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RESEARCH ARTICLE

Analysis of Petrophysical Parameter on Shaly Sand Reservoir by Comparing Conventional Method and Shaly Sand Method in Vulcan Subbasin, Northwest Australia

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Abstract

Vulcan Subbasin is an area with a lot of oil and gas exploration where is located in the Bonaparte Basin, Northwest Australia. There is some formation identified as sandstone reservoir with clay content which is usually called shaly sand based on the screening between resistivity log and density log. Clay content caused lower resistivity log readings so the shaly sand reservoir is considered as non-reservoir. To overcome this, a method besides the conventional method was applied to analyze the petrophysical parameters of shaly sand reservoir, it was shaly sand method. Petrophysical analysis is an analysis of rock physical parameters such as shale volume, porosity, and water saturation based on well log data. In this study, petrophysical analysis was carried out in the Vulcan Subbasin using 35 well log data, including gamma ray log, resistivity log, neutron log, and density log for the conventional method and shaly sand method involved Stieber equation and Thomas Stieber plot. The results obtained from this study are the comparison of petrophysical parameter values and pay summary between the conventional method and the shaly sand method, also its relation to the shale distribution type. By applying the shaly sand method, the average shale volume has decreased, the average porosity has increased, the average water saturation has increased, the average net to gross has increased, the average net thickness has increased, and the average net pay has increased. Changes in the average value were caused by laminated-dispersed shale distribution type which is influenced by diagenesis and the depositional environment of the formation.

Keywords: Vulcan Subbasin, petrophysical analysis, shaly sand, Stieber equation, Thomas Stieber plot

1. Introduction

Bonaparte Basin is one of the most productive offshore hydrocarbon-producing basins in Australia. One of the areas that has many exploration wells is Vulcan Sub-basin (Geoscience Australia, 2021). Vulcan Sub-basin is a Mesozoic northeast-southwest trending extensional depocenter located in the Bonaparte Basin, Northwest Australia, that consist of horst, graben, and terrace (Pattillo & Nicholls, 1990). It borders Ashmore Platform to the west and Londonderry High to the east (Figure 1).

Exploration is carried out to find hydrocarbon reserves. Well log data can be evaluated to increase hydrocarbon productivity by finding other possible productive reservoirs, such as shaly sand reservoir. Shaly sand reservoir is a reservoir that not only has sandstone lithology but also contains shale within the sand (Mkinga et al., 2020). Characteristics of shaly sand can affect the well-log readings so that the reservoir interval of shaly sand is considered non-reservoir. Therefore, a petrophysical analysis was carried out on the reservoir.

Petrophysical analysis was conducted to calculate the values of petrophysical parameters such as shale volume, porosity, and water saturation (Harsono, 1997). These parameters can be used to determine the reservoir thickness. In addition, another method of petrophysical calculation is needed for shaly sand conditions, especially for shale volume and porosity parameters. The method applied to the calculation of shale volume is the Stieber equation, and the method of porosity calculation is the Thomas Stieber plot. Thomas Stieber can also be used to determine the shale distribution type present in the formation. Therefore, two petrophysical calculation methods were carried out, the conventional method and the shaly sand method. Then the results of the two methods are compared to determine the effect of the presence of shale on petrophysical parameters and pay summary.

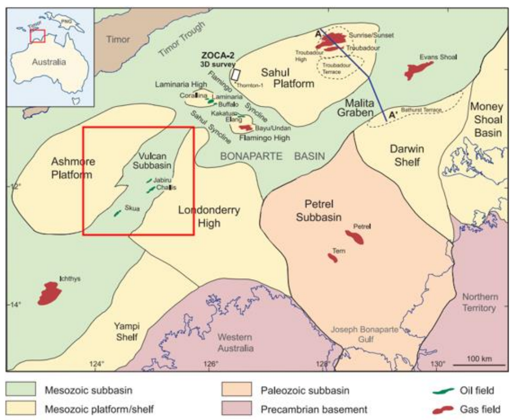

Fig. 1. Location Area of Study (Frankowicz & McClay, 2010).

2. Material and Methods

2.1 Data

This research used 35 well log data that consisted of gamma ray log, resistivity log, neutron log, and density log. The data was downloaded from National Offshore Petroleum Information Management System (NOPIMS) website which is provided by Geoscience Australia (2021).

