Scientific Contributions Oil & Gas, Vol. 49. No. 2, June: 455 - 474

SCIENTIFIC CONTRIBUTIONS OIL AND GAS

Testing Center for Oil and Gas
LEMIGAS

Journal Homepage:http://journal.lemigas.esdm.go.id
ISSN: 2089-3361, e-ISSN: 2541-0520

Identification of Potential Unconventional Oil and Gas Zones Based on Permeability, Mobility, and Transmissibility in The North-East Java Basin

Bagus Sapto Mulyatno[1], Ordas Dewanto[1], Isti Nur Kumalasari[1], Andri Kurniawan[1], Asep Irawan[1], and Andy Setyo Wibowo[2]

[1]Department of Geophysical Engineering, Faculty of Engineering, Universitas Lampung,
Building O, Prof. Sumantri Brojonegoro Street, No. 1 Gedong Meneng, Rajabasa, Bandar Lampung, Lampung, 35145, Indonesia.

[2]Pusat Survei Geologi, Geological Agency,
A.F. Lasut IX Building, Diponegoro Street, No. 57 Cihaur Geulis, Cibeunying Kaler, Bandung, West Java, 40122, Indonesia.

Corresponding author: Bagus Sapto Mulyatno (bagus.sapto@eng.unila.ac.id)

Manuscript received: February 23th, 2026; Revised: March 31th, 2026
Approved: May 08th, 2026; Available online: June 17th, 2026; Published: June 17th, 2026.

ABSTRACT - The North East Java Basin is one of the prospective unconventional hydrocarbon regions characterized by low-permeability carbonate reservoirs. However, quantitative evaluation of fluid flow behavior and the relationships among petrophysical parameters within tight carbonate systems in this basin remains limited. This study aims to identify unconventional hydrocarbon prospect zones and determine the dominant fluid type based on permeability, mobility, and transmissibility parameters in the BGS-2, BGS-4, and BGS-7 wells. The study integrates well-log data, Total Organic Carbon (TOC) estimation, and interparameter relationship analysis using permeability–mobility and permeability–transmissibility crossplots. The results show that TOC values range from 0.51 to 2.78 wt%, indicating moderate to very good organic richness. The main prospective zones occur at depths of 3235–6469.5 ft (BGS-2), 3617–10632 ft (BGS-4), and 1897–1988 ft (BGS-7). These intervals are characterized by very low permeability (<0.1 mD), low mobility (<10 mD/cP), and limited transmissibility (<100 mD·ft/cP), indicating tight carbonate reservoir characteristics. Crossplot analysis reveals a stronger positive relationship between permeability and mobility than between permeability and transmissibility. The integration of petrophysical parameters indicates that gas is the dominant fluid within the prospective intervals, suggesting that carbonate reservoirs in the North East Java Basin represent promising tight-gas unconventional hydrocarbon resources.

Keywords: unconventional oil and gas, identification, permeability, mobility, transmissibility, North East Java Basin

How to cite this article:

Bagus Sapto Mulyatno, Ordas Dewanto, Isti Nur Kumalasari, Andri Kurniawan, Asep Irawan, and Andy Setyo Wibowo, 2026, Identification of Potential Unconventional Oil and Gas Zones and Fluid Types Based on Permeability, Mobility, and Transmissibility Values in BGS Wells in The North-East Java Basin, Scientific Contributions Oil and Gas, 49 (2) pp. 455 - 474. DOI org/10.29017/scog.v49i2.2081.

INTRODUCTION

Indonesia remains highly dependent on conventional hydrocarbons despite rising energy demand and declining reserves. This condition has encouraged the development of unconventional hydrocarbons as an alternative energy source to support the sustainability of both national and global energy supplies (Galih et al., 2019; Kapustin & Grushevenko 2018; Mulyatno et al., 2025; Tryono 2016). Over the past few decades, unconventional hydrocarbons have become one of the primary targets for energy development due to their large and widespread potential, particularly following the successful development of tight reservoirs in several countries (Abdel-fattah et al., 2025; Jia et al., 2021; Muther et al., 2022; Roshdy et al., 2025).

Unconventional hydrocarbon reservoirs generally develop in rocks characterized by very low permeability, low effective porosity, and complex fluid flow systems, resulting in limited natural production capacity (Abdelfattah et al., 2015; Javadpour 2009; Katz et al., 2021; Ross & Bustin 2009). These characteristics require a different evaluation approach compared to conventional reservoirs, particularly in carbonate reservoirs, which commonly exhibit high heterogeneity, complex pore systems, and limited pore connectivity.

Numerous studies have investigated the characteristics of unconventional hydrocarbon systems (Lai et al., 2022; Shen et al., 2018; Song et al., 2015; Valenza et al., 2023; Zou et al., 2022). In Indonesia, unconventional hydrocarbon studies have developed since 2008 and indicate significant resource potential, including shale gas, coal bed methane, tight gas, shale oil, and methane hydrate (Directorate General of Oil and Gas 2021; Maulana & Ranaputri 2024; Winderasta & Amlan 2025). In general, unconventional hydrocarbon reservoirs in Indonesia are characterized by TOC values ranging from 1–5%, total porosity of 1–9%, and very tight permeability conditions (Argakoesoemah 2004; Julikah 2020; Larasati 2015; Herdiyansyah 2020; Murtrijito 2012; Permana 2018; Satria 2017).

One of the prospective regions is the North East Java Basin, which has been included in the recommended pilot project area for multi Stage fracturing horizontal well (MSFHW) development, with an estimated shale gas potential of 42 TCF (Jumiati et al., 2020; Lemigas 2020; Wibowo et al., 2023). In addition to shale gas potential, this basin is also dominated by carbonate reservoirs distributed within the Ngimbang, Kujung, and Paciran-Mundu Groups (Darman et al., 2025). Based on the KKPJM database (2023), several carbonate intervals within the Ngimbang and Kujung Groups exhibit low to very low permeability values, indicating their potential to develop as tight carbonate unconventional reservoirs.

The ultra-low permeability characteristics, reservoir heterogeneity, and limited fluid flow capacity indicate that unconventional reservoir evaluation cannot rely solely on porosity and organic content parameters. Therefore, permeability, mobility, and transmissibility parameters are essential because they quantitatively represent the rock's ability to transmit fluids, the effectiveness of fluid movement relative to viscosity, and the overall reservoir capacity to conduct fluids.

In unconventional reservoirs, small variations in permeability can significantly influence fluid mobility and transmissibility, thereby directly affecting flow behavior and reservoir production response. This parameter-based approach has been applied by Abdelfattah et al. (2015). However, the integrative application of well logging analysis with permeability, mobility, and transmissibility parameters in unconventional carbonate reservoirs in Indonesia, particularly in the North East Java Basin, remains relatively limited, especially in relation to prospect zone identification and dominant fluid type interpretation.

Based on these conditions, this study was conducted on the Bagus (BGS) wells in the North East Java Basin by integrating well logging analysis with permeability, mobility, and transmissibility parameters to evaluate unconventional carbonate reservoir characteristics, identify prospective zones, and interpret the dominant fluid type within the target intervals. This approach is expected to provide a more comprehensive qualitative and quantitative evaluation of unconventional hydrocarbon reservoir characteristics and their relationship to dominant fluid types, thereby supporting the assessment of unconventional hydrocarbon development potential in Indonesia and contributing to the strengthening of national energy security.

METHODOLOGY

Research area

Lokasi The study area, including wells BGS-2, BGS-4, and BGS-7, is located within the North East Java Basin. Geologically, the North East Java Basin was formed through a combination of uplift and unconformity processes, sea-level fluctuations, and tectonic plate movements (Satyana 2005). Based on well stratigraphic data, the target zones in the study wells are distributed within the Ngimbang Formation, Kujung Formation, and Tuban Formation. In general, these formations consist of interbedded lithologies including sandstone, marl, limestone, claystone, siltstone, and shale (Husein, 2016; Satyana and Djumlati, 2003). The study area map and stratigraphic framework of the North East Java Basin are presented in Figures 1 and 2.

