourth, and 18.83% in the fifth field of view (Table 7). The average porosity for the Packstone facies is calculated to be 19.27%.

Table 7. Porosity Values of Corraline Framestone Facies Based on Petrographic Analysis

MP	MP Area (24 mm^2)	Porosity (%)	Average (%)
1	4.85	20.22	19.27%
2	4.37	18.21	
3	4.46	18.58	
4	4.92	20.50	
5	4.52	18.83	

In rock sample FAK 21, the observed porosity is framework growth, where pores formed due to coral framework growth during deposition. The rock predominantly comprises micrite (65%) and sparite (35%), indicating the recrystallization of micrite into sparite as part of the diagenetic process. Although neomorphism occurs, it does not provide specific indications of the diagenetic environment. The hollow structure likely results from micrite recrystallizing into sparite, increasing pore size, and shape modification (Figure 8).

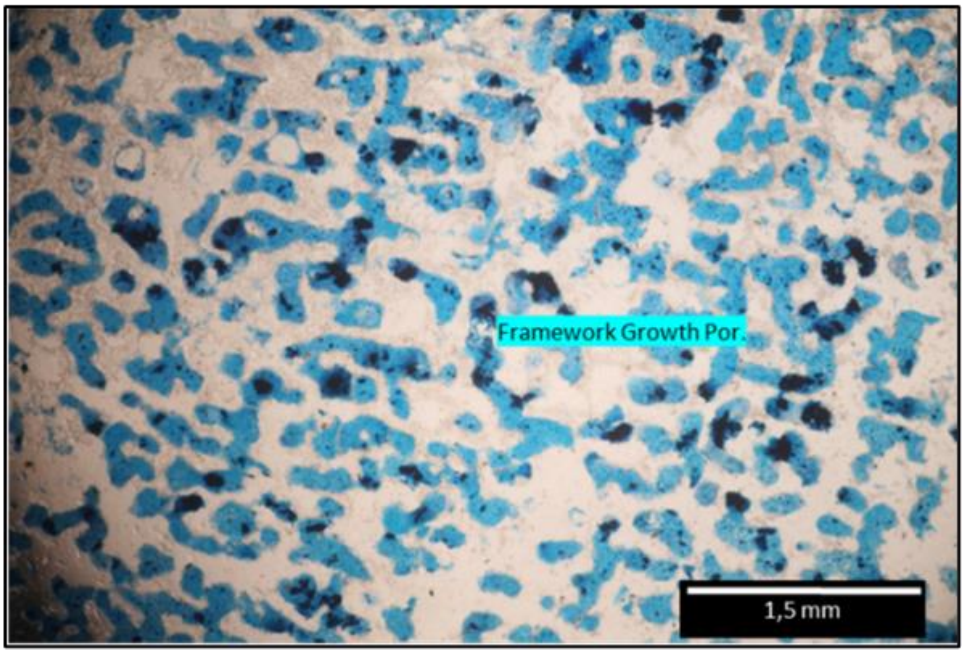

Figure 8. The results of petrographic analysis of Corraline Framestone (PPL), blue color indicates the presence of porosity

3.3. Potential Porosity

After obtaining the calculation results through the Specific gravity test and thin section, the researcher calculated the average value of limestone porosity in the research area based on the analysis of the two methods. The average porosity value in Table 8 was then classified using Koesoemadinata's classification (1980) to determine the quality of limestone in the research area as a reservoir rock in the ground (Table 8).

Table 8. Limestone porosity values from two analysis methods

No.	Sample	Rock Name	Porosity (Specific Gravity Test)	Porositas (Petrographic)	Average	Potential
1.	FAK 15	Wackestone	4.88%	4.11%	4.49%	Negligible
2.	FAK 9	Packestone	12.71%	4.1%	8.4%	Poor
3.	FAK 12	Wackestone	16.6%	4.49%	10.54%	Fair
4.	FAK 2	Crystalline Carbonate	20.5%	4.88%	12.69%	Good
5.	FAK 21	Corraline Framestone	28.13%	19.27%	23.7%	Very Good

