Jurnal Offshore: Oil, Production Facilities and Renewable Energy
Volume 9 No. 1 Juni; 24 ─ 34 **e -ISSN : 2549-8681**

Porosity and Permeability Study of the Mundu Formation Limestone Unit as a Potential Reservoir Rock in Gunung Pegat Area, Bojonegoro East Java

Danang Faisal[*1], Siti Umiyatun[2], Wahyuni Annisa Humairoh[2], Kharisma Idea[3], Samuel Antonio Gutteres[4] and Muhammad Ferdian Yusuf[1]

[1]Undergraduate student of Geological Engineering program,
[2] Lecturer of Geological Engineering program,
[3] Lecturer of Petroleum Engineering program
[4] Geological Engineering Doctoral Program Student,
Faculty of Mineral Technology
Department of Energy, Mineral and Technologies,
University of Pembangunan Nasional Veteran Yogyakarta, Indonesia
**Coresponding author : faisalamri.danang@gmail.com*

Abstract

This research was conducted in the Gunung Pegat area, Babat District, Bojonegoro Regency, East Java. The geographical coordinates of the research location are from 7°7'31" to 7°8'11" South Latitude and 112°9'46" to 112°8'54" East Longitude. Geologically, it is part of the North East Java Basin and is composed of the Mundu Limestone Formation. The research location is one of the sites that shows an outcrop of the Mundu Formation, with limestone lithology that has the potential to be a a target for hydrocarbon reservoir rock. The objective of the research is to study the porosity and permeability characteristics and to evaluate the potential of the limestone as a reservoir rock. The methods used include geological mapping, rock sampling, calcimetry analysis, petrographic analysis, and determination of porosity and permeability values. The results show that the geomorphological units of the research area are divided into anthropogenic, karstic, and fluvial landforms. The rock units at the research location are divided into a limestone unit and a fluvial unit; specifically, the limestone is classified as packstone and wackestone based on calcimetry and petrographic analysis. The stratigraphic sequence from the oldest to the youngest is the Miocene-aged Mundu Limestone Unit and the Holocene-aged Alluvial Unit. The average porosity value of the research area is 30.38%, which falls into the 'excellent' category, and the permeability value is 236.70 mD, which is classified as 'very good,' indicating that the research area has potential as a reservoir.

***Keywords**: porosity, permeability, reservoir, Mt. Pegat.*

Abstrak.

Penelitian ini dilakukan di daerah Gunung Pegat, Kecamatan Babat, Kabupaten Bojonegoro, Jawa Timur. Koordinat lokasi penelitian secara geografis berada pada 7°7′31″ hingga 7°8′11″ LS dan 112°9′46″ hingga 112°8′54″ BT. Secara geologi termasuk ke dalam Cekungan Jawa Timur Utara dan tersusun oleh Satuan Batugamping Formasi Mundu. Lokasi penelitian merupakan salah satu lokasi yang menunjukkan singkapan Formasi Mundu dengan litologi batugamping sebagai target batuan reservoir hidrokarbon. Tujuan penelitian untuk mengkaji karakteristik porositas dan permeabilitas serta mengevaluasi potensi batugamping tersebut sebagai batuan reservoir. Metode yang digunakan meliputi pemetaan geologi, sampling batuan, analisis kalsimetri, analisis petrografi, dan nilai porositas dan permeabilitas. Hasil penelitian menunjukkan bahwa satuan geomorfologi daerah penelitian dibagi menjadi bentuk lahan antropogenik, karst, dan fluvial. Satuan batuan pada lokasi penelitian dibagi menjadi satuan batugamping dan satuan fluvial yang secara spesifik batugamping diklasifikasikan menjadi packstone, dan wackestone berdasarkan analisis kalsimetri dan petrografi. Susunan stratigrafi dari yang paling tua ke yang paling muda yaitu Satuan Batugamping Mundu yang berumur Miosen dan Satuan Aluvial yang berumur Holosen. Nilai porositas rata-rata daerah penelitian 30.38% yang termasuk kedalam kategori istimewa dan nilai permeabilitas 236.70mD yang masuk dalam klasifikasi sangat baik menunjukkan daerah penelitian memiliki potensi sebagai reservoir hidrokarbon.

Kata kunci: porositas, permeabilitas, reservoir, G.Pegat.

