Petrophysical Analysis to Determine Reservoir and Source Rocks in Berau Basin, West Papua Waters

Analisis Petrofisika untuk Menentukan Batuan Reservoar dan Batuan Induk pada Cekungan Berau, Perairan Papua Barat

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ABSTRACT: Berau Basin is assessed to have same potential in clastic sediments with Mesozoic and Paleozoic ages, where reservoirs and source rocks are similar to productive areas of hydrocarbons in Northwest Shield Australia. This study aims to identify the hydrocarbon prospect zones and potential rocks zones using petrophysical parameters, such as shale volume, porosity, water saturation and permeability. Petrophysical analysis of reservoir and source rock are carried out on three wells located in the Berau Basin, namely DI-1, DI-2 and DI-3 in Kembelangan and Tipuma Formation. Qualitative analysis shows that there are 4 reservoir rock zones and 4 source rock zones from thorough analysis of these three wells. Based on quantitative analysis of DI-1 well, it has an average shale volume (V_{sh}) 9.253%, effective porosity (PHIE) 20.68%, water saturation (S_w) 93.3% and permeability (**k**) 55.69 mD. DI-2 well's average shale volume, effective porosity, water saturation and permeability values are 29.16%, 2.97%, 67.9% and 0.05 mD, respectively. In DI-3 well, average shale volume, effective porosity, water saturation and permeability values are 6.205%, 19.36%, 80.2% and 242.05 mD, respectively. From the reservoir zone of these three wells in Kembelangan Formation, there are no show any hydrocarbon prospect.

Keywords: reservoir, source rock, shale volume, porosity, water saturation, permeability, Kembelangan Formation, Tipuma Formation, Berau Basin

ABSTRAK: *Cekungan Berau diperkirakan memiliki potensi yang sama dengan sedimen klastik yang berumur Mesozoikum dan Palezoikum, di mana reservoar dan batuan induknya memiliki kesebandingan dengan daerah produktif hidrokarbon di Paparan Barat Laut Australia. Penelitian ini bertujuan untuk mengidentifikasi zona prospek hidrokarbon dan zona potensi batuan induk dengan menggunakan parameter petrofisika, yaitu volume shale, porositas, saturasi air dan permeabilitas. Analisis petrofisika batuan reservoar dan batuan induk dilakukan pada tiga sumur bor yang terletak di Cekungan Berau yaitu Sumur DI-1, DI-2 dan DI-3 pada Formasi Kembelangan dan Tipuma. Hasil analisis kualitatif menunjukan terdapat empat zona reservoar dan empat zona batuan induk dari keseluruhan tiga sumur. Berdasarkan analisis kuantitatif, sumur DI-1 memiliki nilai rata-rata volume shale* (V_{sh}) *9,253%, porositas efektif (PHIE) 20,68%, saturasi air* (S_w) *93,3% dan permeabilitas* (**k**) *55,69 mD. Pada sumur DI-2, nilai rata-rata volume shale 29,16%, porositas efektif 2,97%, saturasi air 67,9% dan permeabilitas 0,05 mD. Serta pada sumur DI-3, nilai rata-rata volume shale 6,205%, porositas efektif 19,36%, saturasi air 80,2%, dan permeabilitas 242,05 mD. Dari zona reservoar Formasi Kembelangan untuk tiga sumur tersebut, tidak menunjukan adanya prospek hidrokarbon.*

Kata Kunci: *reservoar, batuan induk, petrofisika, volume shale, porositas, saturasi air, permeabilitas, Formasi Kembelangan, Formasi Tipuma, Cekungan Berau*

INTRODUCTION

Hydrocarbon exploration in West Papua region has been found on a field located on the Bintuni Bay of the carbonate rocks. These carbonate rocks deposited in shallow sea that have bigger energy environment as sandy limestone and in deeper sea that have low energy environment as shaly limestone (Ustiawan *et al.*, 2019). Clastic sediments with Mesozoic and Paleozoic ages are the target of exploration in West Papua region including Bintuni, Salawati and Berau Basins (Pigram *et al.*, 1982). These sediments indicate initial prospect areas with reservoir and source rocks similar to

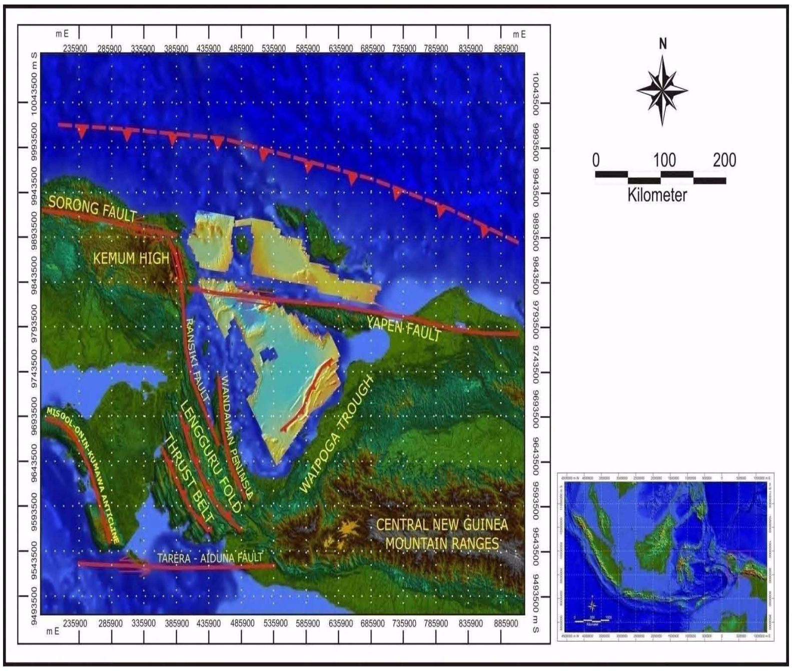

Figure 1. West Papua Bird's Head tectonic elements (Adyagharini, 2009)

