

## Petrographic Analysis and Facies Interpretation of The Mundu Formation Carbonates: Implications For Reservoir Potential

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### Abstract

Carbonate reservoirs account for more than half of the world's hydrocarbon reserves; however, their quality is highly heterogeneous and is influenced by petrographic characteristics. The Mundu Formation in East Java represents one of the important carbonate units in the East Java Basin petroleum system. This study investigates the petrographic characteristics of limestone from the Mundu Formation in Gunung Pegat, East Java, to evaluate its carbonate reservoir quality. Fieldwork included geological mapping, stratigraphic profiling, and rock sampling, followed by petrographic analysis of seven thin sections (LP5, LP7, LP11, LP14, LP16, LP17, LP19). Thin sections were stained with Methylene Blue and examined under Plane Polarized Light (PPL), Cross Polarized Light (XPL), and a  $\lambda$ -530 gypsum plate compensator. The results reveal three main lithological types—wackestone, packstone, and grainstone—with porosity values ranging from 12% (fair) to 47% (excellent), as reported by Koesoemadinata (1980). Facies interpretation indicates deposition in inner and outer back-reef lagoon environments, with the highest reservoir quality observed in high-porosity grainstone. Additional petrophysical analysis on 14 samples reveals permeability values ranging from 42.119 to 361.086 mD, categorized as good to very good. These findings emphasize that lithological variability, depositional facies, and diagenetic processes are the key controls on carbonate reservoir quality in the Mundu Formation. The study provides valuable insights for carbonate reservoir modeling and hydrocarbon exploration in East Java.

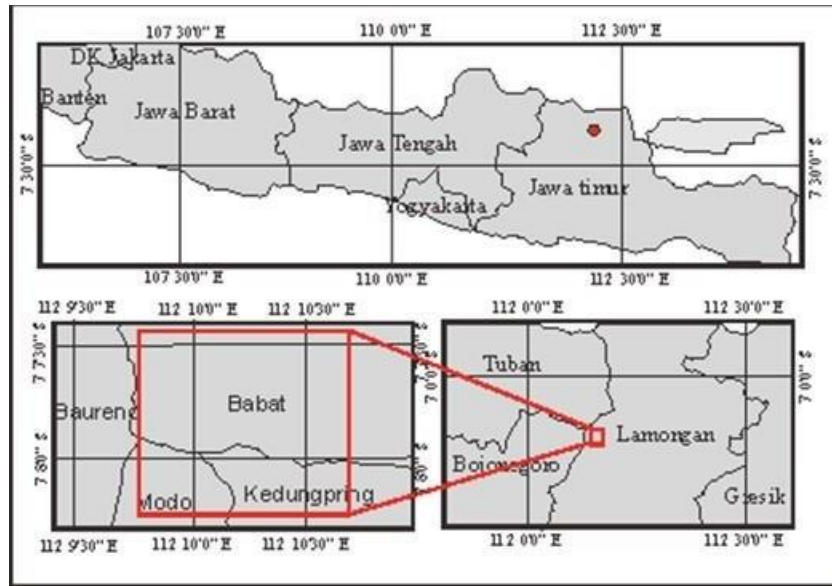
**Keywords** *Petrography, Limestone, Porosity, Carbonate Facies*

### INTRODUCTION

Carbonate rocks, mainly limestone, play a crucial role in the global petroleum system since more than half of the world's hydrocarbon reserves are stored in carbonate reservoirs (Lucia, 2007). The petrographic characteristics of limestone directly determine reservoir quality, particularly porosity, permeability, and facies distribution, which control fluid storage and flow. Petrographic study identifies textures, mineral composition, and porosity types formed during sedimentation and diagenesis. In the Indonesian context, carbonate basins have long been exploration targets, including the East Java Basin, which hosts productive carbonate formations. (Doust & Noble, 2008). The Mundu Formation in the research area is located in Mount Pegat, East Java (Figure 1). Geographically, it lies in the southern part of Lamongan Regency, bordering Bojonegoro Regency to the west and Jombang Regency to the south.

