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Characterisation of unconventional reservoirs in NE Java based on the brittleness index, permeability, mobility, and transmissibility

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ABSTRACT Shale hydrocarbons are sources of oil and gas trapped in shale rock formations which are rich in organic material. Oil and gas reservoirs can be detected by knowing the characteristics of the rocks. This study attempts to determine whether permeability, mobility, transmissibility, and the brittleness index (BI) can be used for identifying unconventional reservoirs. The research area includes the geological formations in the OD Field of the NE Java basin. We perform acoustic impedance seismic inversion on 48 two-dimensional seismic sections and we analyse well logs from three wells (namely M-1, M-2, and M-3). The results obtained show that wells M-1, M-2, and M-3 have small permeability, mobility, and transmissibility parameters. The distribution of the BI values is 0.46-0.54 falling within a less brittle category. The Kujung formation has a BI value of 0.46-0.76 falling within a low brittle category. The Ngimbang formation has a high BI value of 0.52-0.82 with a brittle category.

Key words: brittle, hydrocarbons, organic, permeability, reservoir, unconventional.

1. Introduction

Shale hydrocarbon is an unconventional oil and gas energy source trapped in shale rock formations which are rich in organic material, but tend to have low permeability and porosity values (Jumiati *et al.*, 2020). Several parameters determine whether a shaly formation has potential to be an oil and gas reservoir, including permeability, mobility, transmissibility and the rock brittleness index (BI) (Xu *et al.*, 2022).

This study will characterise unconventional reservoirs by analysing their hosting rock permeability, mobility, transmissibility and rock BI (Xu *et al.*, 2022). The study uses M-1, M-2, and M-3 well logs in the OD Field, NE Java basin, and seismic profiles. The objectives of this study are, first, to determine the occurrence of unconventional reservoirs in wells M-1, M-2, and M-3 in the OD Field and, second, to determine rock parameters that characterise unconventional reservoirs, such that they can be used to recognise unconventional reservoirs elsewhere.

A good shale hydrocarbon prospect zone can be determined based on the total organic carbon values larger than, or equal to, 0.5 wt% (Perez Altamar and Marfurt, 2014; Khan and Bibi, 2016). Unconventional hydrocarbon systems that accumulate in shale reservoirs generally have an effective porosity below 10% (Katz *et al.*, 2021). Several parameters, such as mobility and transmissibility, greatly affect the occurrence of unconventional reservoirs. Information on the physical and chemical properties of unconventional hydrocarbon sources in the NE Java basin can provide very useful information in deciding whether the hydrocarbons are feasible to be exploited or not.

In general, shale is the source rock, but in unconventional oil and gas, shale can be both the source rock and the reservoir rock (Ahmed and Meehan, 2016). Many reservoir models and analyses are based on the assumption that geological formations are homogeneous and have uniform rock properties in all directions, while some heterogeneity is common in formations containing oil and gas (Ahmed, 2019).

Both conventional and unconventional gases have similar chemical compositions, especially methane. However, the term unconventional gas refers to natural gas sources whose extraction relies on special or advanced production techniques and not on traditional techniques (Pang *et al.*, 2021). This is the difference between unconventional gas and widely produced conventional gas (Zheng *et al.*, 2018).

As oil and gas are formed in their source rock, they also function as reservoirs. Oil and gas cannot flow when the reservoir rock's permeability and porosity are small. The NE Java basin has been proven to produce hydrocarbons (Gregersen, 2008). Identifying the characteristics of a reservoir requires the correlation between well-log data and seismic data (Eshimokhai and Akhirevbulu, 2012), used to analyse the distribution of petrophysical properties to determine potential hydrocarbon. In this research, the seismic inversion method used utilises a combination of seismic data, such as input and well-log data, as a controller to provide physical information on the rocks contained in a reservoir (Ronoatmojo and Burhannudinnur, 2021). Acoustic impedance (AI) inversion is useful for distinguishing different lithology types below the Earth's surface. By using AI, seismic amplitudes will be converted into layer properties. The combination of AI and elastic impedance will influence the density value and Vp/Vs value of a layer, so that geomechanical parameters such as the Young modulus and the Poisson ratio, which are useful in calculating the BI, can be obtained (Singha and Chatterjee, 2015).

Rock fragility is very important in the development of unconventional reservoirs (Mews *et al.*, 2019) which, due to their low permeability, need to be stimulated by means of fracturing treatments to provide fluid flow for the wellbore exploitation (Kaczmarczyk and Słota-Valim, 2020).