productive areas in Australia's Northwest Shelf. In Berau Basin, there are clastic sediments with ages in the Mesozoic and Paleozoic eras.

Tectonic studies on the West Papua region indicate that the Indo-Australia continental plate is moving to the north, while the Pacific oceanic plate is moving to the southwest (Adyagharini, 2009). Several important geological features that influenced tectonic history of Bird's Head, such as formed the boundaries of Cenderawasih Bay, the east-west trending Sorong-Yapen Fault Zone, Waipoga Basin, Tarera-Aiduna Fault, Kemum High and Lengguru Fold-Thrust Belt (Figure 1).

Berau Basin is situated in between Salawati-Bintuni Basin in the NE-SW direction and produced by collision between West Papua micro-continent and the northwestern margin of the Australian continent (Pigram *et al.*, 1982) (Figure 2). Deposition of platform and pelagic carbonates were interrupted by several tectonic events during Late Jurassic to Early Tertiary. The deposition formed Kembelangan Formation as reservoir rock objective and Tipuma Formation as underlying source rock.

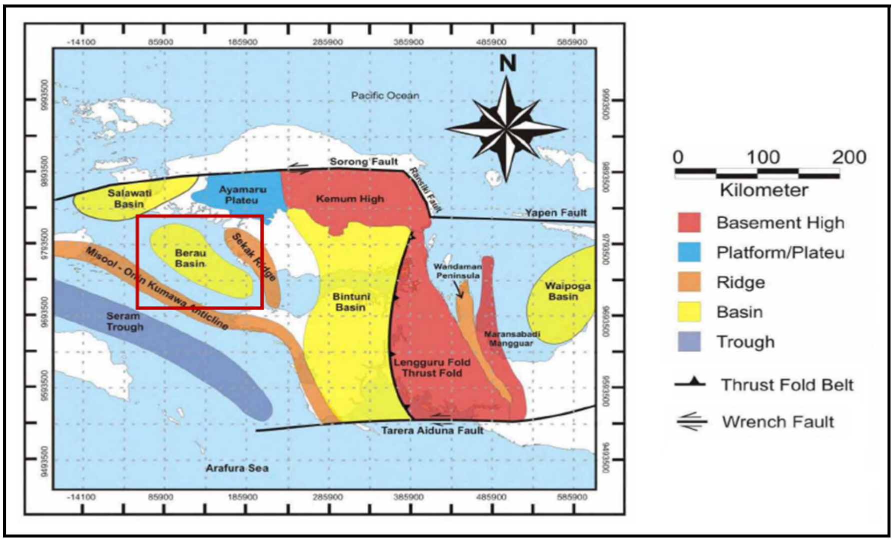

Figure 2. West Papua Bird's Head tectonic elements (Pigram *et al.,* 1982)

As described in Berau Basin stratigraphy, West Papua waters are arranged into several formations, namely Klasaman/ Klasafet Formation, Kais LST Formation, Faumai Formation, Waripi Formation, Kembelangan Formation, Tipuma Formation and Aifam Formation (Figure 3).

According to Yang (2017), basically petrophysics study consists of three parts, namely the physical properties of reservoir fluids (including the physical properties of oil, gas and water at high pressure-temperature and phase changes), physical properties of reservoir rocks (porosity, permeability, water saturation and sensitivity to formation) and physical properties in porous media. In this study, reservoir quality analysis is carried out to identify ideal reservoir based on shale volume, effective porosity, water saturation and permeability.

DATA AND METHODS

Well log data of these three wells are analyzed to obtain information on petrophysical properties of rock formation and its fluid content. The main logs used for this study are gamma ray (GR), resistivity (ILD), density (RHOB) and sonic (DT) logs.

The study area is situated on Berau Basin which is part of the West Papua Province. It is geographically located in between 130^{o} - 132^{o}E and 2^{o} - 3^{o}S (Figure 4). This research focuses on reservoir quality and quantity analysis in 3 (three) wells, namely DI-1, DI-2 and DI-3 wells using petrophysical parameters.