I. INTRODUCTION

Gunung Pegat is located in Bojonegoro Regency, East Java, Indonesia. Administratively, the study area lies within the Randublatung Zone, which is part of the geological framework of The North East Java Basin. The location is situated between coordinates 7°7′31″ to 7°8′11″ S and 112°9′46″ to 112°8′54″ E. This area is one of the outcrops of the Mundu Formation that is considered to have potential as a reservoir rock.

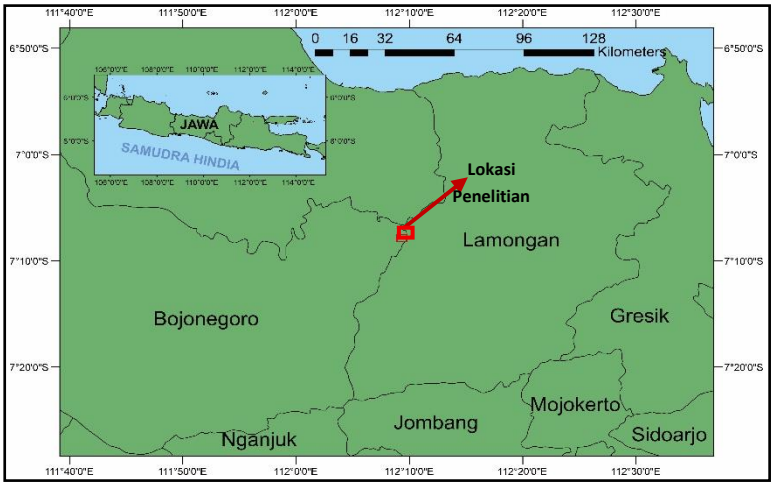

Figure 1. Research Location

Limestone in the Mundu Formation has been recognized as one of the formations that exhibit reservoir quality varying depending on facies, rock texture, and diagenetic processes (Dian et al., 2011). Primary porosity forms during sedimentation and is mainly of the intergranular type, while secondary porosity develops due to fossil dissolution and tectonic activity, leading to the formation of moldic, vuggy, and fracture porosity (Choquette & Pray, 1970 in Mahdi et al., 2022). The carbonate content in the rocks also plays a role in their lithological classification, where rocks with $CaCO_3$ content > 95% are categorized as pure limestone, while those in the 90–95% range are generally classified as dolomitic limestone (Flügel, 2010).

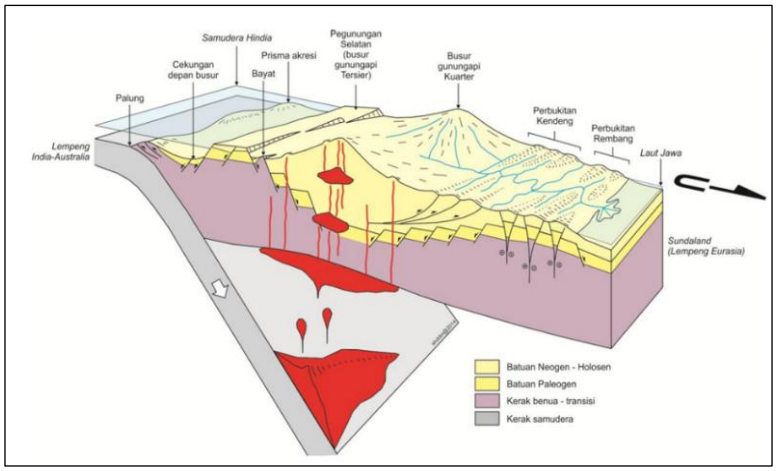

Figure 2 Physiography of The North East Java Basin (Husein, 2016)

Physiographically, the study area falls within the Rembang Zone, which is part of the North East Java Basin that developed as a back-arc basin at the southeastern end of the Sunda Shelf (Sribudiyani et al., 2003 in Dian et al., 2011). This region is bounded to the north by the Sunda Shelf and to the south by the Java volcanic line. The regional tectonic structure is controlled by the Rembang–Madura–Kangean–Sakala (RMKS) system, resulting in a pattern of west–east trending folding and faulting (Brandsen & Matthews, 1992 in Hall, 2002). The stretching phase from the Paleocene to the Middle Miocene caused basin subsidence, followed by a compression phase from the Middle Miocene to the Quaternary, which formed the Pegat anticline as well as horizontal and thrust fault structures (Husein and Nukman, 2015 in Husein, 2016) (Figure 2).