Research data

This study utilized data from three wells, BGS-2, BGS-4, and BGS-7. The selection of these wells was based on the availability of relatively complete well logging data, including gamma ray, resistivity, and sonic logs, as well as supporting geochemical data, core permeability data, fluid viscosity data, and net-pay information required for petrophysical analysis. These wells also represent the main stratigraphic distribution within the North East Java Basin, particularly the carbonate intervals of the Ngimbang, Kujung, and Tuban Formations, which are known to possess unconventional hydrocarbon potential. In addition, the selected wells exhibit preliminary indications of unconventional hydrocarbon reservoir systems, characterized by relatively high resistivity responses, sonic–resistivity log separation (crossover), and low to moderate gamma-ray values within organic-rich carbonate intervals. These characteristics serve as important indicators for identifying tight carbonate unconventional hydrocarbon zones.

The BGS-2, BGS-4, and BGS-7 wells also represent variations in the petrophysical characteristics of unconventional reservoirs within the study area, including TOC, permeability, mobility, and transmissibility values. Therefore, these wells are considered representative of unconventional hydrocarbon target intervals in the North East Java Basin and support the evaluation of fluid occurrence and the regional development potential of unconventional hydrocarbon reservoirs. In this study, the analysis was conducted using corrected well log data, including Gamma Ray Log, deep resistivity logs consisting of induction log deep (ILD) and laterolog deep (LLD), and compressional sonic logs represented by Delta-T (DT). These log data were used as the basis for qualitative interpretation and TOC calculation. Quantitative analysis was supported by additional datasets, including core permeability, geochemical, and fluid viscosity data, all of which were obtained from the well reports of each study well. Meanwhile, net-pay thickness data were adopted from previous reservoir interpretation studies conducted by Mulyatno (2025) for each respective well.

Identification of unconventional hydrocarbon prospect zones

This study applied well logging analysis through the integration of gamma ray (GR), deep

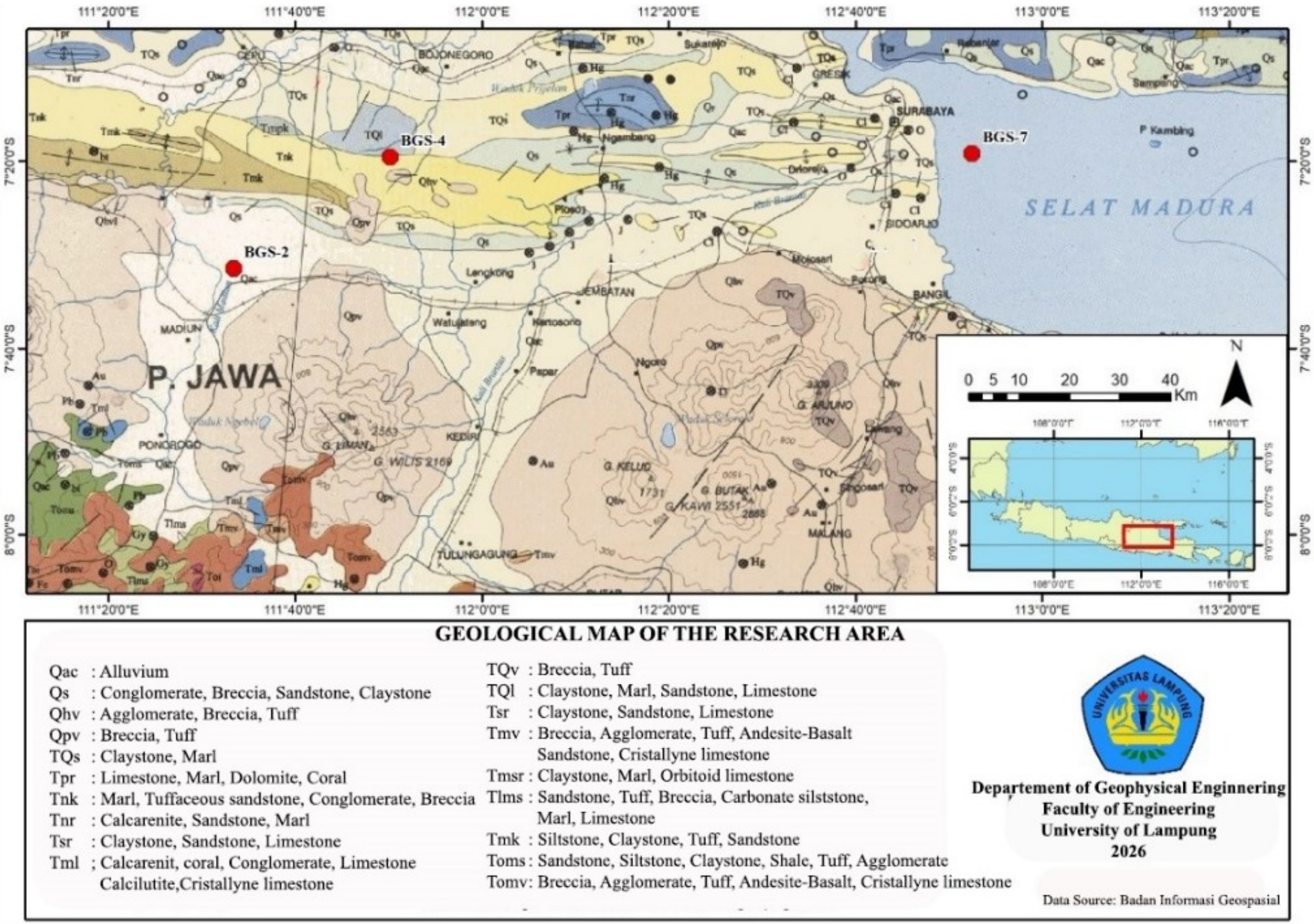


Figure 1. Regional geology of the study area (modified from Ratman et al., 1998).

Figure 2. Stratigraphy of the North East Java Basin (Husein 2015).

resistivity (ILD/LLD), and compressional sonic (DT) logs to identify potential unconventional hydrocarbon zones (Sumotarto et al., 2017). Qualitative interpretation was conducted by selecting candidate intervals based on relatively high resistivity responses, crossover separation between resistivity and sonic logs, and relatively high transit time (Δt) values, which indicate compact rocks with low porosity. High gamma ray values generally indicate shale lithology rich in organic material, whereas in certain carbonate intervals, prospective zones may also be characterized by low to moderate gamma ray values. Therefore, the identification of potential zones was carried out through an integrated interpretation of the three log responses. Subsequently, quantitative analysis was performed through the calculation of TOC, permeability, mobility, and transmissibility across all target well depths to evaluate reservoir characteristics and dominant fluid types. The research workflow is presented in Figure 3.

Total organic carbon (TOC) estimation

Total Organic Carbon (TOC) is a geochemical parameter used to indicate the amount of organic carbon contained within a rock, derived from organic materials such as kerogen and bitumen. TOC values are expressed as the weight percentage of organic matter relative to the total rock weight (Peters & Cassa 1994). According to Peters and Cassa (1994), the level of organic richness within a rock can be classified into several quality categories, as presented in Table 1.