The BI is one of the petrophysical parameters influenced by the Young modulus and Poisson ratio values (Kang *et al.*, 2020), both of which are approached in this study using the shale volume value and effective porosity value. According to Meng *et al.* (2021), rocks with a high BI are characterised by a high Young modulus and density and low Poisson ratio values. Determination of the BI value is carried out to distinguish between brittle and non-brittle (ductile) rocks that can be used in the characterisation of shale hydrocarbons. Based on Sohail *et al.* (2022), the characteristics of commercial shale include being in the gas window period and a BI greater than 48%.

In unconventional reservoirs, shales are categorised as brittle rocks because, despite their low porosity and permeability, they contain shale oil/shale gas. The results of this study can be a reference in determining target areas that have the potential to contain unconventional hydrocarbons (shale) as a further stage of shale oil and shale gas production in the OD Field in the NE Java basin.

2. Materials and methods

2.1. Research materials

The interactive petrophysical method is used in the process of determining the BI value. Geoview Hampson-Russell Suite (HRS-9 Beta 64) software is used in the seismic inversion process of seismic bonds and AI wells. Petrel software (Alizadeh *et al.*, 2015) is used in the process of taking horizons and making petrophysical property distribution maps of the BI.

2.2. Research data

The data used in this study are all sourced from the Geological Survey Center of the Ministry of Energy and Mineral Resources Indonesia, with coordinates that cannot be disclosed to the public. Fig. 1 is a basemap marking wells M-1, M-2, and M-3 with their locations.

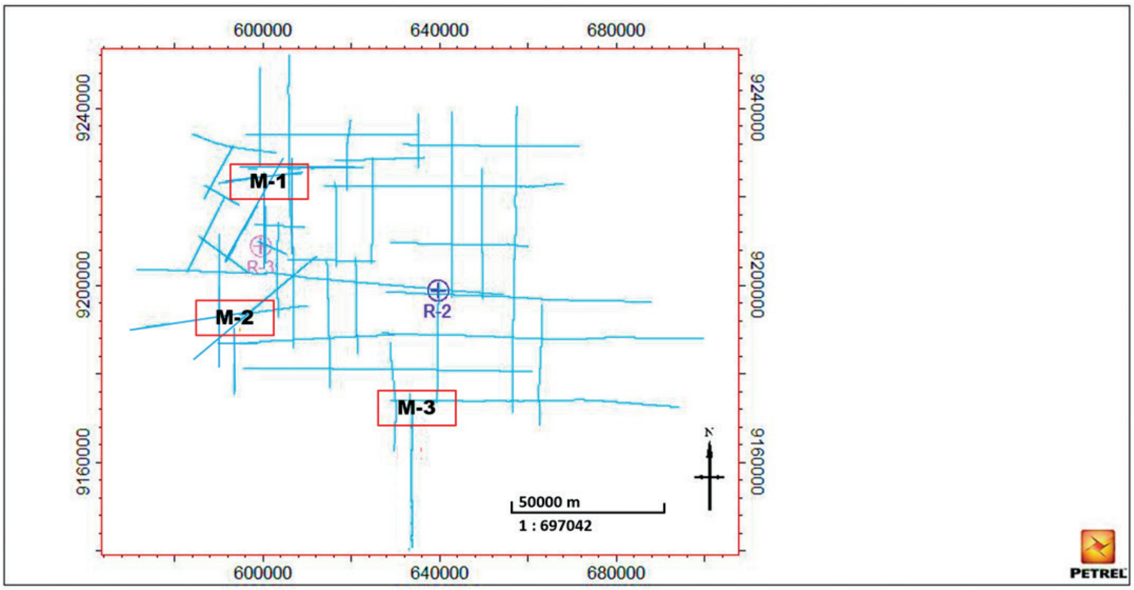

Fig. 1 - Basemap of the research area.

The basemap in Fig. 1 shows the seismic survey of the research area and the position of the wells listed in the following sub sections.

2.2.1. Well data (log data)

The well data used in this data processing are secondary data in the LAS log data format totalling three wells located in the NE Java region. Several theories or equations used in the well-logging method regard the identification of subsurface rock characteristics (Liu, 2017). Well data are used as control data for subsurface rock identification (Arnø *et al.*, 2021) and the parameters measured in the well are displayed in a series of curves that produce depth graphs (Darling, 2005). The parameters of the physical properties of a formation measured continuously at all depth in drilling wells (Bonnelye *et al.*, 2024) are gamma ray, sonic, density, porosity, resistivity logs, and clay content (Chuanmao and Friedman, 1992; Rider, 2002).

2.2.2. Seismic data

In this study, seismic data were used in the well-to-seismic tie process to link time-domain data with depth-domain data from well data, picking horizons and structures to determine layer boundaries, AI seismic inversion, and the distribution of the BI petrophysical property. The seismic data used in this data processing are two-dimensional (2D) Post-Stack Time Migration (PSTM) seismic data, which is 2D time-domain data that has undergone stacking, with a total of 48 seismic lines located in the NE Java region.