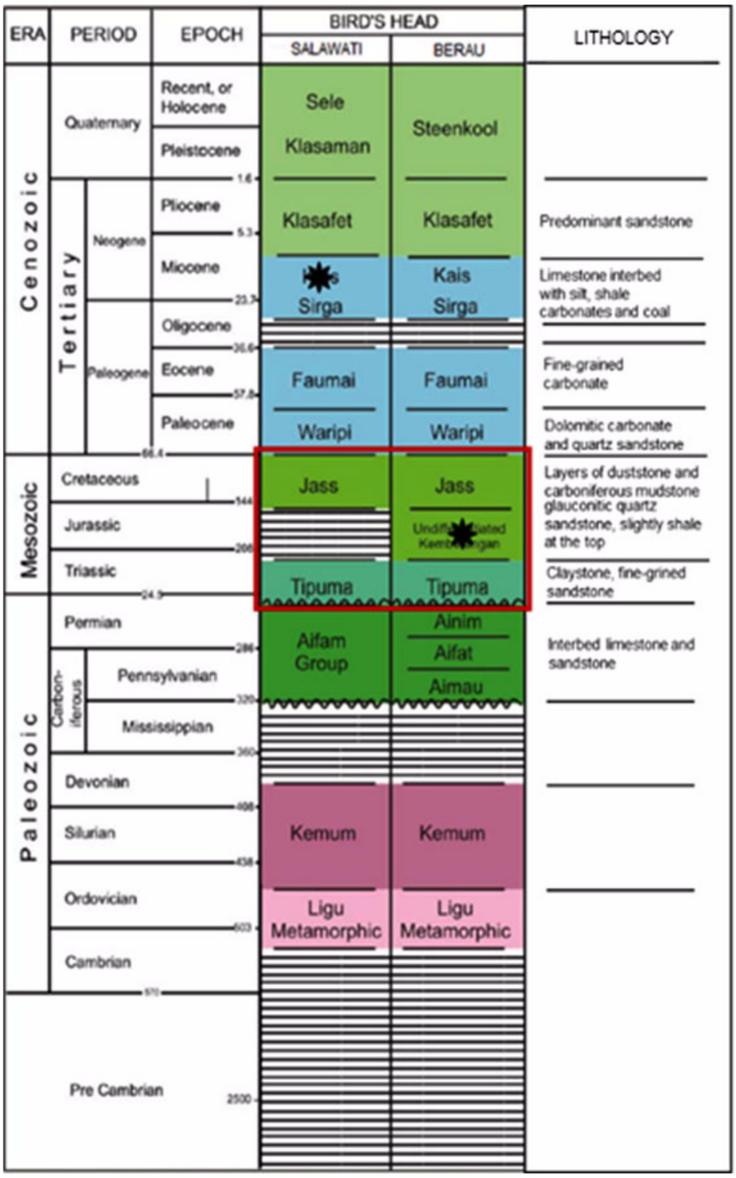

Figure 3. Regional stratigraphy of West Papua waters (modified after Sapiie *et al.,* 2012)

Petrophysical Calculations

Shale volume

The volume of shale is used to calculate the amount of shale in porous rocks. Usually, the shale content is calculated according to the linear equation (Ulum *et al.*, 2014):

$$IGR = \frac{GR_{log} - GR_{clean}}{GR_{shale} - GR_{clean}} \quad (1)$$

where:

$IGR = V_{sh}$ = Gamma Ray Index (%)

GR_{log} = Gamma ray log reading (API)

GR_{clean} = Log response the clean sand GR_{min})

GR_{shale} = Log response in the shale zone (GR_{max})

Besides the simple linear equation, there are non-linear equations for more optimistic calculating of V_{sh}:

- Larionov equation on Tertiary rocks:

$$V_{sh} = 0.083 \text{ x } (2^{3.7\ X\ IGR} - 1) \quad (2)$$

- Steiber equation:

$$V_{sh} = \frac{IGR}{3 - 2\ X\ IGR} \quad (3)$$

- Clavier equation:

$$V_{sh} = 1.7 - [\sqrt{(3.38 - (IGR + 0.7)^2} \quad (4)$$

- Larionov equation for older rocks:

$$V_{sh} = 0.33\ x\ (2^{2\ X\ IGR} - 1) \quad (5)$$

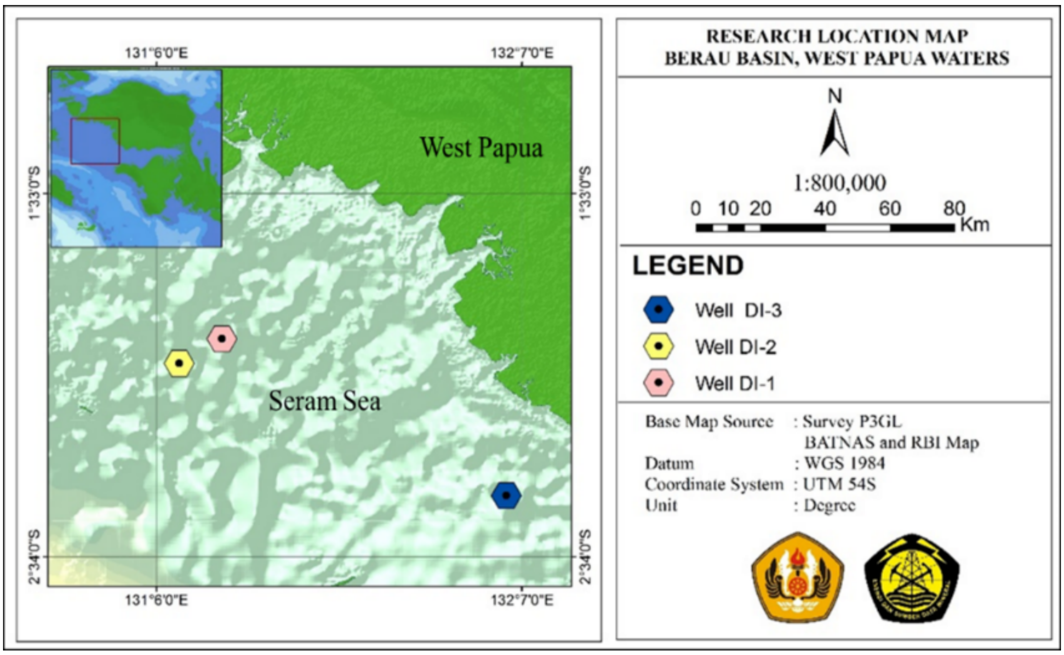

Figure 4. Map of research location, West Papua Waters

Porosity

Porosity is the void fraction of being porous in the rocks formations for accumulating fluids (water, oil and gas). Porosity is further classified as total porosity and effective porosity. Total porosity is defined as the ratio of the entire pore space in a rock to its bulk volume. Effective porosity is the total porosity less the fraction of the pore space occupied by shale or clay. In clean sand formation, total porosity is equal to effective porosity. According to Irawan *et al.* (2009), the value of porosity can be calculated using neutron porosity and porosity density. The porosity can be calculated based on the equations such as:

$$\Phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad (6)$$

$$\Phi_{total} = \frac{\Phi_D + \Phi_N}{2} \quad (7)$$

$$\Phi_{effective} = \sqrt{\frac{\Phi_{Ncorr}{}^2 + \Phi_{Dcorr}{}^2}{2}} \quad (8)$$

$$\Phi_{Dcorr} = \Phi_D - (V_{sh}\ X\ \Phi_{Dsh}) \quad (9)$$

$$\Phi_{Ncorr} = \Phi_N - (V_{sh}\ X\ \Phi_{Nsh}) \quad (10)$$

where:

Φ_D = Porosity density from density log data (%)

ρ_{ma} = Density of rock matrix (gr/cc)

ρ_b = Density of rock matrix (gr/cc) obtained from density log data

ρ_f = Fluid density (value 1.1 for mud, 1 for fresh water)

Φ_{total} = Total porosity (%)

Φ_N = Neutron porosity from Neutron log porosity data (fraction)

$\Phi_{effetive}$ = Effective porosity (%)

Φ_{Ncorr} = Correction of neutron porosity

Φ_{Dcorr} = Correction porosity density

Φ_{Dsh} = Porosity density of the nearest shale zone

Φ_{Nsh} = Porosity neutron of the nearest shale zone

Water Saturation

In a formation containing oil and/or gas, both of which are non-conductors of electricity, with a certain amount of water, the resistivity is a function of water saturation S_W (Tiab and Donaldson, 2004). The water saturation value (S_W) clean sand formation can be calculated using Archie's equation (Harsono, 1997). Simandoux equation:

$$S_w = \frac{C.R_w}{\Phi^2}\left[\sqrt{\frac{5.\Phi^2}{R_w.R_t} + \left(\frac{V_{sh}{}^2}{R_{sh}{}^2}\right)} - \left(\frac{V_{sh}}{R_{sh}}\right)\right] \quad (11)$$

Indonesia equation:

$$S_{w\,Indonesia} = \left(\frac{\sqrt{\frac{1}{R_t}}}{\left(\frac{V_{sh}^{(1-0.5V_{sh})}}{\sqrt{R_{sh}}}\right) + \sqrt{\frac{\Phi^m}{a.R_w}}}\right)^{(2/n)} \quad (12)$$

where:

S_W = Water saturation (fraction)

C = Conductivity values (on sandstones 0.4 and on limestone 0.45)

R_W = Formation water resistivity (ohm.m)

R_t = Formation resistivity value (read from log data) (ohm.m)

Φ = Porosity (%)

V_{sh} = Volume shale (%)

R_{sh} = Resitivity of shale

= Turtosity factor

m = Cementation exponent

n = Saturation exponent

Permeability

Permeability is the ability of rock to drain fluid, in unit of Darcy (D) or milliDarcy (mD). Permeability of the rock formation also depends on the porosity and saturation of water and it can be calculated using the equation,

$$\mathbf{k} = a\,\frac{\Phi_e{}^b}{S_w{}^c} \quad (13)$$

where:

k = Permeability (mD)

S_W = Water saturation (%)

Φ_e = Effective porosity (%)

a, b, c = Schlumberger constants (a = 10000, b = 4.5, c = 2)

RESULTS

Well log correlation can be considered as the identification and/or connection of equivalent strata units in time, age, or position along log curves of adjacent wells. In this research, well log correlation of three wells on Berau Basin are interpreted with assistance of physical characters of lithology, resistivity and porosity logs (Figure 5). Well correlation panel across well log data on three wells creates trajectory horizons into top and bottom layer formations. Gamma ray and spontaneous potential logs are used to determine lithology and boundary of formation. Resistivity logs can determine the type of hydrocarbons by looking at the low and high resistivity formation response to induced electrical current (Erryansyah *et al.*, 2020).