The Mundu Formation is recognized as part of this petroleum system, yet detailed petrographic studies on its limestone units remain limited. The lack of micro-scale data often leads to generalized reservoir interpretations. While previous works in the East Java Basin have focused on stratigraphy and basin-scale petroleum systems, few studies have emphasized petrographic heterogeneity at the microfacies level. Therefore, this study bridges the gap by linking thin-section petrography with porosity-permeability quantification to improve understanding of heterogeneity in the Mundu Formation reservoir.





**Figure 1.** Research location in Gunung Pegat, East Java.

## LITERATURE REVIEW

Carbonate rocks provide essential reservoirs for hydrocarbon systems, and their classification is fundamental in reservoir studies. The depositional textures of carbonate rocks determine their facies and reservoir properties, as first proposed by Dunham (1962) and later refined (Embry & Klovan, 1971). Porosity and permeability are the most critical petrophysical properties that control fluid storage and migration in carbonates, as explained in a detailed framework of petrophysics (Tiab & Donaldson, 2024). Early works emphasized the importance of depositional facies and diagenesis in determining reservoir quality, a fundamental principle established by Choquette and Pray (1970).

Carbonate petroleum systems in Indonesia, including those in the East Java Basin, have long been essential exploration targets. Basin-scale studies demonstrated the strong influence of carbonate stratigraphy and facies on hydrocarbon accumulations, as discussed in petroleum system analyses of Indonesia (Doust & Noble, 2008). The characterization of carbonate reservoir heterogeneity also advanced with the recognition that porosity evolution results from the interaction between depositional textures and post-depositional processes such as cementation, dissolution, and dolomitization, as shown in numerical simulations (Amour & Nick, 2021).

Recent studies provided new insights into the control of depositional environments and diagenetic histories on carbonate reservoir quality. An investigation of the Kawagarh Formation in Pakistan revealed that micritization, cementation, and selective dissolution strongly modified pore structures and influenced permeability (Khattak et al., 2024). A study of the Majiagou Formation in China revealed that dolomitization and dissolution increased porosity, whereas compaction and cementation decreased reservoir quality (Wu et al., 2023). A multi-scale analysis of Jurassic limestones in Abu Dhabi revealed heterogeneity, ranging from microfacies to core levels, that affected fluid flow, as reported by Sulieman et al. (2024). Microfacies analysis of Ordovician carbonates in China revealed that facies variability enhanced sea-level interpretation and facies modeling, as described by Wang et al. (2023).

Additional works also contributed critical perspectives on carbonate systems. Holocene carbonate sedimentation studies demonstrated that early cementation and microbial micritization were critical controls on reservoir evolution (Alsharhan & Kendall, 2020). A comprehensive guide to microfacies interpretation provides a direct link between petrographic features and depositional

models, as synthesized by Flügel (2019). Facies models for carbonate systems emphasize their predictive role in reservoir continuity across geological time, as highlighted by Wilson (2021). The influence of meteoric diagenesis on porosity enhancement was analyzed in shallow-marine reservoirs (Al-Aasm & Morad, 2021). Pore network heterogeneity was quantified with digital rock physics to improve permeability prediction in carbonate reservoirs (Li et al., 2022).