In this study, TOC values were calculated using the Δ log R method. The Δ log R values were obtained through the overlay of deep resistivity logs and compressional sonic logs using the Passey method. The calculation was performed by comparing resistivity and transit time values with baseline values within non-source rock intervals, thereby producing curve separations that represent organic material content. Subsequently, TOC values were calculated using the Δ log R parameter and level of organic maturity (LOM). The LOM value represents the thermal maturity level of the source rock and is generally determined using the relationship curve between vitrinite reflectance (Ro) and LOM based on the Passey method, or by referring to the regional maturity level of the basin. Equations 1 and 2 are used for this purpose,

$$\Delta\, log\, R = \log_{10}\frac{R}{R_{baseline}} + (0.02 \times \Delta t - \Delta t_{baseline}) \quad (1)$$

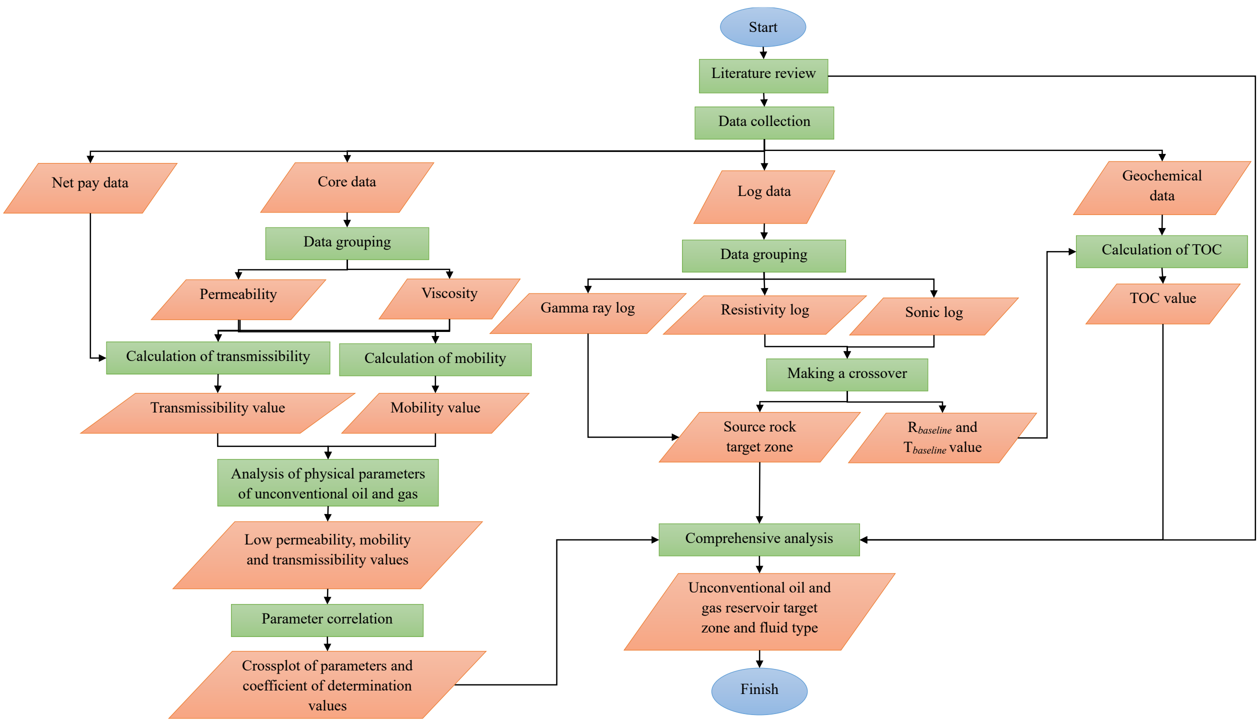


Figure 3. Study workflow.

Table 1. TOC quality classification according to Peters and Cassa (1994).

TOC (%wt)	Quality
< 0.5	Poor
0,5-1	Moderate
1-2	Good
2-4	Very Good
>4	Excellent

Table 2. Classification of rock permeability values (Koesoemadinata 1978).

Permeability value (mD)	Qualitative description
<10.5	Tight
11-15	Poor
15-50	Moderate
50-250	Good
250-1000	Very Good
>1000	Excellent

$$TOC = (\Delta \, log \, R) \times 10^{(2.297-(0.1668 \times LOM))} \quad (2)$$

where TOC, $\Delta \log R$, R, $R_{baseline}$, Δt, $\Delta t_{baseline}$, and LOM are total organic carbon (%wt), crossover between sonic and resistivity log curves, measured resistivity value from the logging tool (Ωm), base-line resistivity value within the non-source rock interval (Ωm), transit time value from the compressional sonic log (μs/ft), and baseline transit time value within the non-source rock interval (ìs/ ft), level of organic maturity, respectively.

Evaluation of permeability, mobility, transmissibility, and fluid type

In this study, permeability, mobility, and transmissibility parameters were used as the primary criteria for identifying unconventional hydrocarbon zones. These parameters were selected because they are capable of representing the ability of rocks to transmit fluids, the effectiveness of fluid movement, and the overall reservoir capacity to conduct fluid flow. Unconventional hydrocarbon reservoirs are generally characterized by very low permeability, low mobility, and limited transmissibility; therefore, these parameters were applied to evaluate reservoir characteristics and determine the dominant fluid type.

Permeability is defined as a measure of the ease with which fluids can flow through a rock. This parameter is represented by the symbol kkk and is commonly expressed in Darcy units (Lyons, 2010). In this study, the permeability values used were obtained from core permeability data from each study well and presented based on specific depth intervals. According to Koesoemadinata (1978), the general classification of permeability quality is shown in Table 2.

Mobility is defined as the ratio between the effective permeability and the viscosity of a fluid. In fluid displacement processes, the mobility ratio represents the comparison between the mobility of the displacing fluid and that of the displaced fluid. The fundamental mechanism of oil displacement by water can be understood by analyzing the mobility of each fluid (Dake 1978). Equation 3 is used to calculate mobility, (λ in mD/cP)

$$\lambda = \frac{k}{\mu} \quad (3)$$

where k and μ are permeability (mD) and vis-cosity (cP).

Transmissibility (Equation 4) is defined as the flow capacity divided by fluid viscosity and is commonly expressed in units of mDft/cP. Transmissibility values increase with increasing reservoir permeability or thickness, or with decreasing fluid viscosity (Lyons 2010). The variable of is net-pay thickness (ft).

$$T = \frac{k \ x \ h}{\mu} \tag{3}$$

In this study, permeability, mobility, and transmissibility parameters were used as preliminary indicators for interpreting fluid characteristics within unconventional hydrocarbon reservoirs. This approach refers to the study of Abdelfattah et al. (2015), which demonstrated that the relationship between reservoir flow capacity and fluid properties can be utilized as a basis for evaluating low-permeability reservoirs. The application of this method in the present study is considered relevant because the study area exhibits unconventional reservoir characteristics with very low permeability, similar to the reservoir conditions reported in previous studies. The classification of fluid types based on permeability, mobility, and transmissibility values is presented in Table 3.

RESULT AND DISCUSSION

This study focuses on unconventional hydrocarbons, which fundamentally differ from conventional hydrocarbon systems in that the source rock functions not only as the hydrocarbon-generating rock but also as the reservoir and accumulation medium. The primary lithologies composing unconventional source rocks generally include shale and other organic-rich rocks, which are characterized by relatively high TOC values. In addition, source rocks within unconventional hydrocarbon systems are commonly characterized by very low permeability values.

The interpretation in this study was conducted through the integration of qualitative well logging analysis using gamma ray, resistivity, and sonic logs. The interpretation was further supported by quantitative evaluation of core permeability data, as well as geochemical and petrophysical parameters, including TOC, mobility, and transmissibility calculations.

Identification of unconventional hydrocarbon prospect zones

Qualitative reservoir interpretation in this study was conducted through the integration of Gamma Ray (GR), resistivity (ILD/LLD), and sonic (DT) logs to identify unconventional hydrocarbon prospect intervals in wells BGS-2, BGS-4, and BGS-7. In general, the target intervals exhibit a combination of relatively low to moderate GR values associated with high resistivity and compact sonic responses. Based on the integrated log responses and regional stratigraphic correlation, the studied intervals are interpreted to have developed within the carbonate units of the Kujung Formation, Tuban Formation, and upper Ngimbang Formation in the North East Java Basin. This interpretation was not solely based on low GR values, since similar responses may also occur in sandstone or coal intervals, but was further supported by resistivity patterns, sonic responses, and consistency with the regional stratigraphic framework of the basin.