2.2.3. Determination of the brittleness index

The BI is useful in the characterisation of shale hydrocarbons because it indicates the level of difficulty when produced by fracturing. The BI value is ideally obtained from the Young modulus and Poisson ratio values resulting from geomechanical tests on shale rock samples. However, the Young modulus and Poisson ratio values can be approximated using porosity and shale volume values, which are, then, classified according to the brittle-ductile classification (Perez Altamar and Marfurt, 2014).

3. Results and discussion

3.1. Unconventional parameter analysis

Generally, unconventional reservoir rocks are located in the source rock layer, namely shale with high gamma ray values and carbonate rocks with relatively low gamma ray values. However, in identifying unconventional reservoirs, it is necessary to calculate several parameters including the permeability, mobility, and transmissibility of each well.

The determination of the permeability values uses the Timur permeability calculation method with calculation constants. Meanwhile, determining unconventional hydrocarbon target areas is characterised by a relatively low level of permeability with a range less than 0.1 mD for gas fluids and less than 1 mD for oil fluids. The Timur equation can be expressed as follows:

$$k = a\frac{\emptyset^b}{Sw^c} \quad (1)$$

with calculation constants a = 0.136, b = 4.4, ∧ c = 2, and Ø as porosity and S_w as water saturation.

The mobility value calculation is obtained from the division between the permeability value and the fluid viscosity. The viscosity constant values are obtained from core data for each well. In determining the target area, unconventional hydrocarbons are characterised by a mobility value less than 10 mD/cP for gas fluids and less than 1 mD/cP for oil fluids.

3.1.1. Calculation of the transmissibility value (Tf) for well M-1

The transmissibility value calculation is obtained by multiplying the permeability value by the thickness of the net pay for each well. Meanwhile, determining unconventional hydrocarbon target areas is characterised by a transmissibility value less than 100 mDm/cP for gas fluids and less than 10 mDm/cP for oil fluids. Calculation of unconventional parameters for wells M-1, M-2, and M-3 is shown in Tables 1 to 3.

Table 1 - Permeability, mobility, and transmissibility values for well M-1. Yellow highlight indicates the unconventional reservoir target prospect zone.

Formation	Marker	Target zone	Depth (m)	Permeability (mD)	Mobility (mD/cP)
Tuban	1	1156–1261	0.0352	0.625	6.23
	2	1262–1429	0.0215	6.760	121
	3	1430–1467	0.0527	0.927	9.34
	4	1468–1503	0.0727	1.340	220
Kujung	1	1504–1596	0.0793	1.460	11.6
	2	1597–1679	0.1100	9.190	255
	3	1680–1737	0.0379	0.702	5.59
	4	1738–1992	0.1340	6.330	119
	5	1993–2150	0.0866	1.600	12.7
Ngimbang	1	2235–2422	0.0757	1.200	85.3
	2	2423–2877	0.1230	1.950	138
	3	2878–2995	0.0557	0.884	62.7
	4	2996–3050	0.0372	0.591	42
	5	3051–3200	2.120	8.440	600

Based on the unconventional parameter calculations that have been carried out on each formation in the M-1 well (Table 1), it can be seen that the prospect zone for the unconventional reservoir target in the Tuban formation is in target zones 1 and 3 which are characterised by permeability values less than 1 mD, mobility less than 1 mD/cP, and transmissibility less than 10 mDm/cP; so it can be said that this zone has fluid content in the form of oil. In the Kujung formation it is in target zones 1, 3, and 5 where target zones 1 and 5 are characterised by permeability values less than 0.1 mD, mobility less than 10 mD/cP, and transmissibility less than 100 mDm/cP; so it can be said that this zone contains fluid in the form of gas. Instead, in target zone 3, the transmissibility meets the parameter values indicating fluid content in the form of oil, and in the Ngimbang formation the transmissibility is located in zones 1, 3, and 4 which are characterised by permeability values less than 0.1 mD, mobility less than 10 mD/cP, and transmissibility less than 100 mDm/cP; so it can be said that these zones contain fluid in the form of gas. Some target zones that are not highlighted in yellow indicate that these zones do not meet the category of unconventional reservoirs in the form of oil or gas.

3.1.2. Calculation of the transmissibility value (Tf) for well M-2

Based on the unconventional parameter calculations that have been carried out for each formation in the M-2 well (Table 2), it can be seen that the prospect zone for the unconventional reservoir target in the Kujung formation is in target zone 2 which is characterised by a permeability value less than 1 mD, mobility less than 1 mD/cP, and transmissibility less than 10 mDm/cP; so it can be said that this zone has fluid content in the form of oil. In the Ngimbang formation, the

Table 2 - Permeability, mobility, and transmissibility values for well M-2. Yellow highlight indicates the unconventional reservoir target prospect zone.