Stratigraphically, the North East Java Basin is filled with rock units ranging in age from Eocene to Pleistocene. The regional stratigraphic sequence begins with the Ngimbang, Kujung, Prupuh, Tuban, Ngrayong, Bulu, Wonocolo, Ledok, Mundu, Lidah, and Paciran Formations (Pringgoprawiro, 1983 in Umiyatun et al., 2023) (Figure 3). This formation is lithologically dominated by marly limestone and calcareous sandstone with an abundance of planktonic foraminifera. This research aims to analyze the porosity and permeability characteristics of the Mundu Formation limestone unit in the Gunung Pegat area, Bojonegoro Regency. Through the integration of petrography, laboratory analysis, and microfossil studies, a comprehensive understanding of the Mundu Formation's potential as a reservoir rock in the North East Java Basin is expected (Dian et al., 2011).

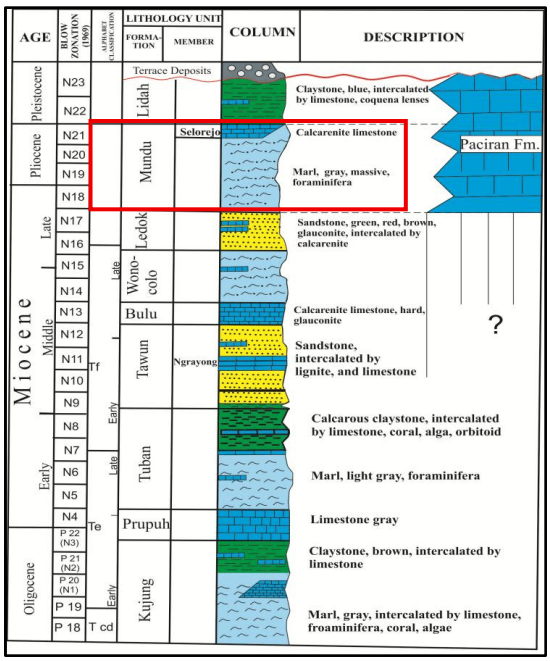

Figure 3 Stratigraphy of the North East Java Basin (Pringgoprawiro, 1983, in Umiyatun et al. 2023

Porosity is the measure of void spaces within rocks, expressed as a fraction of void volume to total rock volume, with values between 0 and 1 or in percentage terms from 0–100% (Koesoemadinata, 1980 in Wiloso & Khoirunnada, 2018). Primary porosity is formed during deposition, whereas

secondary porosity is generated through diagenetic processes such as dissolution, fracturing, and recrystallization (Choquette & Pray, 1970 in Mahdi et al., 2022).

Porosity in rocks can be calculated using the equation proposed by Koesoemadinata (1980). Based on this equation, porosity values can then be classified (Table 1).

$$\emptyset = \frac{Vp}{Vb} x100\% \quad \text{..... 1}$$

Description : Vp = Pore Volume (cm^3)

Vb = Total Volume (cm^3)

Based on equation 1, the data as then classified into Table 1.

Table 1 Porosity Value Classification

No	Term	Percentage (%)
1	Ignored	0 – 5
2	Bad	5 – 10
3	Fair	10 – 15
4	Good	15 – 20
5	Very Good	20 – 25
6	Excellent	>25

Table 2 Permeability Value Classification

No	Term	Permeability Value (mD)
1	Tight	< 5
2	Quite	5 – 10
3	Good	10 – 100
4	Very Good	100 – 1000

Permeability is the ability of a rock to transmit fluids. The relationship between porosity and permeability is strongly influenced by factors such as grain size, sorting, and degree of cementation (Heru & Zulvi, 2022).

According to Darcy's Law (Nurwidyanto et al., 2006), permeability can be calculated with a standard formula, and permeability values are further categorized (Table 2).

$$K = \frac{\mu.Qg.L}{A\Delta P} \quad \text{..... 2}$$

Description :
K = Permeability (darcy)
Qg = Flow rate (cc/s)
μ = viscosity (cp)
A = Area of the entire rock surface(cm^2)
ΔP = Pressure difference (atm)
L = Sample length (cm)

The objective of this study is to analyze the porosity and permeability characteristics of the Mundu Formation limestone unit in the Gunung Pegat area, Bojonegoro Regency. Through the integration of petrographic methods, laboratory analysis, and microfossil study, this research aims to provide a comprehensive understanding of the Mundu Formation's potential as reservoir rock within the Northern East Java Basin (Dian et al., 2011).