2.2 Methodology

The steps of analysis are precalculation, zone determination, conventional petrophysical analysis, shaly sand petrophysical analysis, and comparison between petrophysical parameters and pay summary results obtained from the two methods.

2.2.1 Screening for Shaly Sand Method

Low resistivity readings at reservoir intervals (low resistivity pay zone) are caused by several factors, such as clay content in the reservoir and conductive minerals. The way to identify the cause of low resistivity is by using a cross plot between the resistivity log and the density log. Conductive mineral is characterized by a low resistivity value and a high density value. Meanwhile, the clay content is indicated by a low resistivity value and a intermediate density value.

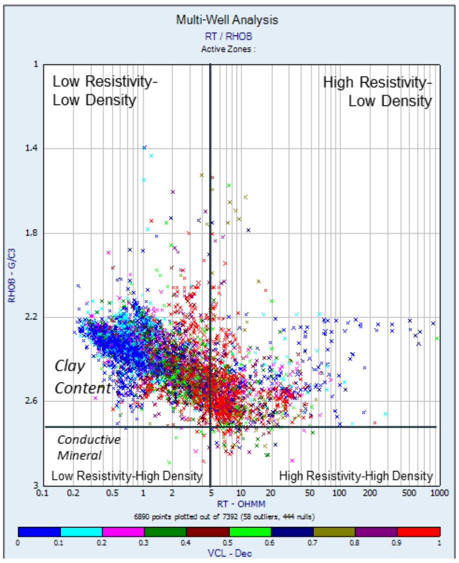

Fig. 2. Crossplot between RT and RHOB for Screening Shaly Sand Method.

Based on the cross plot above in Figure 2, data distribution is mostly found in areas classified as low resistivity and intermediate density. Therefore, the cause of the low resistivity pay zone in the formation is the clay content in the reservoir, so petrophysical analysis using the shaly sand method can be used.

2.2.2 Precalculation

Precalculation is calculating the temperature at each well by temperature data or temperature gradient from each well and data from the nearest well.

2.2.3 Zone Determination

The zones are determined based on top formation from each well. Zones were determined by formation based on the assumption that each formation has the same age and depositional mechanism. In this study, the formation target are Puffin Formation, Montara Formation, and Plover Formation.

2.2.4 Conventional Petrophysics Analysis

Conventional method analyzes petrophysical parameters without considering the presence of shale within the shaly sand reservoir. The calculated parameters include shale volume, porosity, and water saturation. Parameter picking and the equations used in the conventional analysis are as follows.

- Shale Volume

Parameter picking for shale volume was conducted by determining the shale baseline (GRmax) and sand baseline (GRmin) on the gamma ray log histogram, which consists of the number of data frequencies so that the determination of the value is more detailed, as seen in Figure 3.

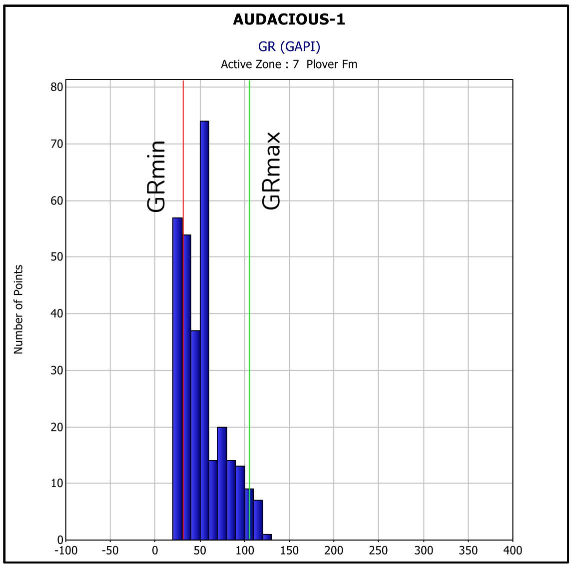

Fig. 3. Parameter Picking for Shale Volume.

The equation used to calculate shale volume is according to the linear equation:

$$V_{sh} = I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

where:
V_{sh}=I_{GR}= shale volume
GR_{log}= gamma ray log reading
GR_{min}= minimum gamma ray
GR_{max}= maximum gamma ray

- Porosity

Parameter picking for porosity was conducted by determining the wet clay point on the neutron-density plot. Wet clay point is a point that shows the condition of the clay volume equal to 100%, consisting of neutron wet clay (Neu Wet Clay) and density of wet clay (Rho Wet Clay), as seen in Figure 4.