In addition, high resistivity responses accompanied by relatively high Ät values indicate compacted carbonate rocks with low porosity and limited pore connectivity. These characteristics are commonly associated with tight reservoirs dominated by restricted pore systems. The well log interpretation results for each study well are presented in Figures 4–6.

Table 3. Definition of unconventional hydrocarbon rocks and fluids (modified from Abdelfattah et al., 2015).

Parameter	Gas	Oil
Permeability (mD)	<0.1	<1
Mobility (mD/cP)	<10	<1
Transmissibility (mD.ft/cP)	<100	<10

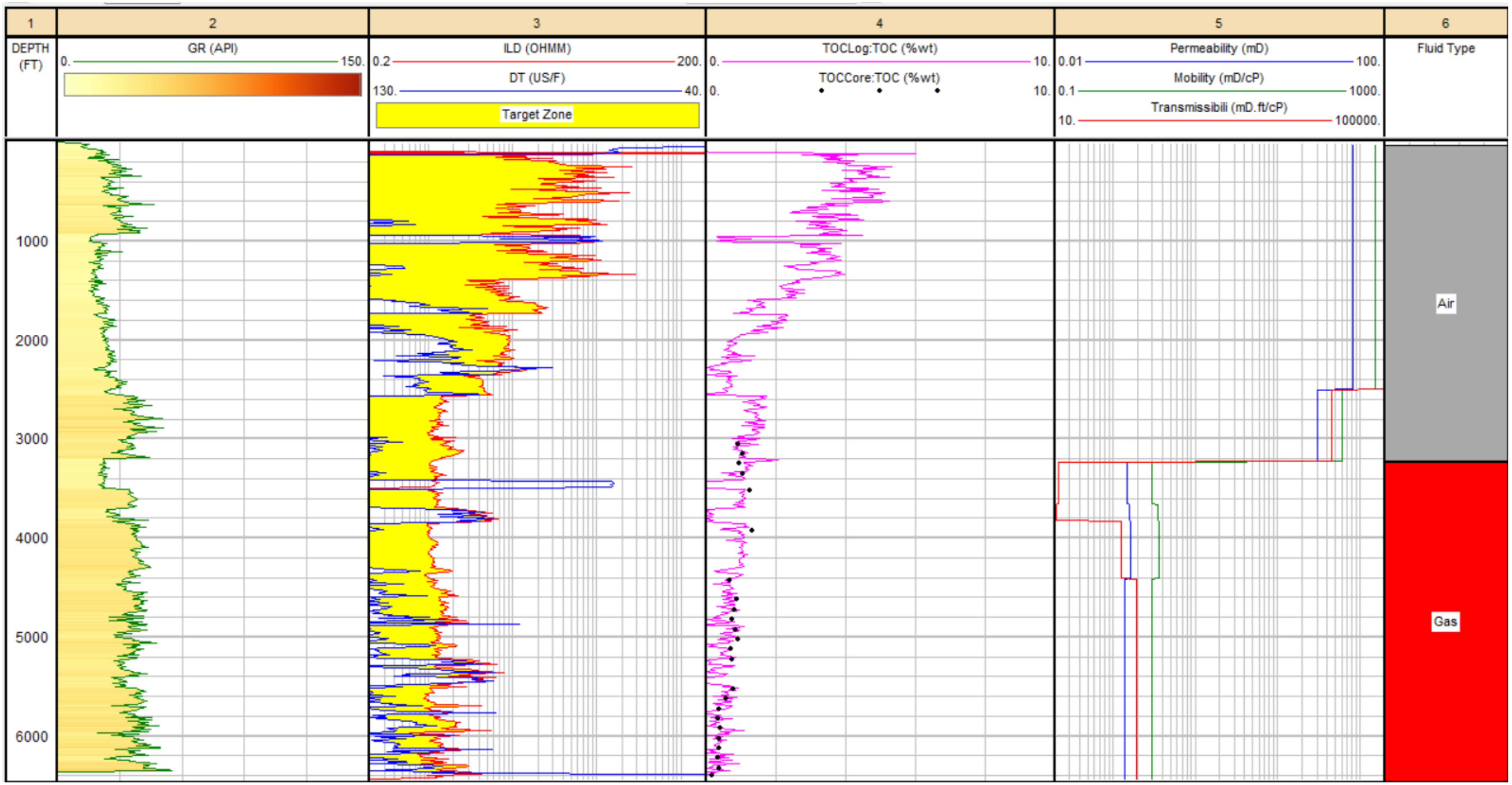


Figure 4. Well log interpretation of Well BGS-2, showing the identified unconventional hydrocarbon prospect zone based on integrated gamma-ray, resistivity, and sonic log responses. The prospective interval occurs at a depth of 3235–6469.5 ft and exhibits a distinct sonic–resistivity crossover pattern, indicating the presence of an organic-rich tight carbonate reservoir.