Formation	Marker target zone	Depth (m)	Permeability (mD)	Mobility (mD/cP)	Transmissibility (mDm/cP)
Tawun	1	0–325	0.5	11	-
Kujung	1	326–949	11	216	99.40
	2	950–1100	0.0165	0.301	0.0542
	3	1101–1441	2.58	47.8	526
Ngimbang	1	1442–1633	0.0858	1.58	15.10

same rock properties of the Kujung formation zone 2 are in target zones 1 and 2. In particular target zone 1 is characterised by a permeability value of less than 0.1 mD, mobility less than 10 mD/cP, and transmissibility less than 100 mDm/cP so it can be said that this zone contains fluid in the form of gas, while in target zone 2, the parameter values indicate fluid content in the form of oil. Some target zones that are not highlighted in yellow indicate that these zones do not meet the category of unconventional reservoirs in the form of oil or gas.

3.1.3. Calculation of the transmissibility value (Tf) for well M-3

Based on the unconventional parameter calculations that have been carried out for each formation in the M-3 well (Table 3), it can be seen that the unconventional reservoir target prospect zone in the Kerek formation is in target zone 1 characterised by a permeability value less than 0.1 mD, mobility less than 10 mD/cP, and transmissibility less than 100 mDm/cP so it can be said that this zone contains fluid in the form of gas, whereas for the target zone which is not highlighted in yellow, it indicates that the zone does not meet the category of unconventional reservoir, either in the form of oil or gas because it has relatively large permeability, mobility, and transmissibility values.

Table 3 - Permeability, mobility, and transmissibility values for well M-3. Yellow highlight indicates the unconventional reservoir target prospect zone.

Formation	Marker target zone	Depth (m)	Permeability (mD)	Mobility (mD/cP)	Transmissibility (mDm/cP)
Pucangan	1	45–748	67.30	1787	680.76
Kalibeng	1	749–1370	31.40	-	-
Kerek/Tuban	1	1400–1490	0.05	0.74	28.07

3.1.4. Determination of the brittleness index value

The determination of the BI value is used to differentiate the character of rocks in unconventional reservoirs by establishing the level of rock brittleness using the Young modulus and Poisson ratio calculations obtained from approaches to the porosity value and shale volume of a rock. In the M-1 well (Table 4), the BI value is determined within three formations according to the top shale and base shale. The Tuban formation is in the 1156-1503 m depth range, the Kujung formation is in the 504-2150 m depth range, and the Ngimbang formation is in the 2235-

3200 m depth range. The BI calculation results for the M-1 well are shown in Table 4.

Based on the brittle-ductile classification according to Perez Altamar and Marfurt (2013), the target zone of the Tuban formation has a BI value in the range 0.33-0.66 and an average of 0.42; so it is classified as less brittle. Then, in the target zone, the Kujung formation has a BI value in the range 0.33-0.65 and an average of 0.42; so it is classified as less brittle and in the target zone the Ngimbang formation has a BI value in the range 0.33-0.82 and an average of 0.67; so it is classified as brittle.

Table 4 - BI calculation values in the M-1 well target zone.

Formation	Marker target zone	Depth (m)	Poisson ratio (dec)	Young's modulus (dec)	BI (dec)	Classification brittle-ductile
Tuban	1	1156–1503	0.34	60.69	0.42	Less brittle
Kujung	2	1504–2150	0.33	57.03	0.42	Less brittle
Ngimbang	3	2235–3200	0.32	105.50	0.67	Brittle

In the M-2 well (Table 5), the BI value is determined within two formations according to the top shale and base shale. The Kujung formation is in the 326-1441 m depth range and the Ngimbang formation is in the 1442-2124 m depth range. The BI calculation results for the M-2 well are shown in Table 5.

Table 5 - BI calculation values in the M-2 well target zone.

Formation	Marker target zone	Depth (m)	Poisson ratio (dec)	Young's modulus (dec)	BI (dec)	Classification brittle-ductile
Kujung	1	326–1441	0.32	40.33	0.38	Less brittle
Ngimbang	2	1442-2124	0.30	105.59	0.72	Brittle

Based on the brittle-ductile classification according to Perez Altamar and Marfurt (2013), the target zone of the Kujung formation has a BI value in the range 0.32-0.82 and an average of 0.38; so it is classified as less brittle. Then, in the target zone the Ngimbang formation has a BI value in the range 0.32-0.81 and an average of 0.72; so it is classified as brittle.

In the M-3 well (Table 6), the BI value is determined within one formation according to the top shale and base shale, namely the Tuban formation in the 1400-1490 m depth range. The BI calculation results for the M-3 well are shown in Table 6.

Table 6 - BI calculation values in the M-3 well target zone.