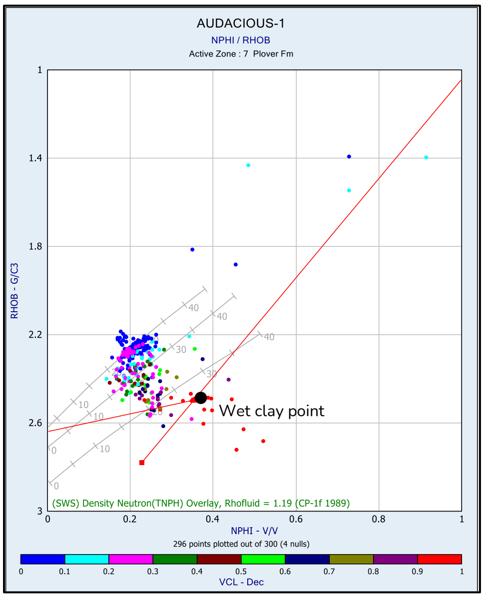

Fig. 4. Parameter Picking for Porosity.

The equation used to calculate porosity is according to equation:

$$\emptyset_E = \emptyset_T(1 - V_{sh})$$

where:
$\emptyset_E$= effective porosity
$\emptyset_T$= total porosity
V_{sh}= shale volume

- Water Saturation

Parameter picking for water saturation was conducted by determining the water zone on the Pickett plot, a plot between resistivity and porosity. The value obtained is the water resistivity (Rw) as input on water saturation. The parameter picking can be seen in Figure 5.

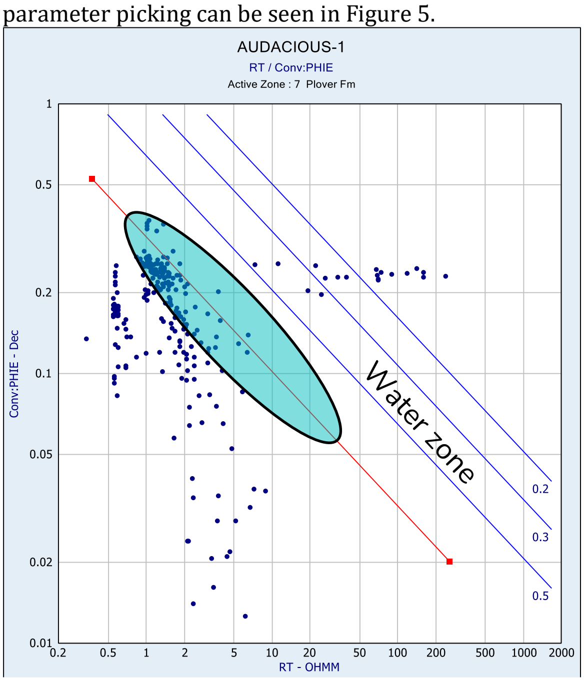

Fig. 5. Parameter picking for water saturation.

The equation used to calculate water saturation is according to Archie equation:

$$Sw = \sqrt[n]{\frac{a \times Rw}{\emptyset^m \times Rt}}$$

where:
Sw = water saturation
a= tortuosity factor
Rw= water resistivity
$\emptyset$= porosity
m= cementation factor
Rt= formation resistivity
n= saturation exponent

2.2.5 Shaly Sand Petrophysics Analysis

Another method is used for shaly sand reservoir to determine the impact of shale occurrence on the calculation of petrophysical parameters. Shaly sand method is applied to the petrophysical parameters such as shale volume and porosity. Shale volume calculation is based on the Stieber equation (Stieber, 1970), while the porosity calculation is based on the Thomas Stieber plot. The equations that shaly sand method use are as follows.

- Shale Volume

Parameter picking for shale volume by shaly sand method was conducted in the same way as the conventional method, which determined GR min and GR max. The difference is shaly sand method applied Stieber equation for shale volume calculation. By applying Stieber equation, shale volume value will be different. The graph below compares shale volume between linear and Stieber (Figure 6).