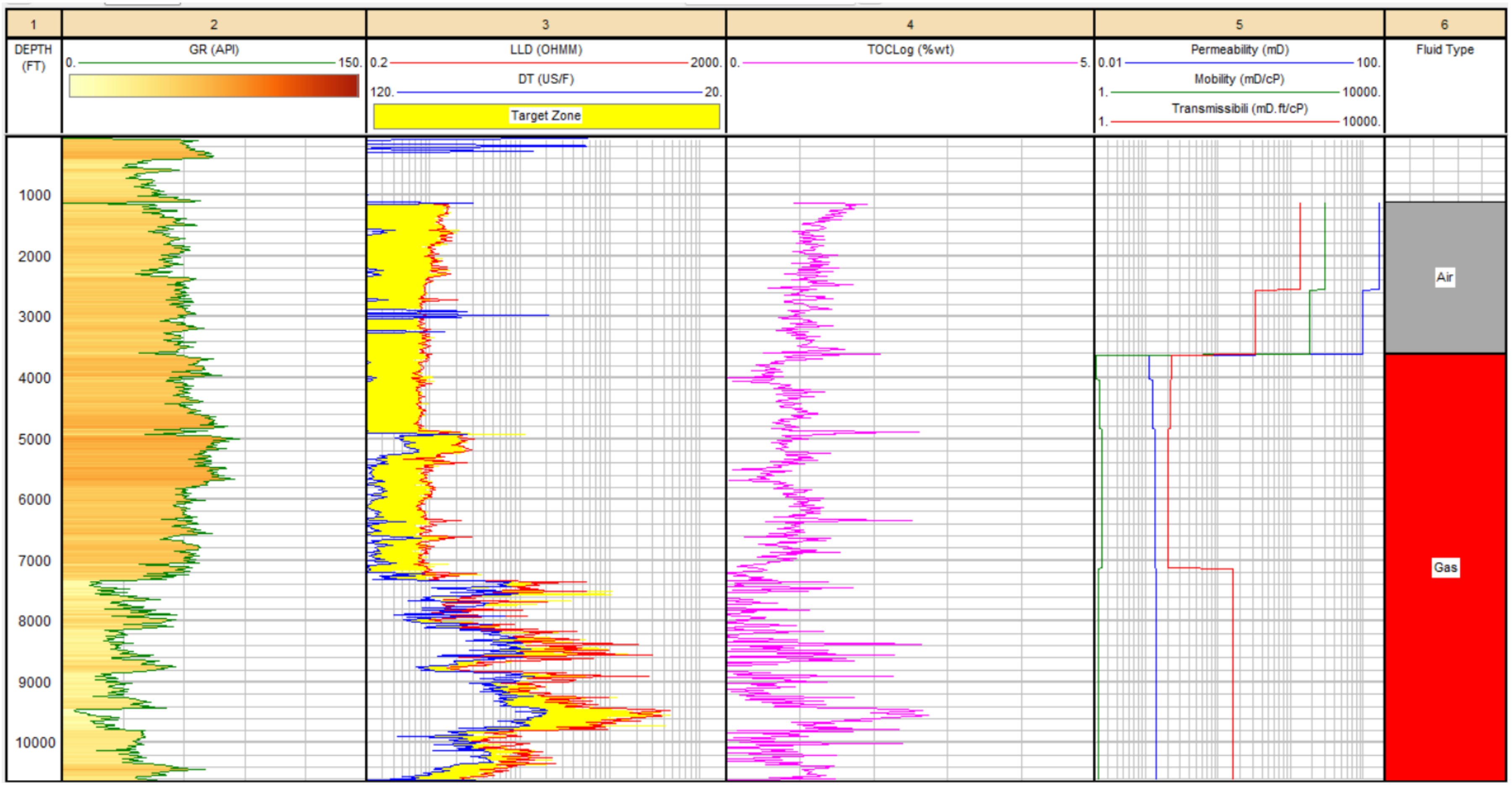


Figure 5. Well log interpretation of Well BGS-4, showing the identified unconventional hydrocarbon prospect zone based on integrated gamma-ray, resistivity, and sonic log responses. The prospective interval occurs at a depth of 3617–10632 ft and exhibits a distinct sonic–resistivity crossover pattern, indicating the presence of an organic-rich tight carbonate reservoir.

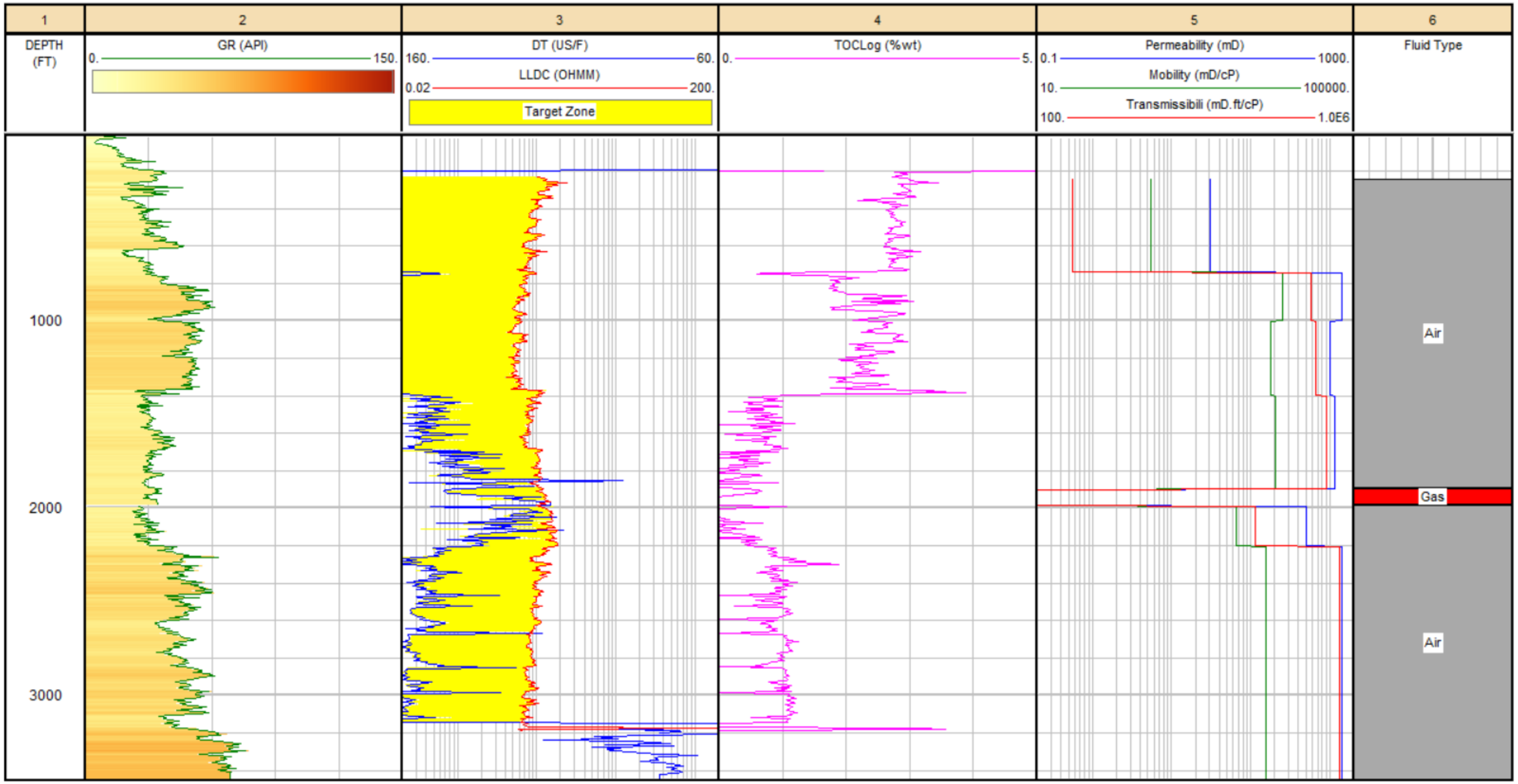


Figure 6. Well log interpretation of Well BGS-7, showing the identified unconventional hydrocarbon prospect zone based on integrated gamma-ray, resistivity, and sonic log responses. The prospective interval occurs at a depth of 1897–1988 ft and exhibits a distinct sonic–resistivity crossover pattern, indicating the presence of an organic-rich tight carbonate reservoir.

Based on Figures 4 to 6, the target intervals in all three wells exhibit relatively consistent crossover or separation patterns between the resistivity and sonic logs. These responses indicate the presence of organic-rich carbonate rocks with a high degree of compaction and limited fluid flow capacity. Such characteristics are commonly associated with tight carbonate reservoir systems, particularly within intervals exhibiting very low permeability values.

To support the qualitative interpretation derived from the log responses, quantitative evaluation was conducted using TOC, permeability, mobility, and transmissibility parameters within each target interval. Summaries of the calculated parameter values are presented in Tables 4 to 6.

As shown in Table 4, the TOC calculations for Well BGS-2 show a range of 0.51–2.53 wt%, which falls into the medium to very good quality category. The target zone in Well BGS-2 is located at a depth of 3235–6469.5 ft, characterized by very low permeability ranging from 0.07–0.083 mD, mobility of only 1.5–1.8 mD/cP, and relatively low transmissibility (10.43–98.91 mD·ft/cP). In relation to the stratigraphic framework, the depth interval of the main unconventional hydrocarbon target zone (3235–6469.5 ft) is likely correlated with compacted carbonate of the Kujung Formation and carbonate of the Upper Ngimbang Formation.

In Table 5, the TOC values in Well BGS-4 range from 0.73–1.24 wt%, classified as medium to good quality. The target zone in Well BGS-4 is located at a depth of 3617–10632 ft, with relatively low permeability in the range of 0.056–0.07 mD, very low mobility (1.04–1.26 mD/cP), and limited transmissibility (10.02–78.91 mD·ft/cP). In a stratigraphic context, this main unconventional hydrocarbon interval (3617–10632 ft) is likely associated with compacted carbonates of the Tuban and Kujung Formations, as well as carbonates of the Upper Ngimbang Formation.

For well BGS-7 (Table 6), the TOC distribution ranges from 0.52–2.78 wt%, indicating medium to very good quality. The target zone in Well BGS-7

Table 4. Unconventional hydrocarbon characteristics of well BGS-2.