II. METHODOLOGY

The methodology applied in this research consists of two stages: geological mapping and laboratory analysis. Fieldwork involved geological mapping, stratigraphic section measurement, and rock sampling. Geological mapping was conducted to document surface geological conditions, including lithology, geological structures, and stratigraphic relationships among rock units.

Petrographic analysis was carried out by preparing standard thin sections with a thickness of 2 cm and examining them using a polarizing microscope under plane-polarized light (PPL) and cross-polarized light (XPL). The main objective of this analysis was to identify mineral composition, rock texture, and porosity type,

Core Analysis (AIB) was conducted on nine core samples. The process included porosity measurement using Boyle's Law with a Coreval 700 instrument and absolute air permeability measurement using the unsteady-state gas flow system. Samples were first cleaned with solvents (toluene and methanol), then oven-dried at 60 °C. Core analysis was conducted at the BBPMGB LEMIGAS laboratory in Jakarta, certified under ISO 17025 and ISO 9001-2000. The Coreval 700 used in this study is fully digital and automatically calibrated with check plugs from BPPT to ensure accuracy of porosity and permeability measurement (LEMIGAS, 2025).

Calcimetry analysis was carried out in the Sedimentology Laboratory, UPN "Veteran" Yogyakarta. This analysis determines calcium carbonate ($CaCO_3$) content in carbonate rocks by reacting samples with hydrochloric acid (HCl) and measuring the volume of CO_2 gas released. The measured CO_2 volume is directly proportional to the $CaCO_3$ content in the rock.

III. RESULTS and DISCUSSION

The outcrop shows limestone lithology coarsening upward with a total thickness of 24 m (Figure 4). The outcrop is characterized by packstone texture that becomes more crystalline upward. There is heterogeneity in color, with darker upper parts and lighter lower parts, likely due to weathering processes rather than facies changes. The darker color at the top is commonly associated with oxidation of organic matter in the carbonate weathering zone.

III. 1. Geology of The Research Area

Figure 4 Outcrop of LP 4

Geology

The dominant unit in the study area is the Mundu Formation Limestone Unit, marked in blue on the map. This formation has a wide distribution and occupies the central part of the map, extending from west to east. The alluvial deposits, composed of weathered material from the Mundu Formation Limestone, are distributed in the northeastern and southwestern parts of the map and occupy relatively gentle plains.

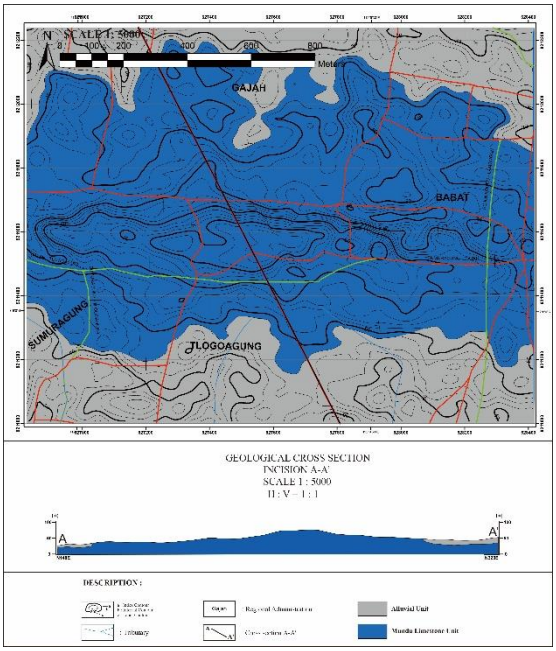

Figure 5 Geological Map of the Research Area

The rocks of the Mundu Formation at the research site are composed of limestone that is white to grayish to brownish and rich in planktonic foraminifera. Based on the geological cross-sections A-A' and B-B' shown in Figure 5, no major geological structures such as faults or folds were found at this map scale. However, regionally, the geological setting of the research area is controlled by a major fold structure in the form of an anticline with a general west-east orientation. This structure is thought to have uplifted the Mundu Limestone Unit to the surface.