Qualitative analysis

Qualitative interpretation in this study uses gamma ray, neutron and density. Shale typically has high concentrations of natural radioactive elements such as potassium, thorium and uranium thus increases the gamma ray log response. Sand and limestone have low concentration of radioactive elements thus decreased gamma ray response. Cross-over neutron porosity NPHI curve log against bulk density RHOB curve log which is overlaid each other to detect hydrocarbon bearing zone (Nopiyanti *et al.*, 2020). Based on those characteristics, the qualitative analysis shows there are

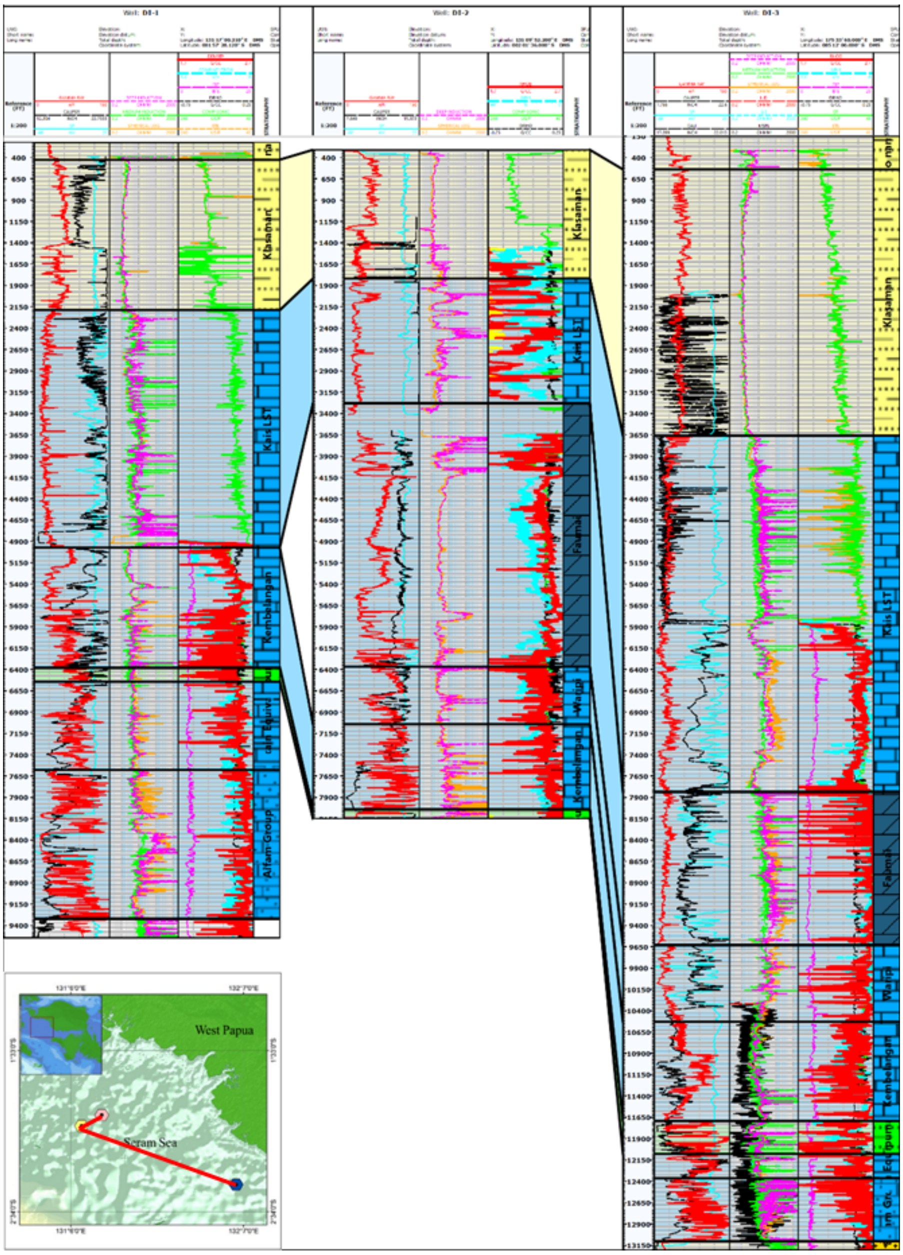

Figure 5. Well logs correlation of three wells on Berau Basin

four reservoir zones that are estimated to have hydrocarbon potential in three wells of Kembelangan Formation. DI-1 well is divided into two zones, zone 1 (5,884-5,940 ft) and zone 2 (6,326-6,364 ft). DI-2 and DI-3 wells have reservoir zones with range of 8,000-8,039.5 ft and 11,350-11,405 ft, respectively (Table 1). Reservoir zones in DI-1 well are marked on several factors including gamma ray log values ranging from 22.71 to 75.44 API which represent low radioactive content. Resistivity values in these zones show range of 2.83-1,841.48 ohm.m, which is likely the reservoir's fluid is water and/or oil. Density values show range of 1.58-2.65

g/cc determines uncompact to slightly compact rock hardness. Neutron values indicate that both zones have low hydrogen content. In conjunction, DI-2 and DI-3 wells indicate similar characteristics in different depths range of 8,000-8039.5 ft and 11,350-11,405 ft. Figure 6 shows the zones in yellow range of reservoir rock in log display.