No	Depth (ft)	TOC (%wt)	TOC Quality	Viscosity (cP)	Permeability (mD)	*Net-pay* (ft)	Mobility (mD/cP)	Transmissibility (mD.ft/cP)
1	32-2504	2.53	Very Good	0.053	40.527	1877.49	764.66	437584.55
2	2504-3235	1.23	Good	0.05	15.22	245.47	304.40	22775.21
3	3235-3665	1.06	Good	0.05	0.075	24.48	1.5	11. 19
4	3665-3826	0.51	Moderate	0.046	0.08	19.68	1.74	10.43
5	3826-4406.5	0.94	Moderate	0.046	0.083	115.98	1.80	63.78
6	4406.5-6469.5	0.52	Moderate	0.046	0.07	213.26	1.52	98.91

Table 5. Unconventional hydrocarbon characteristics of well BGS-4

No	Depth (ft)	TOC (%wt)	TOC Quality	Viscosity (cP)	Permeability (mD)	Net-pay (ft)	Mobility (mD/cP)	Transmissibility (mD.ft/cP)
1	118-382	n/a	-	0.043	n/a	0	-	-
2	380-1120.5	n/a	-	0.043	n/a	0	-	-
3	1120.5-2562	1.24	Good	0.055	81.96	1.51	1490.18	685.48
4	2562-3617	1.08	Good	0.055	49.26	0.59	895.64	161.21
5	3617-4039	0.73	Moderate	0.054	0.056	36.09	1.04	11.41
6	4039-4830	0.86	Moderate	0.054	0.063	31.36	1.17	11. 15
7	4830-7133	0.91	Moderate	0.054	0.068	26.11	1.26	10.02
8	7133-10.632	1.02	Good	0.063	0.07	233	1.11	78.91

Table 6. Unconventional hydrocarbon characteristics of well BGS-7.

No	Depth (ft)	TOC (%wt)	TOC Quality	Viscosity (cP)	Permeability (mD)	*Net-pay* (ft)	Mobility (mD/cP)	Transmissibility (mD.ft/cP)
1	16.5-245	2.92	Very Good	0.057	n/a	0	-	-
2	245-742.5	2.78	Very Good	0.057	15.6	3.41	273.68	284.63
3	742.5-1000	2.14	Very Good	0.057	708.65	76.34	12432.46	289303.25
4	1000-1400.5	2.39	Very Good	0.057	508.34	120.08	8918.25	326407.79
5	1400.5-1897	0.64	Moderate	0.057	579.93	146.82	10174.21	455295.92
6	1897-1988	0.52	Moderate	0.057	0.09	25.59	1.58	12.32
7	1988-2201.5	0.53	Moderate	0.075	250.62	55.74	3341.60	56807.20
8	2201.5-3439.5	1.00	Good	0.09	708.7	277.59	7874.44	666256.74

* n/a : Data limitations

* Grey highlights indicate the prospective zones of unconventional hydrocarbons

is located at a depth of 1897–1988 ft. This interval shows very low permeability of 0.09 mD, mobility of 1.58 mD/cP, and transmissibility of 12.32 mD·ft/cP. In relation to the stratigraphic framework, the main unconventional hydrocarbon potential interval in Well BGS-7 (1897–1988 ft) is likely correlated with compacted carbonate of the Kujung Formation.

The TOC values from the three wells range from 0.51–2.78 wt%, indicating medium to very good organic richness. These values exceed the minimum threshold for productive carbonate source rocks proposed by Tissot and Welte (1984), indicating sufficient hydrocarbon generative potential. Regionally, high-TOC intervals are predominantly developed within the Ngimbang Formation and parts of the Kujung carbonate system, which are recognized as key elements of the petroleum system in the North East Java Basin.

However, not all organic-rich intervals develop as unconventional hydrocarbon reservoirs. In several shallow to intermediate intervals, permeability remains relatively high (>1 mD), accompanied by higher mobility and transmissibility, indicating effective pore connectivity and good fluid flow capacity. These characteristics are more representative of conventional reservoir systems rather than unconventional ones.

In contrast, the main unconventional target zones in Wells BGS-2, BGS-4, and BGS-7 consistently exhibit very low permeability ranging from 0.056–0.09 mD, mobility of 1.04–1.8 mD/cP, and transmissibility of 10.02–98.91 mD·ft/cP. These values indicate tight formation characteristics with low pore system quality and highly limited pore connectivity. The low permeability significantly restricts fluid flow, causing hydrocarbons to be trapped within the rock matrix and making natural production difficult without reservoir stimulation.

In the regional stratigraphic context, these main prospective intervals are developed within compacted carbonates of the Kujung Formation, Tuban Formation, and Upper Ngimbang Formation. These reservoir characteristics indicate that the unconventional petroleum system in the study area occurs as a tight carbonate reservoir controlled by compaction intensity, cementation, and carbonate pore heterogeneity.

In addition to very low permeability (<0.1 mD), the prospective intervals also exhibit relatively low fluid viscosity (0.05–0.057 cP). The combination of low viscosity, low mobility (<10 mD/cP), and limited transmissibility (<100 mD·ft/cP) suggests that the dominant fluid phase in the main target zones is likely gas. The reduced mobility and transmissibility are not primarily caused by fluid viscosity, but rather by limited rock permeability due to strong compaction and poor pore connectivity.

Overall, the integration of well logging interpretation and petrophysical parameters indicates that all three studied wells contain organic-rich carbonate intervals with medium to very good TOC quality. However, only intervals characterized by very low permeability, low mobility, and restricted transmissibility fulfill the criteria of unconventional hydrocarbon reservoirs of the tight carbonate gas reservoir type.

Evaluation of petrophysical parameters: permeability, mobility, and transmissibility in the BGS Well

The parameters permeability, mobility, and transmissibility are used in this study as quantitative indicators to evaluate fluid flow characteristics and reservoir quality in unconventional petroleum systems. This approach follows Abdelfattah et al. (2015), who demonstrated that the relationships among petrophysical parameters can be used as early indicators for identifying reservoir characteristics and fluid-type tendencies in tight reservoir systems.

The results show that the main prospective intervals in Wells BGS-2, BGS-4, and BGS-7 are characterized by very low permeability (<0.1 mD), low mobility, and limited transmissibility, indicating very poor fluid flow capacity. These characteristics suggest that hydrocarbons are trapped within a low-connectivity pore system, where fluid movement is severely restricted and cannot occur naturally without reservoir stimulation.

Such reservoir characteristics are consistent with the general concept of unconventional petroleum reservoirs, which typically develop in formations with extremely low permeability and complex fluid flow systems, resulting in limited natural productivity. In such conditions, even small variations in permeability may significantly affect general reservoir fluid flow efficiency.

The results of this study are also in agreement with the general characteristics of unconventional hydrocarbons in Indonesia, which are typically associated with moderate to high organic content and very tight permeability. In this study, the main prospective intervals exhibit medium to very good TOC values combined with very low permeability, indicating tight reservoir characteristics developed in organic-rich carbonate rocks. In addition, the reservoir characteristics of the studied intervals are consistent with regional data from the North East Java Basin. Several carbonate intervals within the Ngimbang Group and Kujung Formation are known to exhibit low to very low permeability, indicating their potential as unconventional tight carbonate reservoirs. This condition aligns with the findings of this study, where the main prospective zones are developed within the Upper Ngimbang and Kujung carbonate intervals, characterized by very low permeability and limited fluid flow capacity.

The relationship between permeability, mobility, and transmissibility in this study also indicates that permeability is the primary controlling parameter governing reservoir fluid flow efficiency. Intervals with relatively higher permeability generally exhibit higher mobility and transmissibility, reflecting effective pore connectivity and good fluid transport capacity. Conversely, intervals with very low permeability consistently show reduced mobility and transmissibility, indicating the development of tight carbonate reservoir systems. This relationship demonstrates that reservoir evaluation based on permeability, mobility, and transmissibility can serve as an early indicator for identifying reservoir characteristics and fluid-type tendencies in tight reservoir systems.