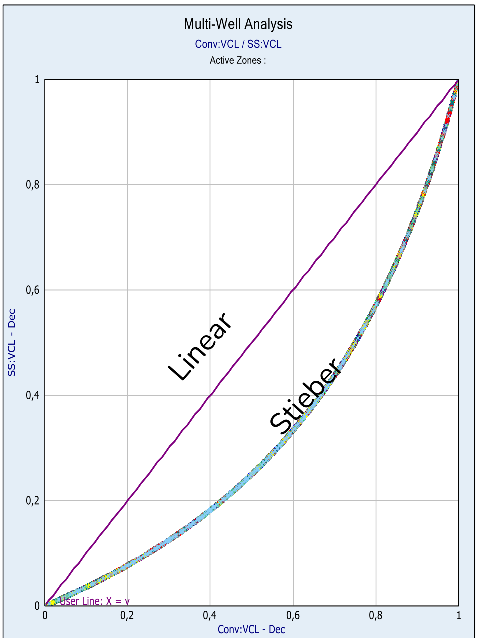

Fig. 6. Shale volume comparison between Linear and Stieber equation.

Stieber equation is used as written below:

$$V_{sh\,Stieber} = \frac{I_{GR}}{3 - 2I_{GR}}$$

Where:
$V_{sh\ Stieber}$= shale volume by Stieber equation
I_{GR}= gamma ray index or shale volume by linear equation

- Porosity

Parameter picking for porosity was conducted by picking Phimax and PhiTCl point in Thomas Stieber plot. Phimax is a point that indicates the porosity of clean sand. PhiTCl is a point that indicates the porosity of shale. The two points are determined according to the distribution of the plot data as seen in Figure 7.

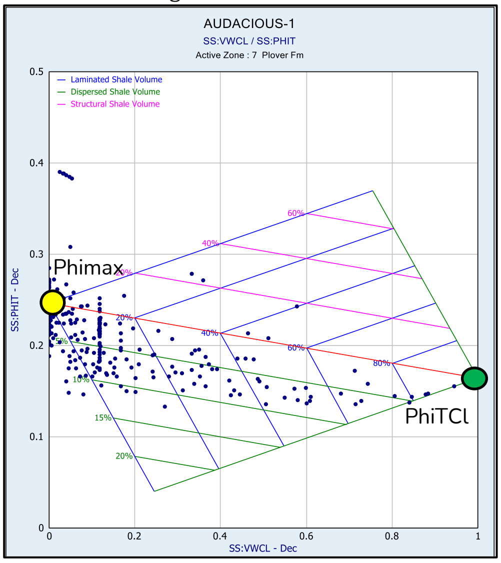

Fig. 7. Parameter picking for porosity in Thomas Stieber plot.

Then, the equation is applied as below:

$$\emptyset_{E\ ss} = \frac{\emptyset_E}{(1 - V_{lam})}$$

Where:
$\emptyset_{E\ ss}$= effective porosity by shaly sand method
$\emptyset_E$= effective porosity by conventional method
V_{lam}= shale volume of shale lamination

2.2.6 Shale Distribution

Thomas Steiber plot also defines shale distribution from shale volume and total porosity cross plot as seen on Figure 8. Thomas Stieber plot is based on calculating the laminar shale volume from the total volume, and the remaining shale volume is considered structural shale or dispersed shale. The principle of this method is to remove the laminar shale effect from the porosity of the sand. Removing the shale affects the net to gross ratio of shale and sand (Ghaleh et al., 2017). This method requires input from maximum porosity or clean sand porosity and total shale porosity to calculate the shale distribution model that consist of laminated shale, structural shale, and dispersed shale.

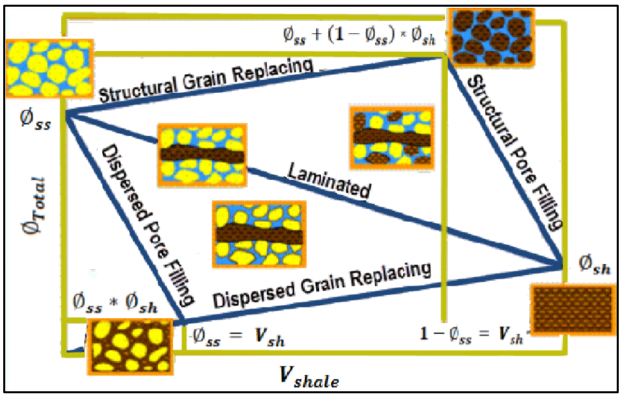

Fig. 8. Thomas Stieber plot shows the shale distribution model (Thomas & Stieber, 1975 in Ali et al., 2016).