There are four zones of source rock on various depths in Tipuma Formation based on lithology, resistivity and density-neutron logs. DI-1 and DI-2 wells have zones of source rock with range of 6,436-6,539 ft and 8,041-8,092 ft, respectively. DI-3 well is divided into two zones, zone 1 (11,877.5-11,920 ft) and zone 2 (11,978.5-12,078 ft) (Table 2). These zones in three wells are marked on several factors including high gamma ray values until 155.79 API, it tends to absorb radioactive elements as impermeable rock properties. Resistivity values in each zone tends to be low and sonic log values tend to be high and analyze as source rock but not yet mature. Figure 7 shows the zones in yellow range of source rock in log display.

Quantitative analysis

Shale Volume

Figure 8 shows the comparison graph of shale volume values calculated using the linear, Larionov, Steiber and Clavier equations on DI-1 well in

Table 1. Zones of reservoir rock

Well	Zone	Depth (ft)	Gamma ray (API)	Resistivity (ohm.m)	Density (g/cc)	Porosity (v/v)
DI-1	1	5,884-5,940	22.71-70.12	2.83-66.91	1.71-2.65	0.039-0.381
	2	6,326 – 6,364	32.66-75.44	2.11-1,841.48	1.58-2.62	0.015-0.43
DI-2	1	8,000-8039.5	36.66-97.67	4.74-52.02	2.48-2.73	1-17
DI-3	1	11,350-11,405	30.09-79.171	7.35-1,990.88	1.79-2.69	0.04-0.53

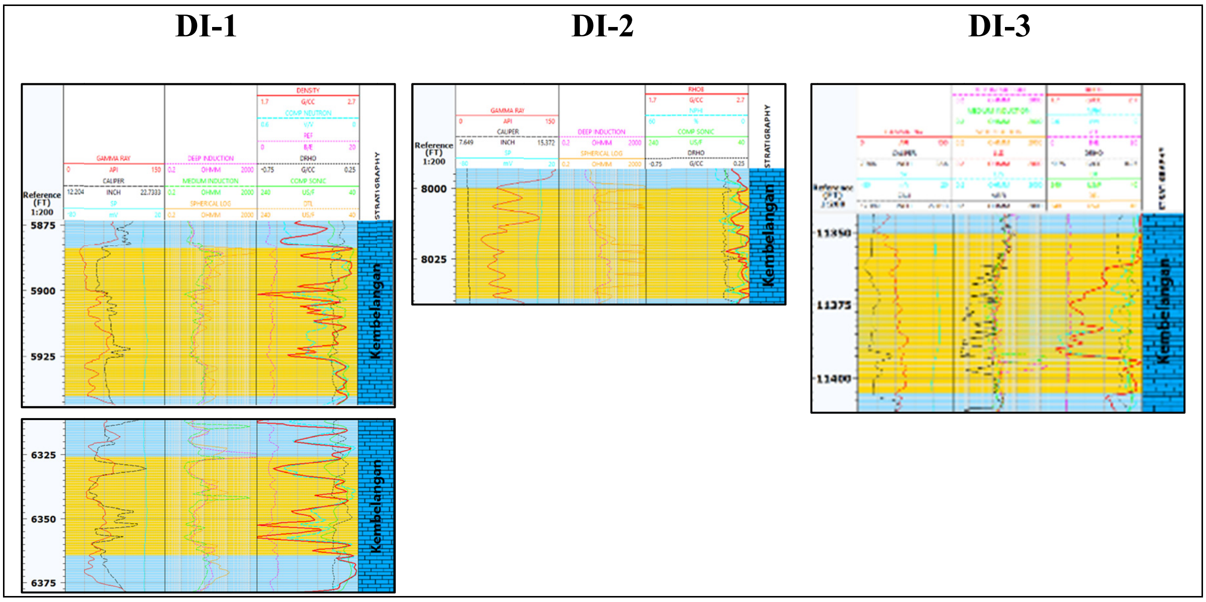

Figure 6. Log display on zones of reservoir rock

Table 2. Zones of source rock

Well	Zone	Depth (ft)	Gamma ray (API)	Resistivity (ohm.m)	Sonic (µs/ft)
DI-1	1	6,436-6,539	63.87-113.55	1.81-9.35	66.47-111.96
DI-2	1	8,041-8,092	25.94-130.03	6.64-1,397.47	4.70-74.63
DI-3	1	11,877.5-11,920	62.62-155.79	1.97-24.79	67.67-83.35
	2	11,978.5-12,078	32.30-132.78	4.25-18	61.92-98.23