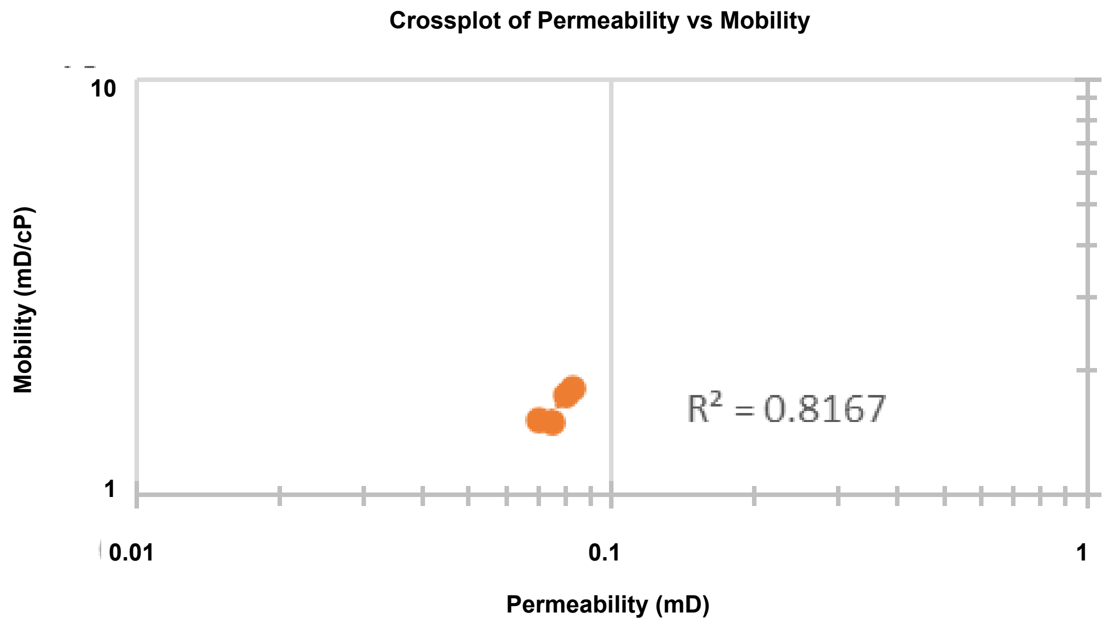
However, the fluid-type interpretation in this study is still based on petrophysical analysis and reservoir fluid flow behavior. Therefore, further validation using PVT data, production tests, and geochemical analysis is still required to improve the reliability of reservoir characterization and fluid -type interpretation.

Correlation analyses

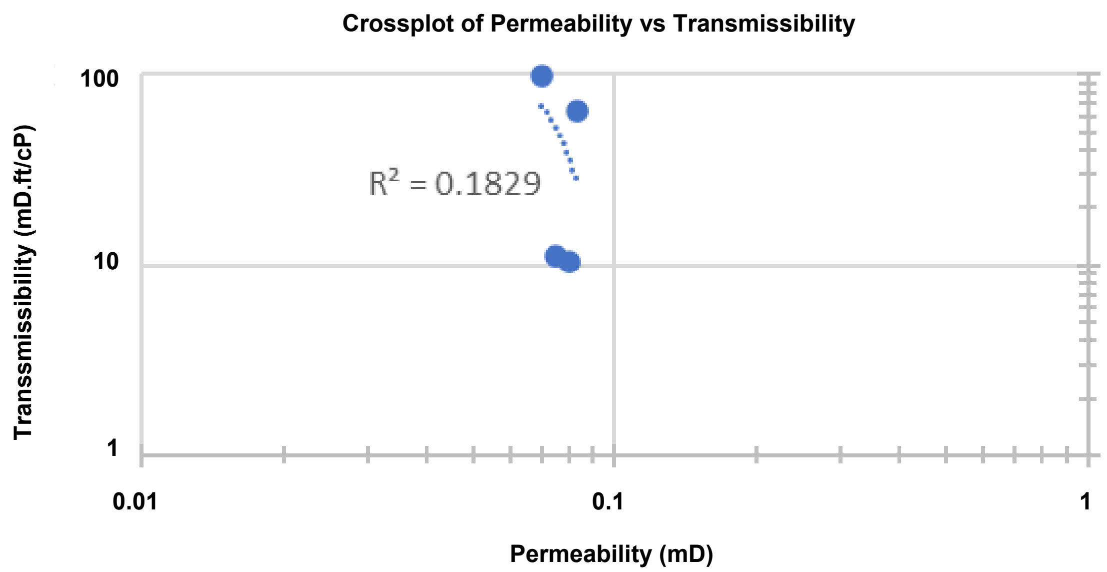
To evaluate the relationships among petrophysical parameters, crossplot analyses between permeability–mobility and permeability–transmissibility were conducted for Wells BGS-2 and BGS-4. This analysis aims to understand the influence of permeability on fluid flow efficiency and the overall reservoir capacity to transmit fluids. The correlation analysis was limited to Wells BGS-2 and BGS-4 because both wells contain more than one target zone with sufficiently representative variations in permeability, mobility, and transmissibility, allowing for statistical evaluation.

In contrast, Well BGS-7 has only a single main unconventional hydrocarbon target zone; therefore, the relationships among parameters cannot be visualized through crossplots or assessed using correlation approaches. The results of the crossplot analyses are presented in Figures 7 and 8.

Based on Figure 7, the crossplot analysis for Well BGS-2 shows a strong positive relationship between permeability and mobility, with an R^2 value of 0.8167. This result indicates that an increase in permeability is generally accompanied by an increase in fluid mobility, suggesting that

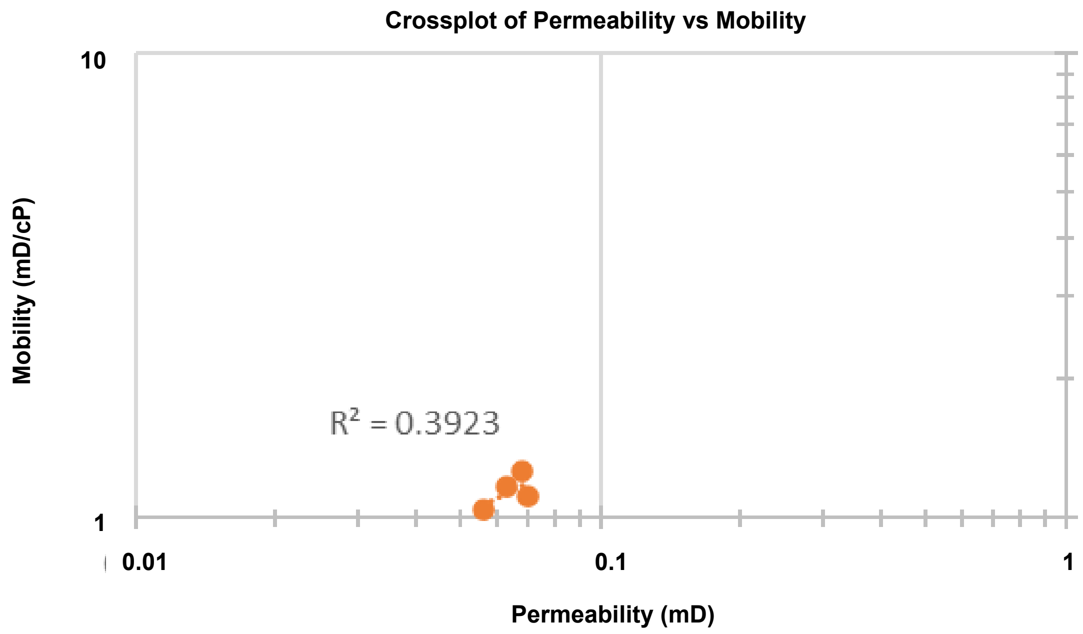


a)



b)