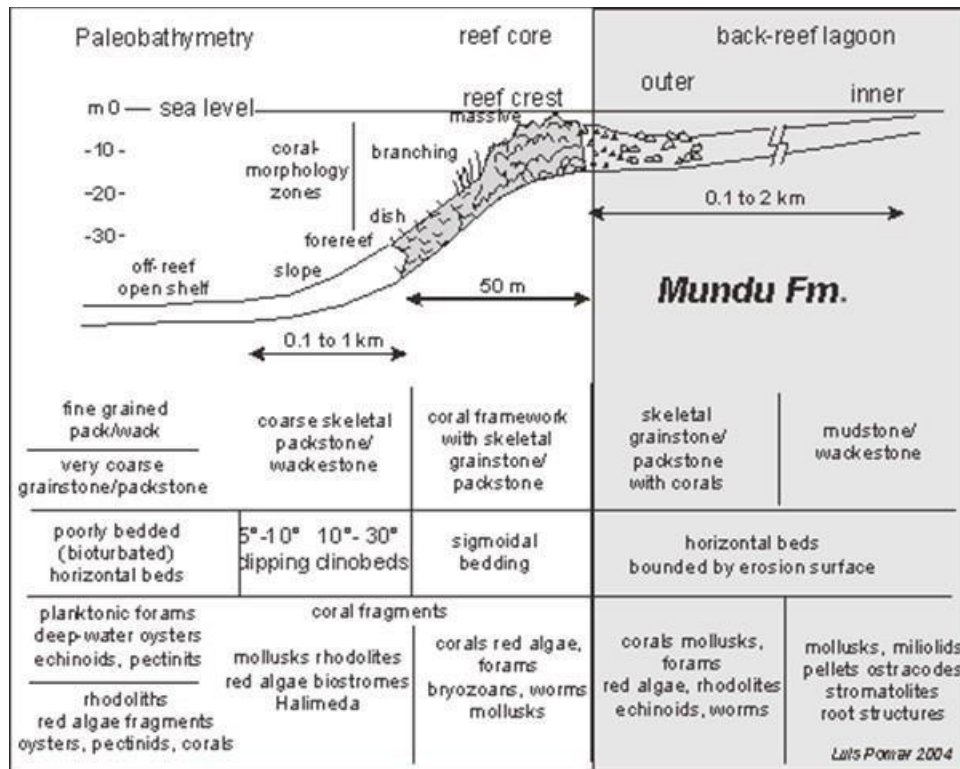
Despite these advances, essential research gaps remain. Many studies relied on advanced geochemical or digital imaging methods but did not integrate petrographic thin-section analysis with quantitative petrophysical data. Regional carbonate studies often focused either on depositional facies or on diagenetic overprints, but rarely combined both to explain heterogeneity at multiple scales. Only a limited number of investigations used outcrop analogues to directly connect depositional facies, diagenetic modifications, and reservoir properties. These knowledge gaps are particularly relevant for the Mundu Formation in East Java, where detailed integration of petrographic and petrophysical data remains limited.

## RESEARCH METHOD

Fieldwork involved geological mapping, stratigraphic profiling, and sampling at Gunung Pegat. Seven representative thin sections were prepared, stained with Methylene Blue, and analyzed using PPL, XPL, and a  $\lambda$ -530 gypsum plate. Lithology was classified according to Embry and Klovan (1971) can be seen in Figure 2 below. Porosity estimation followed the method of Koesoemadinata (1978), while permeability was measured using a gas permeameter with repeat measurements to ensure reproducibility. Depositional facies were interpreted based on Pomar (2001) (Figure 3). Additionally, permeability measurements were conducted on 14 samples using a gas permeameter with repeated measurements to ensure reproducibility. This stepwise methodology ensured the systematic acquisition and validation of data.

| Allocherts not organically bound during deposition |              |                            |            | Autocherts bound during deposition |          |                                                                           |           |            |
|----------------------------------------------------|--------------|----------------------------|------------|------------------------------------|----------|---------------------------------------------------------------------------|-----------|------------|
| Clast > 2 mm make up < 10%                         |              |                            |            | Clasts > 2 mm make up > 10%        |          |                                                                           |           |            |
| Contains lime mud (< 0.03 mm)                      |              | No lime mud                |            |                                    |          |                                                                           |           |            |
| Mud supported frameworks                           |              | Clast supported frameworks |            | Matrix supported                   |          | Organisms act as baffles that trap sediment                               |           |            |
| < 10% grains < 2 mm                                | > 10% grains |                            |            | Supported by clasts > 2 mm         |          | Organisms that encrust and bind e.g. algal mats, calcareous algae, bryozo |           |            |
|                                                    |              |                            |            |                                    |          |                                                                           |           |            |
| Mudstone                                           | Wackestone   | Packstone                  | Grainstone | Floatstone                         | Rudstone | Bafflestone                                                               | Bindstone | Framestone |

Figure 2. Carbonate rock classification by Embry & Klovan (1971).