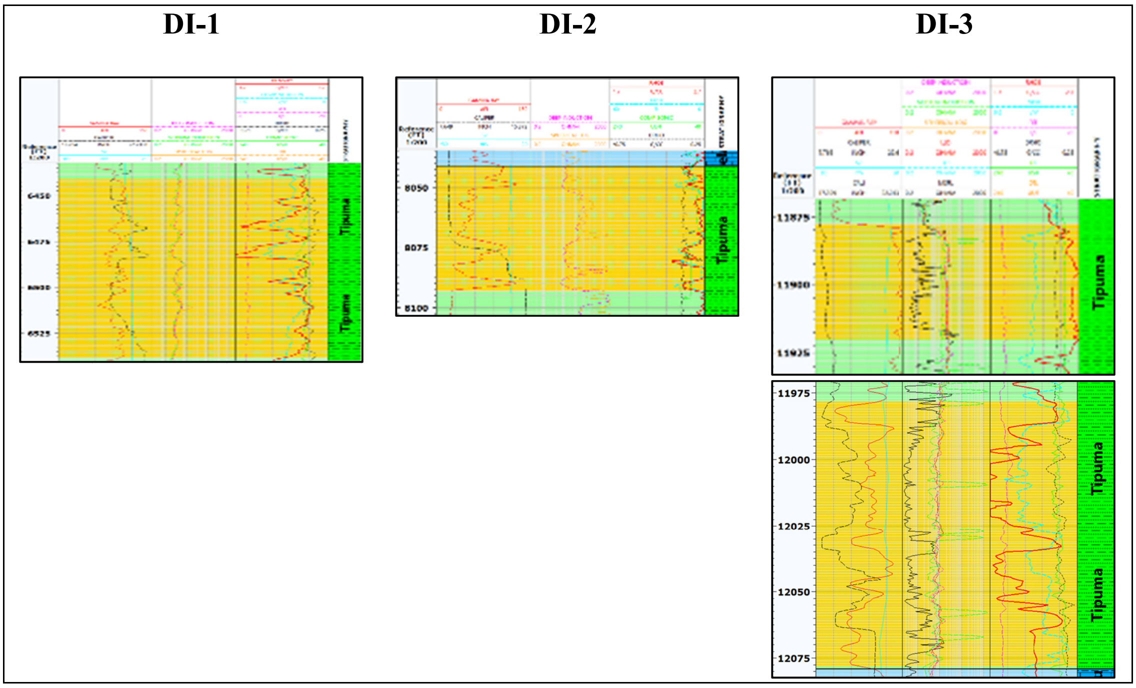

Figure 7. Log display on zones of source rock

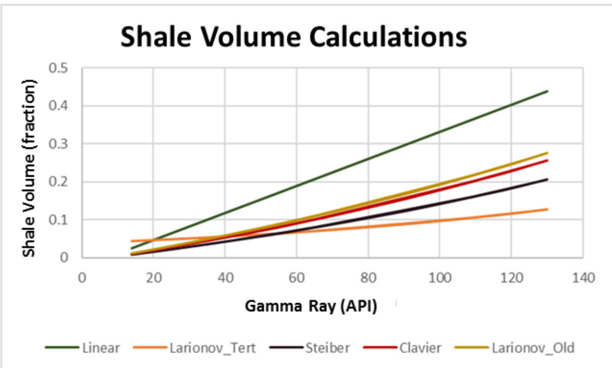

Figure 8. Comparison graph of linear and non-linear shale volume calculations

Kembelangan Formation. Based on comparison graph, Larionov equation has a high degree of optimism because it produce lower shale volume values. It shows on gamma ray value rising slowly but shale volume values are not increasing rapidly compared to the other linear and non-linear methods. Therefore, this study adopts the Larionov equation for tertiary rocks. Shale volume values using Larionov equation on Tertiary rocks (Equation 2) in DI-1, DI-2 and DI-3 wells are 9.253%, 29.16% and 6.205%, respectively.

Porosity

In this study, porosity is calculated using neutron and density logs. The total porosity (PHIT) and effective positivity (PHIE) values in the calculation are porosity values in one selected point of each reservoir zones (Table 3).

Table 3. Total porosity and effective porosity in reservoir zones

Well	Zone	Depth (ft)	PHIT (%)	PHIE (%)
DI-1	1	5,884-5,940	17.65	17.56
	2	6,326-6,364	23.86	23.79
DI-2	1	8,000-8,039.5	5.1	2.97
DI-3	2	11,350-11,405	19.99	19.46

Water Saturation

The important parameter to calculate saturated fluid in place from well log is the formation water resistivity (R_w). Determination of R_w is done using the pickett plot method by plotting a crossplot between PHIE and R_t. The outermost points of the crossplot are on a line called the R_o-line. All points on this line have S_w = 100% or S_w = 1 (Manurung *et al.*, 2017). At the point of intersection between the line S_w = 1 with porosity 100%, if a = 1, the R_w value can be determined. Based on the results of the crossplot between PHIE and R_t, R_w values range of 0.04-0.804 ohm.m of the three wells (Figure 9). DI-1 well has R_w values of 0.28 ohm.m in zone 1 and 0.738 ohm.m in zone 2. DI-2 and DI-3 wells have R_w values range of 0.04 ohm.m and 0.804 ohm.m, respectively.