2.2.7 Cut Off Determination

Cut off is needed to obtain net to gross (NTG), net thickness, and net pay. Cut off value is determined by a frequency plot between effective porosity and shale volume for shale volume cut off and porosity cut off (Figure 9). In contrast, water saturation cut off is determined by effective porosity and water saturation frequency plot (Figure 10).

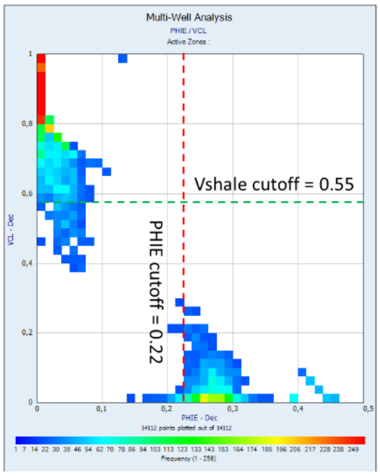

Fig. 9. Shale volume cut off and porosity cut off determination.

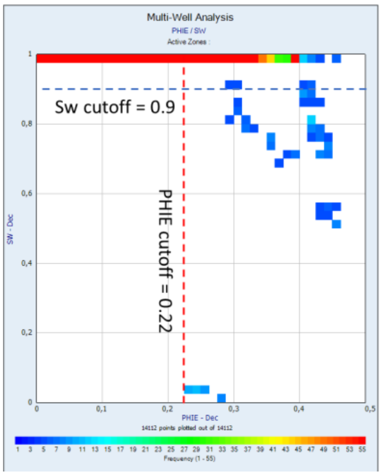

Fig. 10. Water saturation cut off determination.

3. Results and Discussion

3.1 Shale Volume

Shale volume was obtained by parameter picking of GRmax and GRmin, then calculated by linear equation. While the shaly sand method used Stieber equation to calculate the shale volume The average value of shale volume by conventional and shaly sand method is written in Table 1.

Table 1. Average shale volume by conventional and shaly sand method

Formation	Average shale volume (%)	
	Conventional	Shaly Sand
Puffin Formation	11,5	6,242
Montara Formation	8,413	5,625
Plover Formation	10,453	9,042

3.2 Porosity

Porosity was obtained by parameter picking of wet clay point, then calculated by the effective porosity equation. While the shaly sand method used Thomas Stieber plot to determine the porosity value. The average value of porosity by conventional and shaly sand method is written in Table 2.

Table 2. Average porosity by conventional and shaly sand method

Formation	Average porosity (%)	
	Conventional	Shaly Sand
Puffin Formation	29,374	30,184
Montara Formation	20	20,15
Plover Formation	16,332	16,4

3.3 Shale Distribution

Shale distribution model was determined by Thomas Stieber plot, which includes laminated shale, structural shale, scattered shale, or a combination of each other. Laminated shale exists as shale layers within the rock matrix. Structural shale exists in the form of a fragment considered a part of the matrix. Dispersed shale occupies the pore spaces between the matrix by adhering to the surface of the grains.

Based on the Thomas Stieber plot, Puffin Formation, Montara Formation, and Plover Formation dominantly have a combination of laminated-dispersed shale because the major scatter plot between shale volume and total porosity of each formation in most of the wells falls in the area between the laminated and dispersed line. In contrast, structural shale is rare, as shown in the example of Thomas Stieber plot below in Figure 11-13.

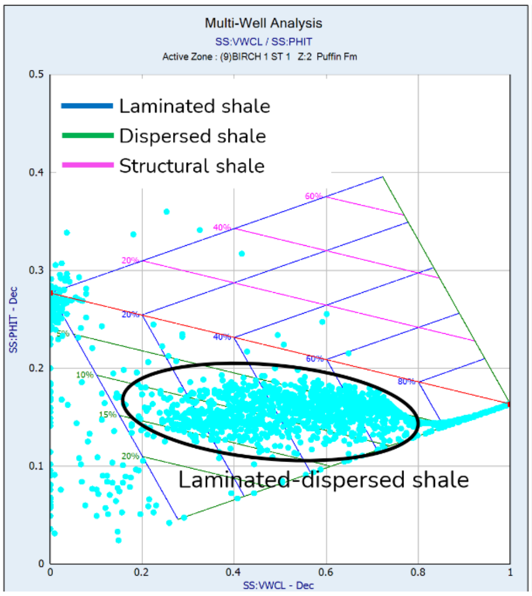

Fig. 11. Shale distribution in Puffin Formation.