**Figure 3.** Carbonate Facies Model

Source: [Pomar, \(2001\)](#)

## FINDINGS AND DISCUSSION

### Macroscopic Observations

The Mundu Formation limestone outcrops exhibit steep hilly morphology and quarry scars (Figure 4). The limestones range from white to pale brown, dominated by planktonic foraminifera, mollusk shells, and coral fragments. Some samples display visible pores, indicating variable depositional energy in back-reef lagoon environments.



**Figure 4.** Morphology of the Mundu Formation limestone outcrops in Gunung Pegat.

### Petrographic Analysis

Petrographic observation of thin sections provides a detailed understanding of the limestone microfacies, including grain composition, textural relationships, pore type, and diagenetic



overprints. This approach allows the identification of lithological variability that cannot be recognized in hand specimens, particularly in distinguishing between wackestone, packstone, and grainstone.

The thin-section analysis quantifies porosity types, such as interparticle, intraparticle, and vuggy porosity-using blue-dye impregnation, highlighting pore networks under transmitted light. Combining observations under plane-polarized light (PPL), cross-polarized light (XPL), and compensator plates ensures the accurate identification of mineralogy and pore fabrics.

This section presents the petrographic description of each sample (LP5, LP7, LP11, LP14, LP16, LP17, and LP19), highlighting their texture, composition, porosity values, and depositional facies (Figures 5 and 6). The results provide insights into the heterogeneity of the Mundu Formation limestones and their implications for reservoir quality

#### 1. Petrographic Description of Sample LP5

The sample is brownish-white in color with an excellent sand-sized fraction (0.0625–0.125 mm) and non-fabric-selective vuggy porosity. Rock composition consists of grains (9%), mainly bioclastic fragments such as benthonic foraminifera and mollusk fragments, set within a micritic matrix. Skeletal grains (E–H, 11–13) and dolomite (C, 11) are present. The matrix (51%) appears blackish-brown and fine-grained. Porosity is 40% (excellent), with blank areas (K, 12–13). The rock is classified as Wackestone ([Embry & Klovan, 1971](#)) and represents an Inner Back-Reef Lagoon Facies ([Pomar, 2001](#)).

#### 2. Petrographic Description of Sample LP 7

This sample has a brownish-white color, with grain size ranging from medium sand (0.25–0.5 mm) to very fine sand (0.0625–0.125 mm). Porosity is non-fabric-selective, dominated by vugs. Rock composition is grains (79%), primarily skeletal fragments (B–E, 9–12) and dolomite (I–J, 9–10), with grain sizes <1 mm. Porosity is 21% (very good) with blank areas (G, 1). The rock is classified as Grainstone ([Embry & Klovan, 1971](#)) and corresponds to an Outer Back-Reef Lagoon Facies ([Pomar, 2001](#)). The texture is dominated by skeletal grains, planktonic foraminifera, and coral fragments, with relatively lower interparticle porosity.

#### 3. Petrographic Description of Sample LP 11

The sample is brownish-white, with excellent sand grain size (0.0625–0.125 mm) and non-fabric-selective vuggy porosity. Rock composition includes grains (59%), dominated by large planktonic foraminifera, coral fragments, and sparite cement. Skeletal grains (H–L, 9–13) and dolomite (I, 4) (<1 mm) are present. The matrix (10%) is blackish-brown, fine-grained (<0.06 mm), slightly rounded, with low relief. Interference colors include blackish-brown (order 1) and greenish-yellow (order 1) (B, 15). Porosity is 31% (excellent) with blank areas (L, 13; Fig. 9). The rock is classified as Packstone ([Embry & Klovan, 1971](#)), belonging to an Outer Back-Reef Lagoon Facies ([Pomar, 2001](#)).