Sample FAK 15, a Wackestone, has an average porosity of 4.49%, categorized as "Negligible" because its porosity is so low that it does not have much space between grains. Meanwhile, sample FAK 9 (Packestone) has an average porosity of 8.4% and is classified as "Poor," indicating that although its porosity is slightly higher than FAK 15, it is still less effective for fluid storage. In sample FAK 12, also a Wackestone, the average porosity reached 10.54% and was categorized as "Fair," indicating moderate pore space. Sample FAK 2, which is Crystalline Carbonate, has an average porosity of 12.69% and is classified as "Good," meaning that its porosity is high enough to store more fluid. Finally, sample FAK 21 (Corraline Framestone) is considered "Excellent" and has the highest porosity of 23.7%, making it the best choice for fluid storage. In general, the capacity of the rock to store fluid increases with its porosity value, as depicted in the graph below. The difference in porosity indicates that mineral composition, rock type, grain structure, and diagenesis processes play a key role. Rocks like FAK 15, with a high sparite content, have low porosity due to the filling of intergranular spaces by carbonate cement. In contrast, rocks like FAK 21 with coral frameworks or FAK 2 with more open carbonate crystals have higher porosity. This trend suggests that the less intergranular filling material and the greater the pore connectivity, the higher the fluid storage capacity (Figure 9).

The variation in micrite and sparite percentages between Wackestone samples FAK 15 and FAK 12 affects their porosity differences. In FAK 15, 35% micrite and 50% sparite fill many intergranular spaces, reducing porosity. Sparite acts as a cement, binding the grains tightly, while micrite provides a smooth texture. In contrast, FAK 12 has more intergranular gaps, with 30% micrite and 35% sparite, resulting in higher porosity. This indicates that FAK 15 has lower porosity than FAK 12 due to its denser mineral content.

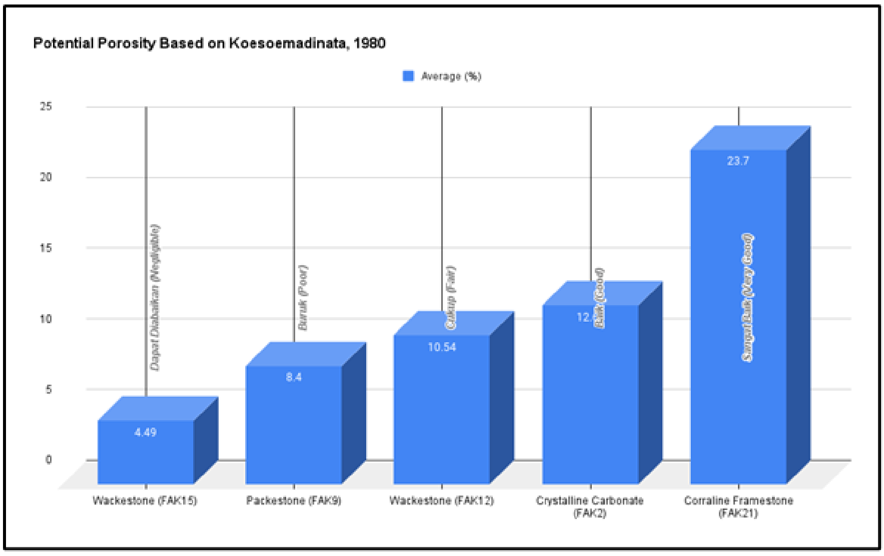

Figure 9. Potential porosity of limestone (Koesoemadinata, 1980)

4. CONCLUSIONS

In Kayubulan Village, Batudaa Pantai District, the potential of limestone to act as a reservoir varies across different rock types, or "facies." The Wackestone FAK 15 facies have very low reservoir potential, while Packstone is rated as poor. Wackestone FAK 12 has moderate potential, Crystalline Carbonate is good, and Coralline Framestone is excellent. The main reason for the difference in porosity between Wackestone FAK 15 and FAK 12 is their micrite and sparite content. FAK 15, with 35% micrite and 50% sparite, has lower porosity because it is more filled with these materials. In contrast, FAK 12, with 30% micrite and 35% sparite, has higher porosity. The amount of micrite and sparite strongly influences the rock's structure and porosity, supporting findings by (Janjuhah et al., 2021) and (Folk, 1959).

This study shows that rocks with higher porosity generally have lower density, allowing them to absorb more fluids, which makes them better suited as hydrocarbon or groundwater reservoirs. In comparison, denser rocks with low porosity hold less fluid and may be less stable for structural uses.

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