Formation	Marker target zone	Depth (m)	Poisson ratio (dec)	Young's modulus (dec)	BI (dec)	Classification brittle-ductile
Tuban	1	1400–1490	0.33	53.3	0.39	Less brittle

Based on the brittle-ductile classification according to Perez Altamar and Marfurt (2013), the target zone of the Tuban formation has a BI value in the range 0.28-0.57 and an average of 0.39 so it is classified as less brittle.

The distribution of the BI values for each top shale and bottom shale for each formation is shown in Figs. 2 to 7.

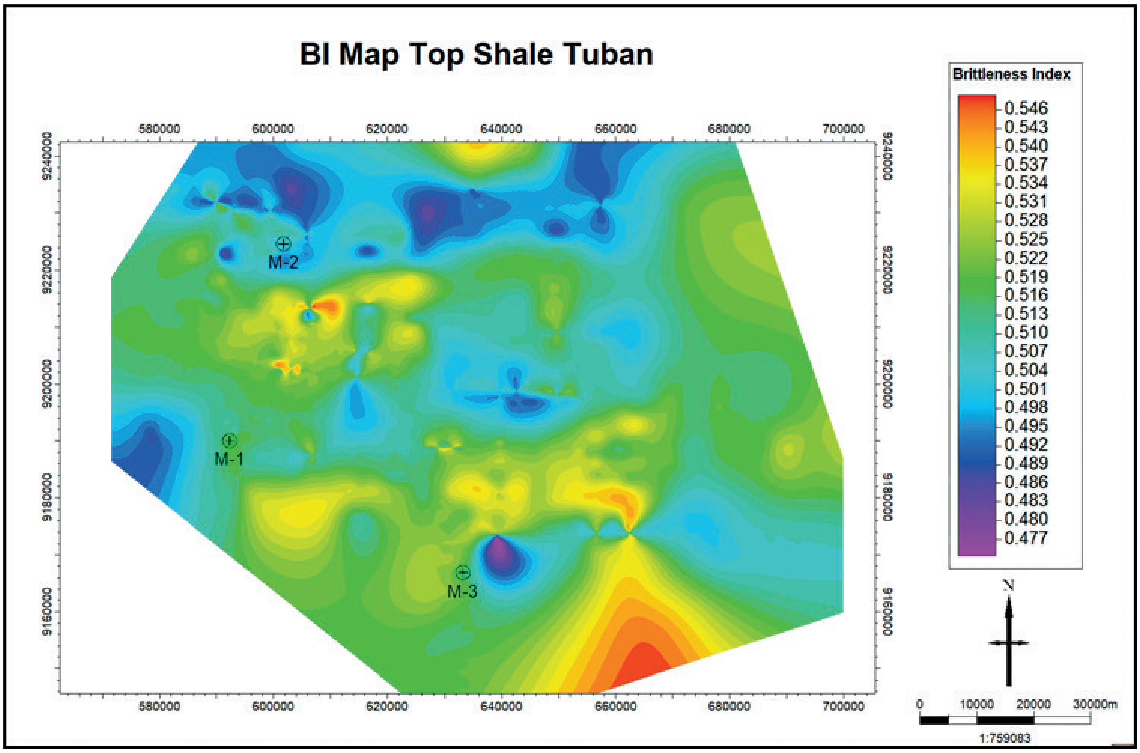

Fig. 2 - Distribution of the BI in the Tuban top shale.

In Fig. 2, showing the distribution of the BI Tuban top shale, it can be seen that the area with a high BI value of 0.52 is spread in the south-eastern direction (in yellow) and the area with a low BI value of 0.48 is spread from west to north (in blue).

Next, in Fig. 3, showing the distribution of the BI base shale in Tuban, it can be seen that areas with a high BI value of 0.5 are spread in the south-eastern direction (in red) and areas with low BI values of 0.4 are spread from west to north (in purple).

Furthermore, in Fig. 4, showing the distribution of the BI top Kujung shale, it can be seen that the areas with a fairly high BI value, namely 0.7, are spread in the south-eastern area (in yellow) and the areas with a low BI value, namely 0.46, are spread in the NW (in purple).

Fig. 5 shows the distribution of the Kujung base shale BI, and it can be seen that areas with a fairly high BI value of 0.7 are spread in the south direction (in red) and areas with a low BI value of 0.4 are spread from west to NE (in purple).

In Fig. 6, showing the distribution of the BI top Ngimbang shale, it can be seen that the areas with a high BI value of 0.82 are spread in the south direction (in red) and the areas with a lower BI value of 0.54 are spread in the west to NW direction (in purple).