#### 4. Petrographic Description of Sample LP 14

This sample is brownish-white in color with very fine sand grain size (0.0625–0.125 mm) and non-fabric-selective vuggy porosity. Grain content is 10%, dominated by skeletal grains (A–G, 11–15) and dolomite (B, 7). The matrix (43%) is blackish-brown, fine-grained (<0.06 mm), slightly rounded, with low relief. Interference colors include greenish-yellow (order 1) (F, 15). Porosity is 47% (excellent) with blank areas (O, 14–15; Fig. 10). The rock is classified as Wackestone and represents an Inner Back-Reef Lagoon Facies.

#### 5. Petrographic Description of Sample LP 16

The sample is brownish-white, with very fine sand grain size (0.0625–0.125 mm). Both interparticle and vuggy types dominate porosity. Rock composition consists of grains (34%), mainly skeletal fragments (K–M, 11–14) and dolomite (H, 1–2). The matrix (42%) is

blackish-brown, fine-grained (<0.06 mm), slightly rounded, with low relief. Interference colors include greenish-yellow (order 1) (I, 9). Porosity is 23% (very good) with blank areas (A, 5–6; Fig. 11). The rock is classified as Packstone, belonging to an Outer Back-Reef Lagoon Facies. This sample exhibits a packstone texture, characterized by abundant bioclastic grains and planktonic foraminifera, and is supported by a dominant micritic matrix.

6. Petrographic Description of Sample LP 17

This sample is brownish-white, with very fine sand grain size (0.0625–0.125 mm) and non-fabric-selective vuggy porosity, predominantly intraparticle pores formed by partial dissolution. Rock composition consists of grains (46%), primarily skeletal fragments (K–M, 11–14) and dolomite (D, 10) (<1 mm). The matrix (42%) is blackish-brown, fine-grained (<0.06 mm), slightly rounded, with low relief. Interference colors include blackish-brown (order 1) and greenish-yellow (order 1) (B, 8–9). Porosity is 12% (fair) with blank areas (J–K, 4; Fig. 12). The rock is classified as Packstone, belonging to an Outer Back-Reef Lagoon Facies.

7. Petrographic Description of Sample LP 19

The sample is brownish-white with very fine sand grain size (0.0625–0.125 mm) and non-fabric-selective vuggy porosity. Rock composition includes grains (25%), mainly skeletal fragments (F–I, 1–7) and dolomite (E–F, 5–6) (<1 mm). The matrix (52%) is blackish-brown, fine-grained (<0.06 mm), slightly rounded, with low relief. Interference colors include blackish-brown (order 1) and greenish-yellow (order 1) (A, 3–4). Porosity is 23% (very good) with blank areas (0.9; Fig. 6). The rock is classified as Packstone, belonging to an Outer Back-Reef Lagoon Facies (Fig. 14). This sample demonstrates the development of secondary voids associated with diagenetic processes. These observations highlight lithological and diagenetic controls that contribute to heterogeneous reservoir quality, even within samples from the same formation.

The quantitative Porosity values range from 12% (fair) in LP17 to 47% (excellent) in LP14. Grainstones consistently show higher porosity compared to packstones and wackestones. This heterogeneity reflects textural control on reservoir quality (Table 3). The findings align with Southeast Asian studies emphasizing facies control on carbonate reservoir properties (Khalid et al., 2022; Pamenta et al., 2023). Unlike previous basin-scale stratigraphic studies, this research demonstrates microfacies-based reservoir heterogeneity in the carbonates of the Mundu Formation.

**Table 1.** Porosity classification

| No | Term       | Porosity (%) |
|----|------------|--------------|
| 1  | Negligible | 0–5          |
| 2  | Poor       | 5–10         |
| 3  | Fair       | 10–15        |
| 4  | Good       | 15–20        |
| 5  | Very Good  | 20–25        |

Source: [Koesoemadinata, \(1978\)](#)

**Table 2.** Permeability Classification.

| No | Term  | Permeability (mD) |
|----|-------|-------------------|
| 1  | Tight | <5                |
| 2  | Fair  | 5–10              |

| No | Term      | Permeability (mD) |
|----|-----------|-------------------|
| 3  | Good      | 10–100            |
| 4  | Very Good | 100–1000          |