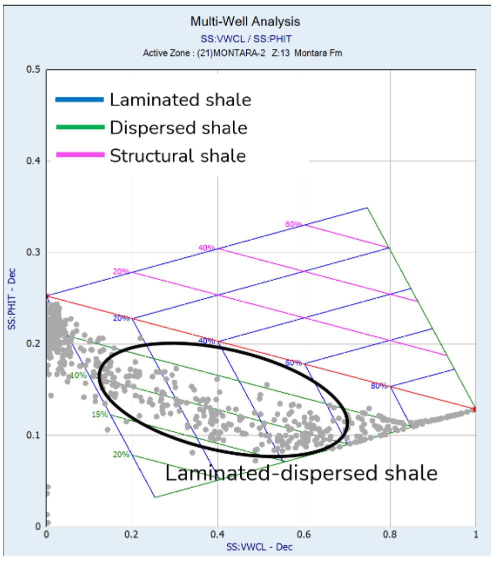

Fig. 12. Shale distribution in Montara Formation.

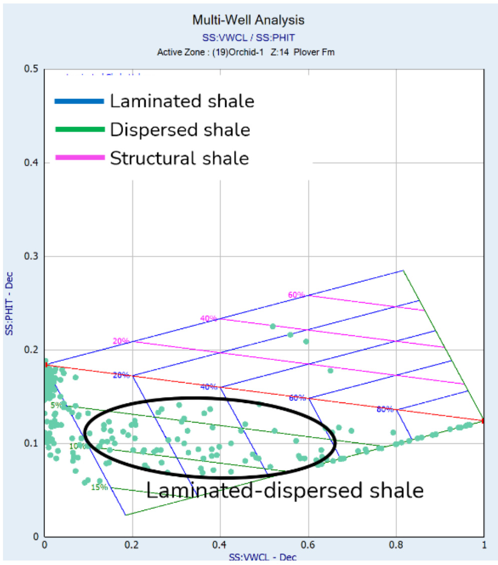

Fig. 13. Shale distribution in Plover Formation.

3.4 Water Saturation

Water saturation was obtained by parameter picking of water resistivity, then calculated by the Archie equation. In the shaly sand method, water saturation was calculated by same equation as conventional method, Archie equation because there is limited data to apply the other equations (Dwiyono & Winardi, 2014). But, the water saturation value is based on the porosity input that obtained from shaly sand method by Thomas Stieber plot. The average water saturation value by conventional and shaly sand method is written in Table 3.

Table 3. Average water saturation by conventional and shaly sand method

Formation	Average water saturation (%)	
	Conventional	Shaly Sand
Puffin Formation	57,8	61,439
Montara Formation	34,987	35,85
Plover Formation	48,04	50,164

3.5 Cut Off and Summation

Shale volume cut off, porosity cut off, and water saturation cut off can be seen in the Table 4 below.

Table 4. Cut off value

Formation	Cut Off (%)		
	Shale Volume (≤)	Porosity (≥)	Water Saturation (≤)
Puffin Formation	55	22	90
Montara Formation	72	17	77
Plover Formation	57	8	80

The results of the pay summation from the application of the cut off value in the conventional method and the shaly sand method can be seen in Table 5 and Table 6 below.

Table 5. Pay summation of conventional method

Formation	Net to Gross (%)	Net Thickness (m)	Net Pay (m)
Puffin Formation	29,295	102,318	19,991
Montara Formation	18,913	65,846	27,056
Plover Formation	46,274	88,275	14,107

Table 6. Pay summation of shaly sand method

Formation	Net to Gross (%)	Net Thickness (m)	Net Pay (m)
Puffin Formation	35,326	118,276	21,072
Montara Formation	21,9	81,609	31,151
Plover Formation	56,916	108,498	16,479

3.6 Comparison between Conventional Method and Shaly Sand Method

After getting the result, comparing the petrophysical parameters and pay summary between the conventional and shaly sand methods was conducted. Applying Stieber equation to shale volume calculation decreased the average shale volume in each formation, as seen in Figure 14. This decrease in shale volume is due to the common radioactive characteristics of the formation, thus giving a lower shale volume value than the linear equation. Applied the Thomas Stieber plot to calculate porosity also increases the average porosity value (Figure 15). The shale distribution model influences the increase slightly in porosity. Based on the Thomas Stieber plot, each formation has laminated-dispersed shale model. The dominant laminated combined with dispersed shale model has a minor effect on porosity, so when Thomas Stieber is applied, the porosity calculation does not increase much. In addition, the water saturation value increases in the shaly sand method (Figure 16). The difference in water saturation values in the conventional and shaly sand methods is influenced by the porosity as input on water saturation calculation. The increase in value is caused by the equation used, which is Archie equation, so it still causes an overestimation of the water saturation value in shaly sand (Poupon & Leveaux, 1971).