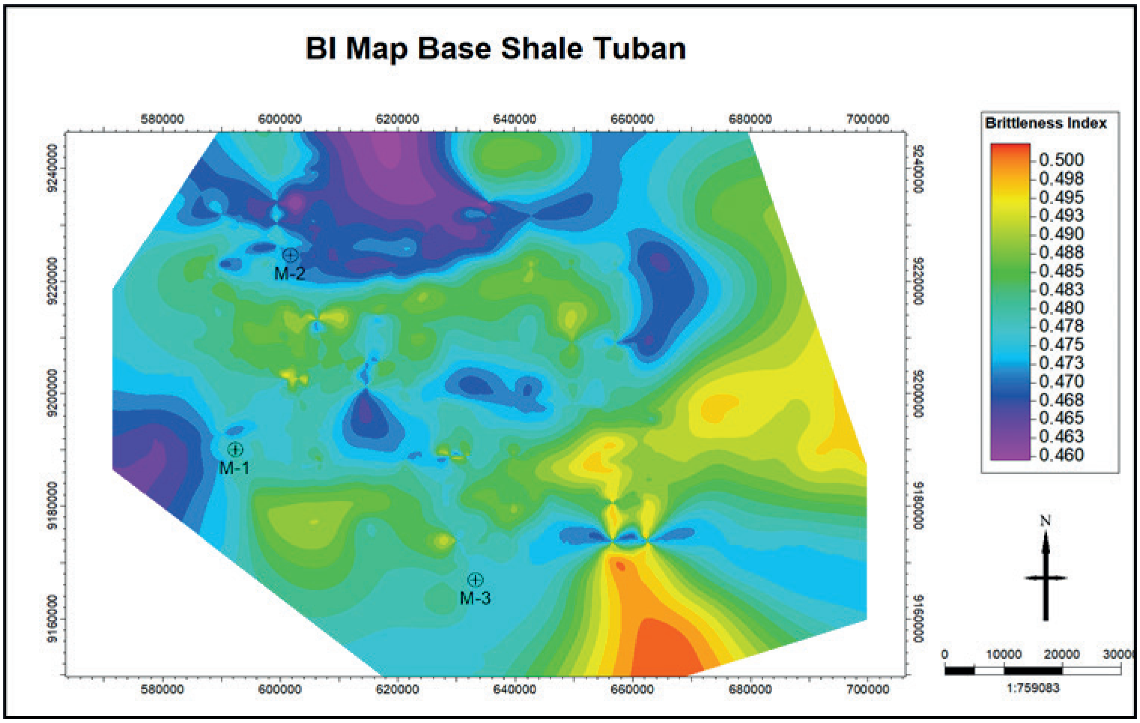

Fig. 3 - Distribution of the BI in the Tuban shale base.

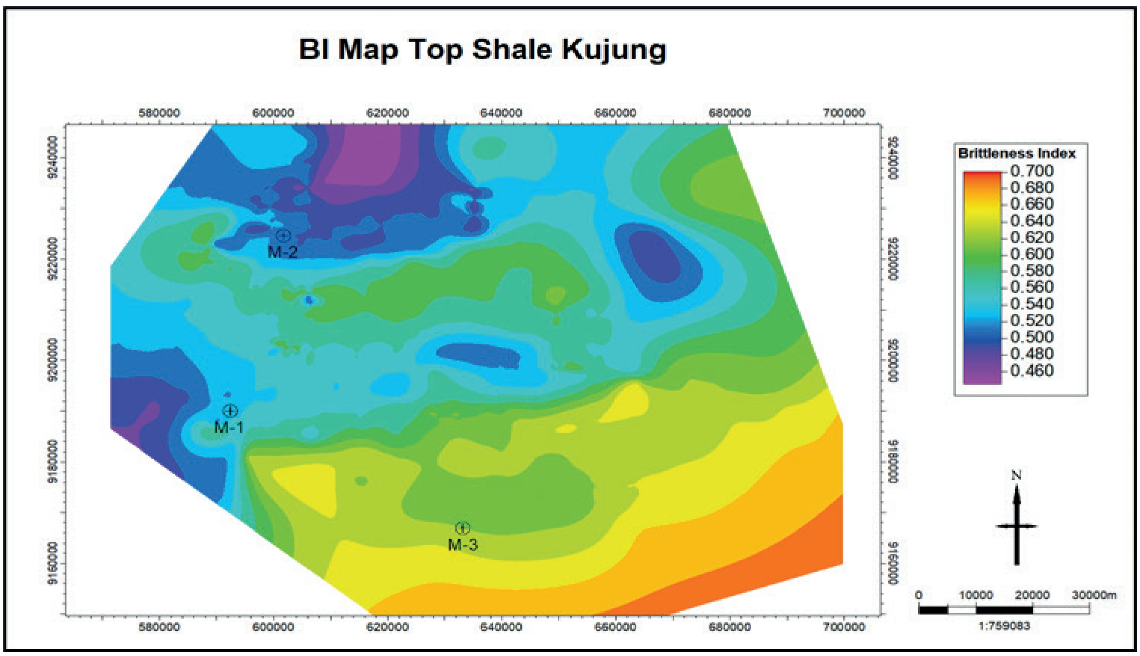

Fig. 4 - Distribution of the BI in the Kujung top shale.