Morphology of the research area

The study area is characterized by anthropogenic landforms created by limestone quarrying at Gunung Pegat, which produces artificial slopes, terraces, and flat quarry floors (Figure 6). To the north and south, karst landforms with residual hills dominate, reflecting carbonate dissolution processes.

Fluvial landforms occur in lowland areas, characterized by soil development from weathered limestone. In the northern and southern parts of the study area, the landform unit changes to karst, characterized by the presence of residual hills. This change is marked by a steeper topography and closely spaced contours. These landforms represent the original state of the study area before mining activities. This zone reflects more advanced carbonate dissolution, which has created the rugged relief characteristic of exposed carbonate rocks.

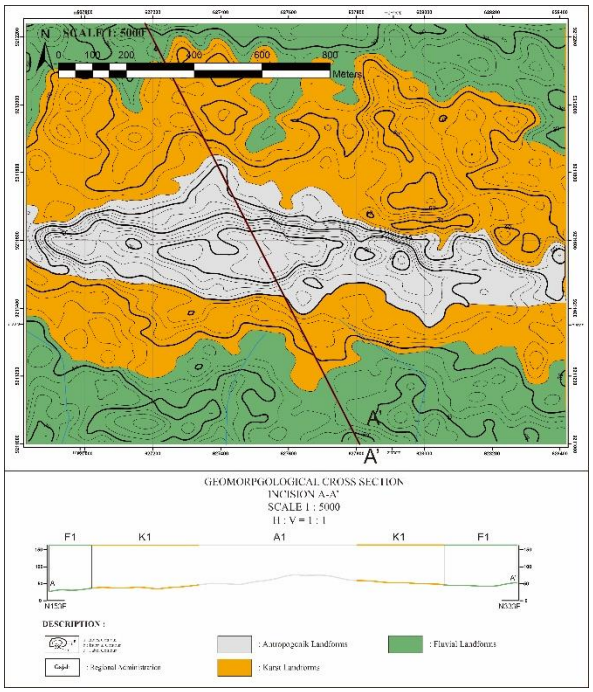

Figure 6 Geomorphological Map of the Research Area

In the northern and southern sections of the geomorphological map, fluvial landforms are shown. These are characterized by low-relief morphology with active rock weathering that transforms the rock into soil.

III. 2. Laboratory Analysis Results

Petrographic Analysis

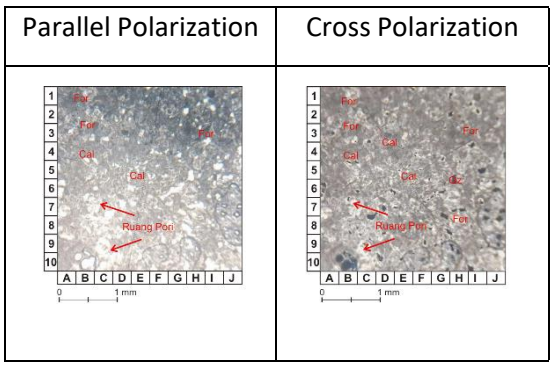

Figure 7 Petrographic Features LP 4

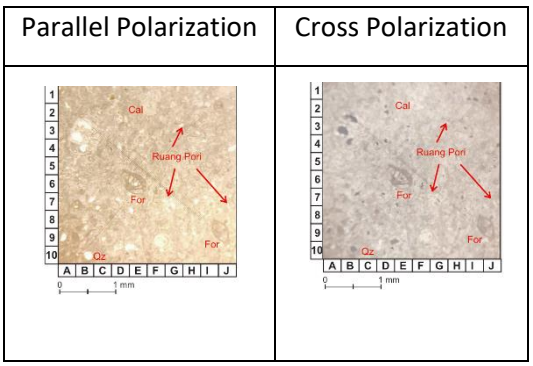

Figure 8 Petrographic Features LP 3

Petrographic analysis was carried out to understand the microscopic characteristics of the rock that influence its porosity and permeability. Under plane-polarized light observation (Figures 7 and 8),

the rock is dominated by light-colored transparent mineral grains (ranging from white to light gray) that appear in contact with each other (grain supported). The grain shapes vary from sub-angular to anhedral. Under cross-polarized light, several darker areas can be observed (Figures 7 and 8). Pore spaces are also present, predominantly intergranular, representing voids located between the mineral grains composing the rock. The mineral grains appear to be in mutual contact, confirming the grain-supported texture. These irregularly shaped pores indicate that porosity develops between relatively compact grains.