The shaly sand method generally increases the average net to gross, net thickness, and net pay (Figure 17-19), so the shaly sand method can be effective for reservoir characterization and thickness calculations more optimistic, although there must be other applications for water saturation parameters.

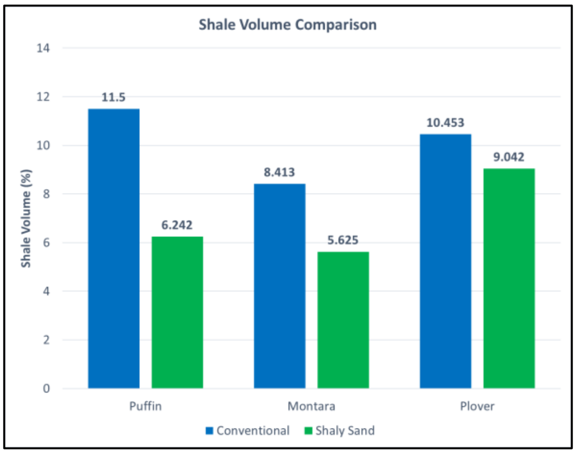

Fig. 14. Shale volume comparison between conventional and shaly sand method.

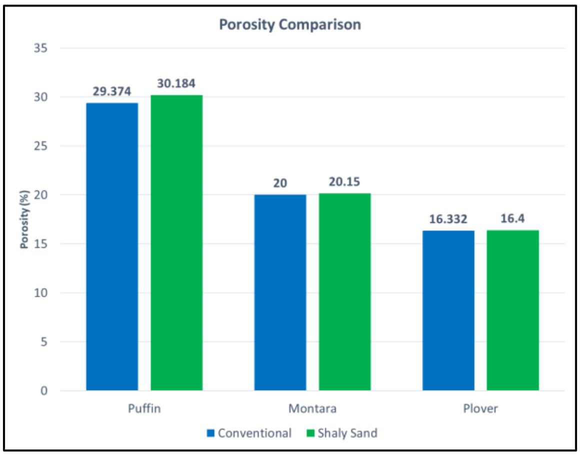

Fig. 15. Porosity comparison between conventional and shaly sand method.

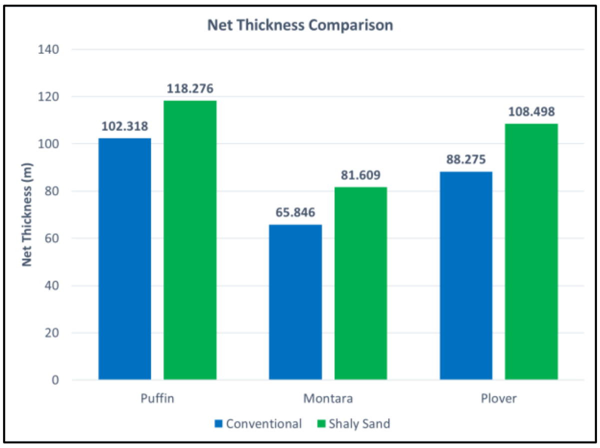

Fig. 18. Net Thickness Comparison between Conventional and Shaly Sand Method.

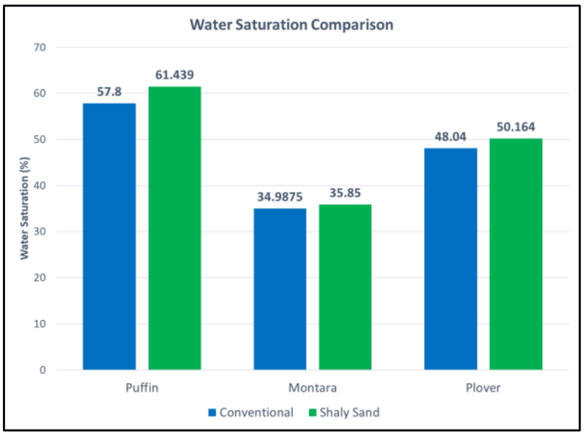

Fig. 16. Water Saturation Comparison between Conventional and Shaly Sand Method.