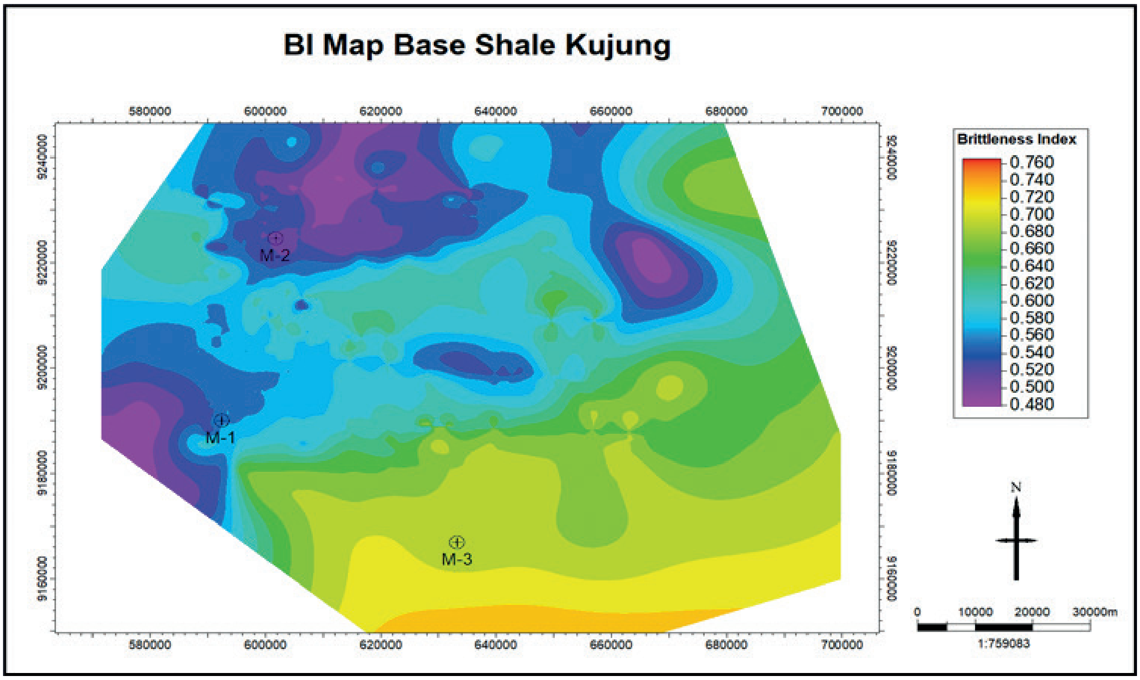

Fig. 5 - Distribution of the BI in the Kujung shale base.