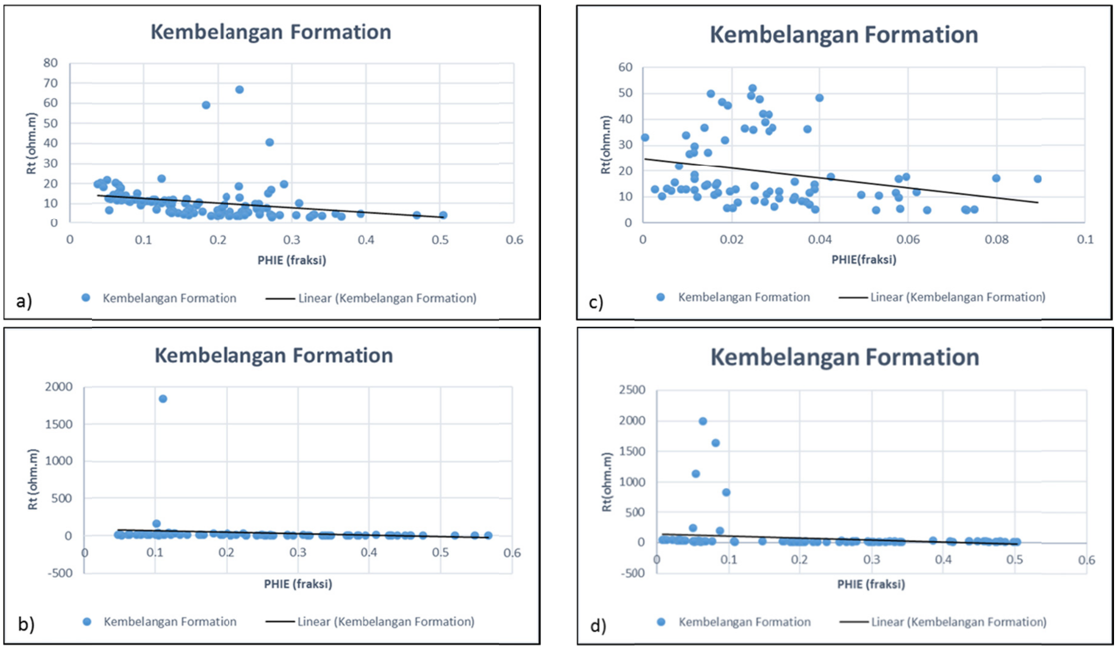

Figure 9. PHIE to Rt plot of 2 zones in Kembelangan Formation

Based on the three wells consisting shaly sand formation, calculation of water saturation is decided by using Indonesian equation. It shows that the formation does not only contain sand, but there are shale fraction in sand content. If water is the only fluid contained in rock pores, then the value of S_w = 1, but if the rock pores contain hydrocarbon fluid, the value of S_w<1 (Tiab and Donaldson, 2004). S_w values in DI-1 well are range of 92.2-94.4%. DI-2 and DI-3 wells have S_w values 67.9% and 80.2%.

Permeability

The permeability values in the calculation are permeability values in one selected point of each reservoir zones. DI-1 well has permeability values range of 18.35-93.04 mD, while DI-2 and DI-3 wells have permeability values of 0.05 and 242.05 mD, respectively.

DISCUSSION

Based on shale volume calculation, highest shale content are found in the Kembelangan Formation of DI-2 well that inhibits rock in flowing fluid. DI-3 well has a lower shale content compared to other wells so it can be stated as the most consolidated carbonate reservoir rock. DI-1 and DI-3 wells are categorized as good to very good reservoir rock with effective porosity values range of 17.56-23.79%. While, DI-2 well has poor effective porosity value range of 2.97%. DI-1 and DI-3 wells tend to have high water saturation percentage so that they are estimated to contain water fluid. Whereas DI-2 well has water saturation value that tends to be fair to good so it is estimated to contain hydrocarbon fluid. DI-1 and DI-2 wells are considered as moderate and impermeable for fluid flow because it has a relatively low permeability. Whereas DI-3 well is categorized as excellent for fluid flow because they have high permeability. The quantitative petrophysics calculation results are shown in Table 4.

From stratigraphic and well log correlation, Kembelangan Formation lies in Early Cretaceous to Late Jurassic age. Shale intermittent sedimentary rocks with sandstone and limestone are found, with coarse grained sandstone, coarse grained, not compact until well consolidated. Shale is not compact and generally contains carbonate material. Source rock Tipuma Formation contains shale and sandstone with shale dominantly.

Table 4. Quantitative petrophysics calculation of three wells in Berau Basin

Well	Depth (ft)	Reservoir lithology	Shale Volume (%)	Effective Porosity (%)	Water Saturation (%)	Permeability (mD)	Remarks (high, moderate, low)
DI-1	5,884-6,364	Sandstone	9.253	23.79	92.2-94.4	18.35-93.04	Moderate
DI-2	8,000-8,039.5	Shaly sandstone	29.16	2.97	67.9	0.05	Low
DI-3	11,350-11,405	Shaly sandstone	6.250	19.46	80.2	242.0.5	Moderate

CONCLUSION

The petrophysical analysis of this study appraise the reservoir rocks and source rocks of three wells in Berau Basin and suggest no show hydrocarbon prospect. The neighboring area to the north east of Berau Basin is economically viable for hydrocarbon exploration including Bintuni and Salawati Basin. The southern side of the study area is avoided due to the high concentration of water and excessive impermeable reservoir rocks. Based on the result of petrophysical analysis in this study, the Kembelangan reservoir rocks in Berau Basin are considered not similar to productive areas of hydrocarbons in Northwest Shield Australia.

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