**Table 3.** Petrographic Analysis Results with Porosity Values.

| Sample No. | Lithology  | Porosity Value (%) | Classification | Facies                 |
|------------|------------|--------------------|----------------|------------------------|
| LP5        | Wackestone | 40                 | Excellent      | Inner back-reef lagoon |
| LP11       | Packstone  | 31                 | Excellent      | Outer back-reef lagoon |
| LP7        | Grainstone | 21                 | Very good      | Outer back-reef lagoon |
| LP14       | Wackestone | 47                 | Excellent      | Inner back-reef lagoon |
| LP16       | Packstone  | 23                 | Very good      | Outer back-reef lagoon |
| LP17       | Packstone  | 12                 | Fair           | Outer back-reef lagoon |
| LP19       | Packstone  | 23                 | Very good      | Outer back-reef lagoon |

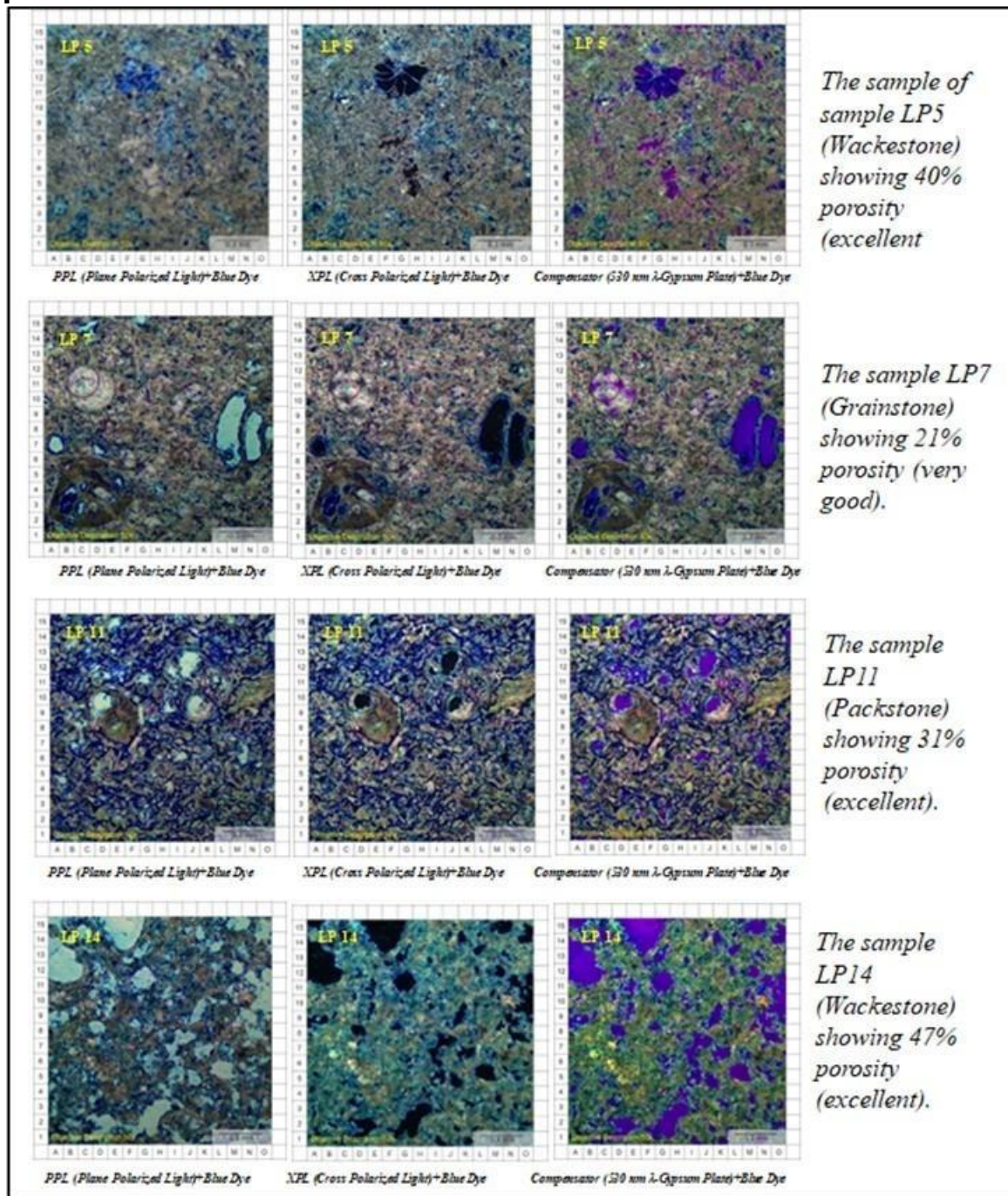
**Table 4.** Permeability Analysis Results