Microfossil Analysis

The age of the Mundu Limestone Unit, identified regionally, is indicated by the presence of planktonic foraminifera such as *Globigerina bulloides*, *Globigerinoides trilobus*, and *Globorotalia menardii*, as well as benthic forms including *Amphistegina* sp., *Textularia* sp., and *Bolivina* sp. The occurrence of *G. trilobus* and *G. menardii* serves as an important indicator, as these species are markers of the Late Miocene (zones N17–N20) according to Blow's (1969) classification.

Based on the microscope appearance, foraminifera in the sample show good preservation, with many tests still intact. This indicates a slow sedimentation process without strong physical disturbance and supports the formation of a planktonic bioclastic-rich packstone–wackestone structure. The presence of partially dissolved foraminifera tests also suggests the possibility of moldic porosity forming as part of the secondary porosity, which directly influences the quality of the carbonate reservoir.

Calcimetry Analysis

Calcimetry analysis is performed to determine the calcium carbonate (CaCO3) content in a limestone sample. The CaCO3 content is a crucial indicator for determining the purity of the limestone, which directly affects the rock's physical and chemical characteristics, as well as its potential as a reservoir rock..

Table 1 Rock Classification at the Research Location

No	Kode Sampel	Kandungan $CaCO_3$ (%)	Klasifikasi Batuan
1	LP1 Top	100%	Pure Limestone
2	LP1 Bottom	94,8%	Marl Limestone
3	LP3 Top	98%	Pure Limestone
4	LP3 Midle	98%	Pure Limestone
5	LP3 Bottom	100%	Pure Limestone
6	LP4 Top	98%	Pure Limestone
7	LP4 Middle	100%	Pure Limestone
8	LP10 Top	91,6%	Marl Limestone
9	LP10 Bottom	90%	Marl Limestone

High CaCO3 content, with results showing carbonate percentages ranging from 90% to 98%. These percentages classify the rock as marl-to-pure limestone (Flügel, 2010). This indicates that the unit is predominantly composed of carbonate bioclastic components, such as fragments of foraminifera and other marine biota, which supports the findings from previous microfossil and petrographic analyses. It also suggests that the depositional environment was a carbonate-rich and relatively stable marine setting, without a significant influx of clastic material.

Porosity and Permeability Analysis

Porosity and permeability tests were conducted on nine limestone samples from the Mundu Formation, collected from several locations: LP1, LP3, LP4, and LP10. The samples were taken from the top, middle, and bottom of the formation, respectively (Table 2). The high porosity and permeability values in some samples, such as LP4 Top and LP3 Bottom, suggest the potential for interconnected intergranular pore space, as well as fractures or secondary dissolution that have improved the pore connectivity. The test results show significant variation in porosity (ϕ) and permeability (Ka) values among the samples.

Table 2 Porosity and Permeability Values of the Research Location

No	Sampel	D (mm)	L (mm)	W (gr)	φ (%)	Ka (mD)
1	LP1 Bot	25.33	40.43	41.64	22.23	5.238
2	LP1 Top	25.33	47.94	54.86	14.62	10.803
3	LP3 Top	25.13	40.38	31.16	40.88	236.244
4	LP3 Bot	25.17	53.21	38.95	44.38	252.46
5	LP3 Mid	25.32	32.85	34.87	21.48	3.083
6	LP4 Mid	25.01	26.27	17.47	40.65	217.479
7	LP4 Top	25.07	44.36	31.21	44.82	1402.788
8	LP10 Bot	25.18	24.26	26.6	15.05	0.637
9	LP10 Top	25.31	32.01	29.8	29.31	1.609

The observed variations in porosity and permeability are strongly influenced by textural factors, carbonate content, and diagenesis. Rock sections with a grain-supported texture and high carbonate content show the best potential as a reservoir rock. This aligns with the concept of carbonate reservoirs, where the combination of both primary and secondary porosity determines the overall reservoir quality.