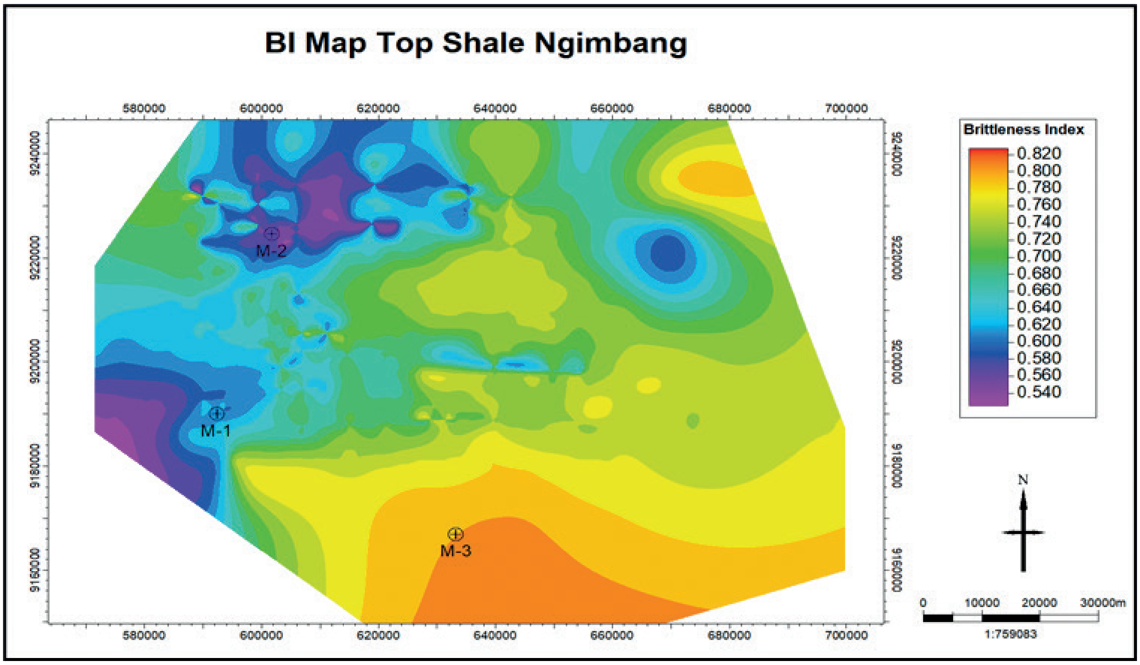

Fig. 6 - Distribution of the BI in the Ngimbang top shale.

In Fig. 7, showing the distribution of the Ngimbang BI base shale, it can be seen that areas with a high BI value of 0.80 are spread in the south to SE direction (in red) and areas with a lower BI value of 0.52 are spread from the west to the west seas (in purple).

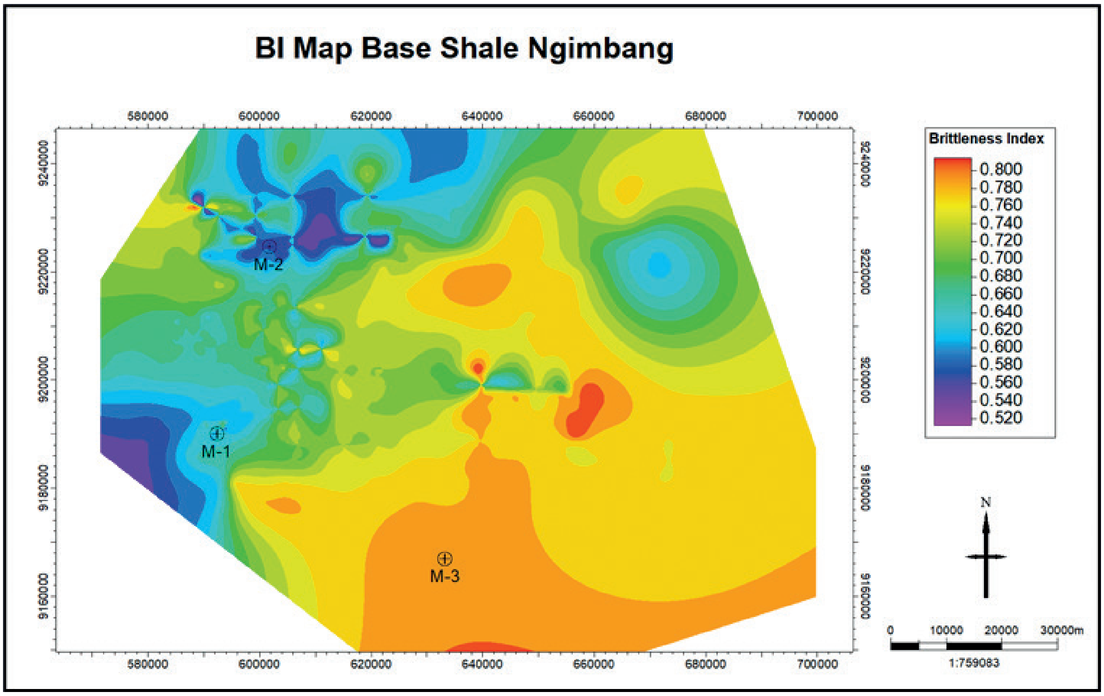

Fig. 7 - Distribution of the BI in the Ngimbang base shale.

4. Conclusions

Well M-1 at a depth of 1156-1261 m, 1430-1467 m, 1504-1596 m, 1680-1737 m, 1993-2150 m, 2235-2422 m, 2878-2995 m, and 2996-3050 m and well M-2 at a depth of 950-1100 m, 1442-1633 m, and 1634-2124 m, each have a permeability value less than 10 mD, mobility less than 10 mD/cP, and transmissibility less than 100 mDm/cP which are indicated to contain fluids in the form of oil and unconventional. Meanwhile, well M-3 at a depth of 1400-1490 m has a permeability value less than 0.1 mD, mobility less than 10 mD/cP, and transmissibility less than 100 mDm/cP which indicates that it contains fluid in the form of unconventional gas. From the distribution of the BI values, each formation in wells M-1, M-2, and M3 is known to have a fragile category that spreads to the NW and south. Wells M-1, M-2, and M-3 meet the requirements of unconventional reservoir parameters. Based on the results of this work, we predict that in the southern part of the OD Field, unconventional reservoir is present because the rocks exhibit high BI values.

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