| Sample No. | Porosity (%) | Density (gr/cm3) | Permeability (milli darcy) |                 |
|------------|--------------|------------------|----------------------------|-----------------|
|            |              |                  | Darcy                      | Mili Darcy (mD) |
| LP1        | 12.554       | 1.708069         | 0.211601                   | 211.601         |
| Lp1 mid    | 3.601        | 1.92905          | 0.095792                   | 95.792          |
| Lp1 bot    | 7.717        | 1.918987         | 0.065192                   | 65.192          |
| LP5 bot    | 16.609       | 1.665742         | 0.361086                   | 361.086         |
| LP5 mid    | 20.196       | 1.643021         | 0.338862                   | 338.862         |
| LP9 top    | 3.298        | 1.926444         | 0.042119                   | 42.119          |
| LP9        | 7.999        | 2.06069          | 0.050006                   | 50.006          |
| LP9 mid    | 7.999        | 2.06069          | 0.050006                   | 50.00           |
| LP9 bot    | 8.404        | 1.973044         | 0.069181                   | 69.181          |
| Lp9 bot    | 1.504        | 2.03446          | 0.053630                   | 53.630          |
| LP18 top   | 1.536        | 2.011543         | 0.042619                   | 42.619          |
| LP18 bot   | 2.129        | 2.024335         | 0.059401                   | 59.401          |
| LP19 top   | 10.609       | 1.989429         | 161392                     | 161.392         |
| LP19 mid   | 8.597        | 1.909233         | 0.080821                   | 80.821          |