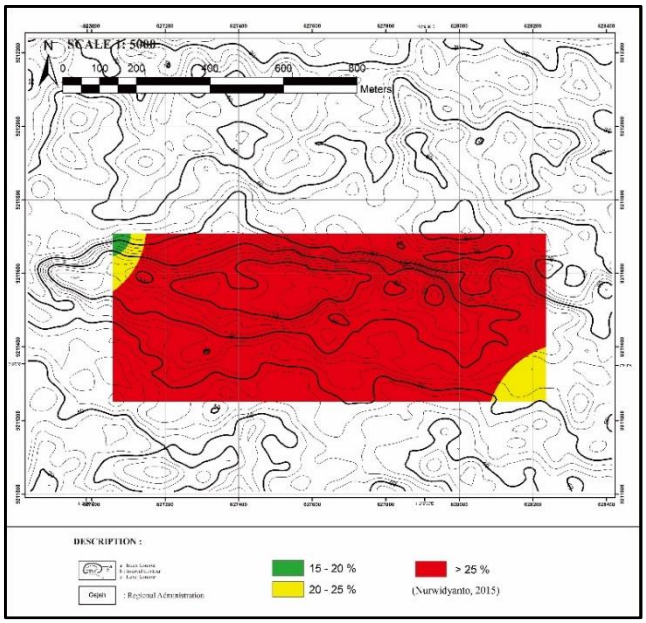

Figure 9 Porosity Value Distribution Map

The distribution of porosity and permeability values in the Mundu Formation is visualized using a porosity map and a permeability map (Figures 9 and 10). Based on the porosity map, it's evident that zones with high porosity values (>25%) are predominantly distributed in the central part of the study area, particularly around points LP4 and LP3. This distribution aligns with the petrographic analysis, which showed that samples from these locations have a grain-supported texture with intergranular spaces that have not yet been filled by carbonate cement. They also show dissolution of bioclasts, which has formed secondary moldic and vuggy porosity.

Otherwise, the northwestern and southeastern parts of the study area show relatively lower porosity values (<20%). This is likely related to a denser micritic texture, strong cementation, or a lower degree of secondary dissolution activity in those zones. This relationship indicates a lateral variation in diagenetic intensity and depositional facies within the Mundu Formation.

On the permeability map, a nearly identical pattern can be observed, although the relationship between porosity and permeability isn't entirely linear. Locations with high porosity values, such as LP4 Top, also show very high permeability values (>1000 mD), which indicates excellent pore connectivity. However, there are also locations like LP10 Top and LP10 Bot that have moderate porosity (15–20%) but show very low permeability (<5 mD). This suggests poor pore connectivity in those areas, likely due to factors like pore size, or high levels of compaction and cementation that inhibit fluid flow.

III. 3. Reservoir Potential of the Research Area

The Mundu Limestone Formation in the Gunung Pegat area shows highly prospective potential as a reservoir rock, with quality ranging from "Good" to "Excellent". This potential is controlled by a combination of favorable depositional facies and post-depositional diagenetic processes that enhance reservoir quality. Laboratory analysis results show a very high average porosity of 30.38%, which falls into the "Excellent" category. This value peaks in sample LP4 Top at 44.82%. Meanwhile, the average permeability is recorded at 236.70 mD, classified as "very good," with the highest value reaching 1402.788 mD in the same sample.

IV. CONCLUSION

Based on the analysis of limestone samples from the Mundu Formation in the Gunung Pegat area, Bojonegoro, it can be concluded that this rock unit has significant potential as a hydrocarbon reservoir rock. The reservoir characteristics of this limestone show significant variation, influenced by depositional facies and diagenetic processes. Laboratory test results show porosity values ranging from "Fair" (14.62%) to "Excellent" (44.82%). Meanwhile, permeability values vary from "Tight" (0.637 mD) to "Very Good" (1402.788 mD). Petrographic and microfossil analyses confirm that this rock was deposited in a neritic (shallow marine) environment and possesses primary intergranular porosity as well as secondary porosity in the form of moldic and vuggy pores resulting from the dissolution of bioclasts. Samples with a grain-supported texture tend to exhibit high porosity and permeability values, as seen in sample LP4 Top. This study confirms that the Mundu Formation limestone, particularly in layers with

favorable textural and diagenetic characteristics, has reservoir qualities ranging from "very good" to "excellent," making it a prospective target for further exploration.

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