Figure 7. Crossplots of (a) permeability versus mobility and (b) permeability versus transmissibility for Well BGS-2. Positive relationships are observed in both crossplots, indicating that permeability plays an important role in controlling fluid mobility and transmissibility within the identified tight carbonate interval.



a)

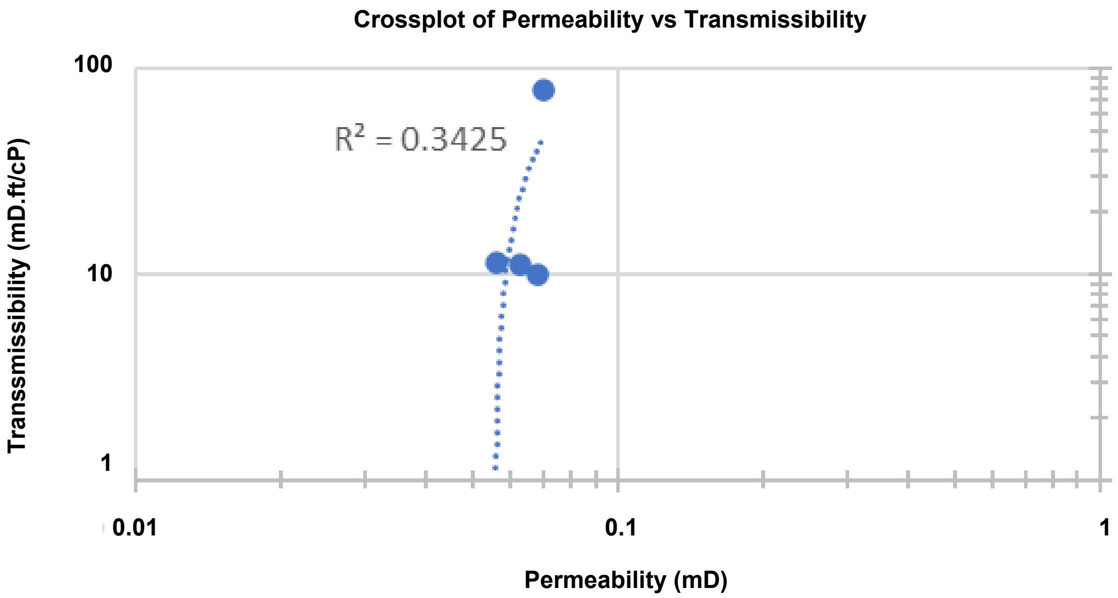


Figure 8. Crossplots of (a) permeability versus mobility and (b) permeability versus transmissibility for Well BGS-4. Positive relationships are observed in both crossplots, indicating that permeability plays an important role in controlling fluid mobility and transmissibility within the identified tight carbonate interval.

permeability is the primary controlling parameter governing fluid flow capacity within the carbonate reservoir in the study area. In contrast, the relationship between permeability and transmissibility exhibits a relatively weak correlation, with an R^2 value of 0.1829. This suggests that transmissibility is not solely controlled by permeability but is also influenced by variations in effective reservoir thickness (net pay thickness).

In Figure 8, the crossplot analysis for Well BGS -4 shows a positive but relatively moderate relationship between permeability and mobility, with a coefficient of determination (R^2) of 0.3923. This result indicates that an increase in permeability tends to be accompanied by an increase in fluid mobility, although the relationship is not strongly dominant. The moderate correlation suggests that fluid mobility in the reservoir is not only controlled by permeability but is also influenced by other factors such as fluid viscosity, rock heterogeneity, and pore distribution and connectivity. Meanwhile, the relationship between permeability and transmissibility shows an R^2 value of 0.3425. This moderate correlation indicates that both mobility and transmissibility are not governed solely by permeability but are also affected by additional factors such as reservoir thickness. Overall, the permeability–mobility relationship exhibits a relatively stronger correlation compared to the permeability–transmissibility relationship. This indicates that fluid mobility is more sensitive to changes in reservoir permeability because it is directly influenced by rock flow capacity and fluid viscosity. In contrast, transmissibility is affected by additional parameters such as effective reservoir thickness, resulting in a more heterogeneous relationship among the variables.

The crossplot results also show that ultra-low permeability intervals consistently exhibit low mobility and transmissibility, indicating restricted fluid flow within the studied reservoir. This characteristic supports the interpretation that the main prospective zones across the studied wells develop as a tight carbonate gas reservoir system. This finding is consistent with Abdelfattah et al. (2015), who stated that reservoirs with very low permeability and low fluid viscosity commonly develop as tight gas systems with limited flow capacity. Nevertheless, all data from both wells consistently show very low permeability (<0.1 mD), low mobility, and limited transmissibility, reflecting poor fluid flow capacity within the carbonate reservoir. These characteristics indicate a tight carbonate reservoir system with limited pore connectivity and support the interpretation of unconventional tight gas potential in the North East Java Basin.

CONCLUSION

Based on the integration of well logging analysis, petrophysical parameters, and correlation assessment through crossplots, the unconventional petroleum system in the study area in the North East Java Basin is developed in a limited manner within specific intervals characterized by tight carbonate reservoir properties. The main prospective zones in Wells BGS-2, BGS-4, and BGS-7 are defined by medium to very good TOC content (>0.5 wt%), but are associated with very low permeability (<0.1 mD), low mobility (<10 mD/cP), and limited transmissibility (<100 mD·ft/cP), resulting in extremely poor reservoir fluid flow capacity. From a stratigraphic perspective, these prospective zones are developed within compacted carbonate intervals of the Upper Ngimbang Formation, Kujung Formation, and parts of the Tuban Formation, which have undergone intensive diagenesis and cementation. These processes significantly reduce pore connectivity and severely restrict fluid flow within the reservoir.

The crossplot analysis indicates a positive relationship between permeability and both mobility and transmissibility, with the permeability –mobility correlation being relatively stronger than the permeability–transmissibility relationship. This suggests that fluid mobility is more directly controlled by rock permeability and fluid viscosity, whereas variations additionally influence transmissibility through effective reservoir thickness and reservoir heterogeneity. Generally, the integrated petrophysical evaluation indicates that the dominant fluid within the prospective zones is likely gas. Therefore, the carbonate reservoirs in the study area are interpreted as unconventional tight carbonate gas systems that require reservoir stimulation techniques, such as hydraulic fracturing, to achieve economically viable production.

ACKNOWLEDGEMENT

The authors express their gratitude to the Head of the Geological Survey Center (PSG), Ministry of Energy and Mineral Resources (KESDM), Bandung, for granting permission to use data, which enabled the completion of this research.

DECALARATIONS

Author Contribution

B.S. Mulyatno: Conceptualization, Methodology, Data Collection, Data Analysis, Manuscript Writing, & Editing. O. Dewanto: Supervision (co), Conceptualization, & Data Analysis. I.N.

Kumalasari: Supervision (co) & Manuscript Review. A. Kurniawan: Supervision (co) & Manuscript Review. A. Irawan: Conceptualization, Methodology, Manuscript Writing, & Editing. A.S. Wibowo: Data Collection & Data Analysis.

Funding statement

The funding for this research comes solely from the authors' funds.

Competing interest

The authors declare that they have no competing interests that could have influenced the work reported in this paper.

The use of AI-assisted technologies

The authors acknowledge that some components of the manuscript, such as language refinement and paragraph structure, were developed with the assistance of artificial intelligence (AI) tools. However, all conceptual decisions, interpretations, and conclusions were made entirely by the authors to ensure the integrity and originality of the research.

GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
TCF	Trillion cubic feet	
MSFHW	Multi-stage fracturing horizontal well	
TOC	Total organic carbon	%wt
GR	Gamma ray	API
DT	Delta-T	US/F
ILD	Induction log deep	OHMM
ft	Feet	
mD	Millidarcy	
cP	Centipoise	
LLD	Laterolog deep	OHMM

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