### Permeability Analysis

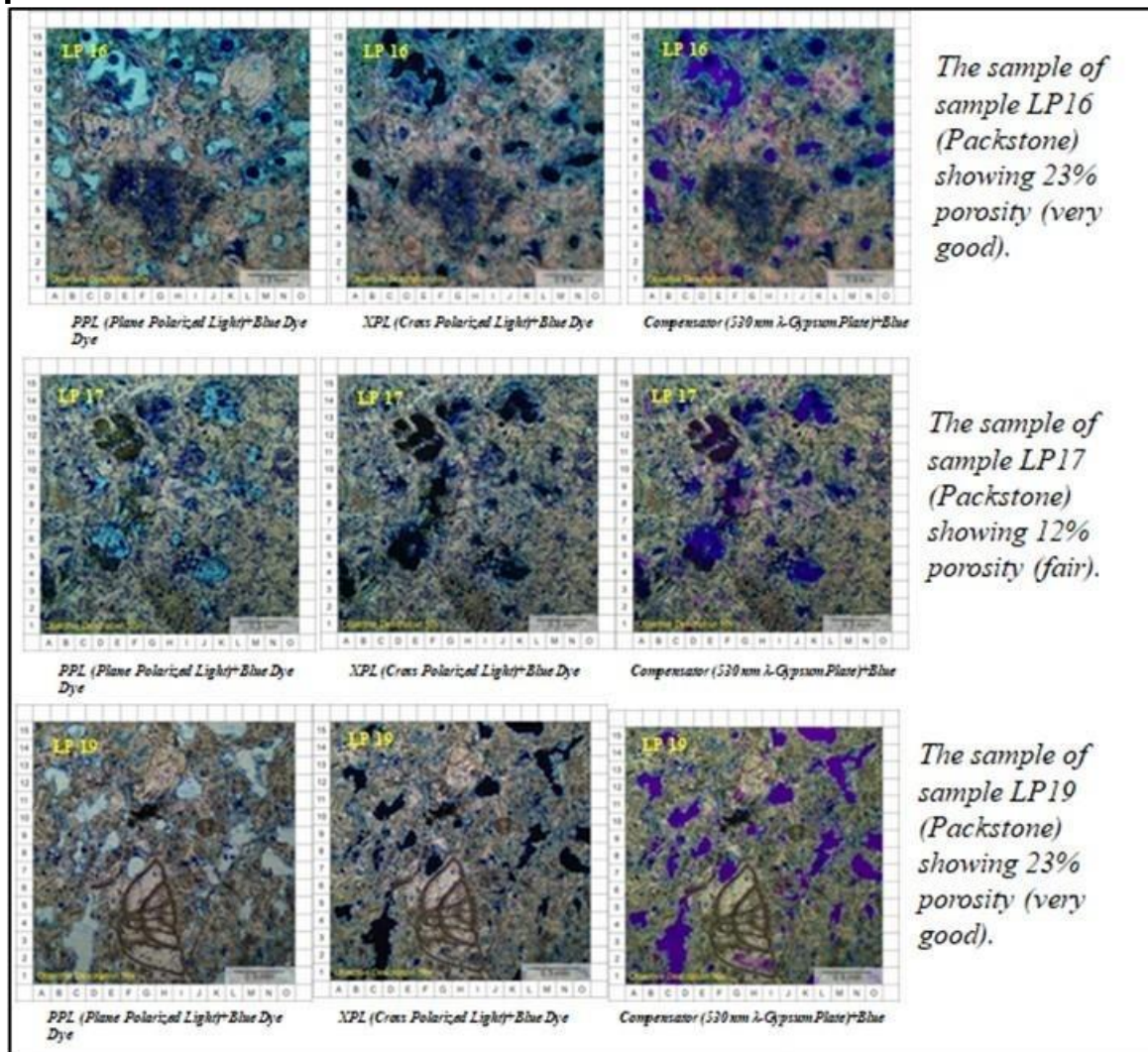
In addition to porosity, permeability is a key petrophysical property that governs the ability of reservoir rocks to transmit fluids. While porosity reflects a rock's storage capacity, permeability determines the efficiency of fluid flow through it. Permeability values are highly influenced by grain size, sorting, cementation, and diagenetic alterations such as dissolution and dolomitization (Choquette & Pray, 1970; Amour & Nick, 2021).

From the analysis of 14 representative limestone samples of the Mundu Formation, permeability values range from 42.119 mD to 361.086 mD, indicating reservoir quality that varies from good to very good. This wide range highlights the heterogeneity of pore connectivity across different facies. Higher permeability values are typically associated with grain-supported textures (grainstone), while matrix-supported textures (packstone, wackestone) show more restricted fluid pathways.



**Figure 5.** Thin Section Image (Blue Dye) of samples LP.5 -LP14.





**Figure 6.** Thin section image (Blue Dye) of samples LP.16 -LP19.

## CONCLUSIONS

This study concludes that the Mundu Formation carbonates comprise wackestone, packstone, and grainstone with porosity values ranging from 12% (fair) to 47% (excellent). Depositional facies and diagenetic processes strongly influence reservoir quality. Grain-supported textures (grainstone) exhibit higher porosity and permeability compared to matrix-supported textures (wackestone and packstone). The novelty of this study lies in integrating thin-section petrography with petrophysical measurements, providing microfacies-based insights into reservoir heterogeneity that have not been previously reported for the Mundu Formation.

## LIMITATIONS & FURTHER RESEARCH

This study is limited by the small sample size and the restricted analytical methods, which were confined to petrography and basic petrophysics. Future research should expand the number of samples and incorporate advanced diagenetic characterization (e.g., XRD, SEM-EDS), 3D facies modeling, and geophysical integration to achieve a more comprehensive understanding of carbonate reservoir heterogeneity in the Mundu Formation.

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