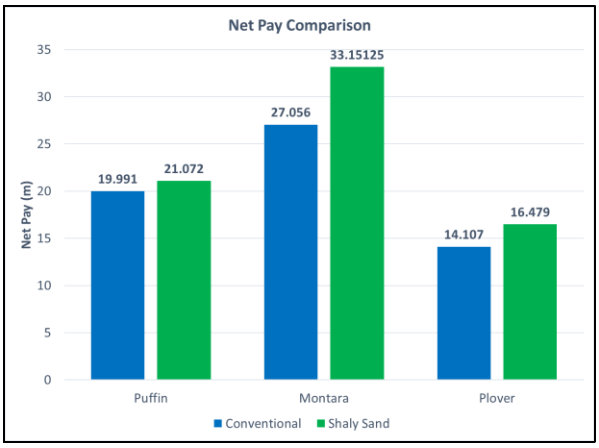

Fig. 19. Net Pay Comparison between Conventional and Shaly Sand Method.

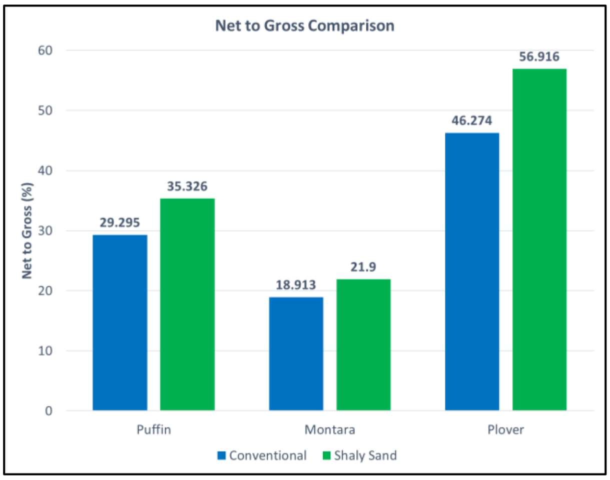

Fig. 17. Net to Gross Comparison between Conventional and Shaly Sand Method.

4. Discussion

The petrophysical parameter includes shale volume, porosity, water saturation, and pay summary includes net to gross, net thickness, and net pay were calculated using conventional and shaly sand methods. Conventional method analyzed petrophysical parameters without considering the presence of shale within the shaly sand reservoir. In the conventional petrophysical method, Linear equation was applied in shale volume calculation, it also used effective porosity and Archie equation in water saturation. Meanwhile, shaly sand method analyzed the petrophysical parameter by considering the shale content in the shaly sand reservoir. Stieber equation is used in the shale sand method to calculated shale volume, and the Thomas Stieber plot is used to determine porosity. But it also used Archie equation in water saturation calculation, as same as conventional method, due to the research limitation. So, if the shaly sand method applied, the value of petrophysical parameter would change.

The different results between conventional method and shaly sand method were caused by the type of shale distribution found in the shaly sand reservoir. Shale distribution type contained in the formation is also influenced by rock diagenesis and depositional environment. In this study, the dominant type of shale distribution in the target formation is laminated shale and dispersed shale. Laminated shale is in the form of layers of flakes that fill the spaces between grains. The clay that makes up this shale is an allogenic clay that undergoes transportation, then is deposited between the pore of grains. The lamination condition is caused by constant sediment sources and depositional currents. Dispersed shale is the shale that sticks to the grain's surface. The constituent clays are authigenic clays formed after deposition due to chemical precipitation between minerals and formation water. The development of dispersed shale is affected by changes in temperature, pressure, and formation water conditions during loading and compaction.

5. Conclusion

The application of the shaly sand method to shale volume, porosity, and pay summary, such as net to gross, net thickness, and net pay makes values more optimistic average value for reservoir calculations, where the shale volume is lower, and porosity, net to gross, net thickness, and net pay are greater than the conventional method. However, the calculation of water saturation must be considered, and must apply other methods to lower water saturation and give more optimism for shaly sand reservoirs.

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