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Reservoir Characterization Using Amplitude Versus Offset (AVO) Analysis of Lakota Formation, Teapot Dome Field, Wyoming, USA

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Abstract. *Lakota Formation is one of the prolific formations at Teapot Dome Field. The objective of this study is to analyze hydrocarbon potential of Lakota Formation using Amplitude Versus Offset (AVO) analysis. AVO analysis is performed to determine AVO class, intercept (A) and gradient (B) values of Lakota reservoir. This study uses pre-stack 3D gather data and three wells, 17-WX-21, 48-X-28 and 41-2-X-3. The Lakota formation is known to be an oil-bearing sandstone reservoir which supported by log interpretation. Analysis of AVO modelling using well data by crossplotting reflectivity (R) with* $\sin^2 \theta$*, shows that the Lakota Formation is in Class IIP for wells 17-WX-21 and 41-2-X-3 and Class II for well 48-X-28. An estimation of AVO intercept and gradient based on the seismic data show that the Lakota Formation is class II AVO response. A-B plane shows that the pay zones of Lakota formation are fall within hydrocarbon zone, but very close to background trend (wet sands/shale). AVO attributes; A*B and scaled Poisson Ratio at well location showing difficulty in differentiate the presence of oil and brine. Therefore, it can be concluded that AVO attributes can not distinguish between water and oil zone in Lakota Formation, and therefore we can not determine distribution of oil in the Lakota reservoir.*

Keywords: *AVO attributes; intercept and gradient; Lakota Formation; Teapot Dome*
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INTRODUCTION

The Powder River Basin is one of the hydrocarbon-producing basins in Wyoming, USA. One of the oil and gas fields located in this basin is the Teapot Dome Field. The Teapot Dome field is an anticline structure which was formed during the Laraminade period. The anticline extends north-south, with a total of two anticlines. Based on the seismic cross section, there is a reverse fault that cuts the fold in the northwest - southeast direction and an asymmetrical fold pattern [1]. An east-west orientated normal fault separates the Teapot Dome into two parts. The southern part of the dome is deeper than the northern part. This fault is the hydrocarbon migration pathway in this study area. This field has several rock formations that become potential reservoirs, one of them is the Lakota formation which is dominated by sandstone lithology. In this research, reservoir characterization of Lakota Formation is carried out using Amplitude Versus Offset (AVO) analysis.

AVO (Amplitude Variation with Offset) analysis has been widely used to identify the presence of hydrocarbons [2]. AVO is the change in amplitude of the reflected signal against variations in distance from the source to the receiver or also known as offset. The purpose of AVO analysis in this study is to determine potential hydrocarbon content in Lakota Formation of Teapot Dome Field.

In this study, the AVO analysis is done by modelling AVO response at available well, determining AVO classification and deriving attributes from 3D pre-stack seismic data. Many AVO derived attributes are in practice to discriminate hydrocarbon and non-hydrocarbon saturated reservoir rocks [3].

AVO modelling from well data is conducted to understand the behaviour of amplitude versus offset and to determine AVO class. AVO anomaly can be interpreted by crossplotting an intercept (A) versus gradient (B) attributes estimated from seismic data. The reliability of this method depends on the accurate prediction of background trend. Successful hydrocarbon indicators show significant departure from background trend in the A – B plane [4]. Other derived AVO attributes is product of A*B and scaled Poisson Ratio. Product (A*B) is an attribute used to identify Class III brightspot and Class II dimspot. Scaled Poisson Ratio (A + B) usually used to indicate anomalous hydrocarbon saturated areas.

METHODS

The principle of AVO method is to analyse the amplitude of seismic waves versus offset or angle. AVO anomalies arise due to the division of energy at the boundary plane which depends on the angle of incidence, density, and Vp/Vs ratio.

One of the assumptions of seismic data is that seismic waves penetrate the layer at a vertical angle of incidence. P-waves arriving at an incident angle θ when passing through the surface boundary plane will be converted into reflection and transmission waves. Zoeppritz (1919) created an equation to determine the amplitude of reflection and transmission waves when P-waves passing through the boundary plane. The Zoeppritz equation then simplified by Aki and Richards by taking a linear approximation for the reflection of the compression wave [5].

The equation was modified again by Shuey, into a three-term equation that is used to perform AVO analysis at large angles. At small angles from $0^o < \theta < 30^o$ the value of $sin^2\,\theta \approx tan^2\,\theta$, so Shuey's equation can be written into two-term terms as follows [6]:

$$R(\theta) = A + Bsin^2\theta \quad (1)$$

Where :
$R(\theta)$ = Reflectivity
A = $\frac{1}{2}\left(\frac{\Delta Vp}{Vp} + \frac{\Delta \rho}{\rho}\right)$ = intercept
B = $\left(\frac{1}{2}\frac{\Delta Vp}{Vp} - 4\frac{V_S^2}{V_P^2}\frac{\Delta Vs}{Vs} - 2\frac{V_S^2}{V_P^2}\frac{\Delta Vp}{Vp}\right)$ = gradient

Classification of AVO Class

The AVO method was first introduced to show amplitude anomalies associated with the presence of gas fluids in reservoirs [7]. The wave amplitude will attenuate as the offset increases, but the presence of hydrocarbon fluid in a layer of earth will cause the wave amplitude to change either increasing, decreasing, or reversing. Based on this, AVO is divided into three classes by Rutherford and Williams [8] which were later refined into four classes [9] (Castagna and Swan, 1997). The classification can be seen in Figure 1 and Figure 2. Figure 1 is the classification based on the plot between angle and reflectivity. Meanwhile, Figure 2 shows the classification using intercept (A) and gradient (B) values.

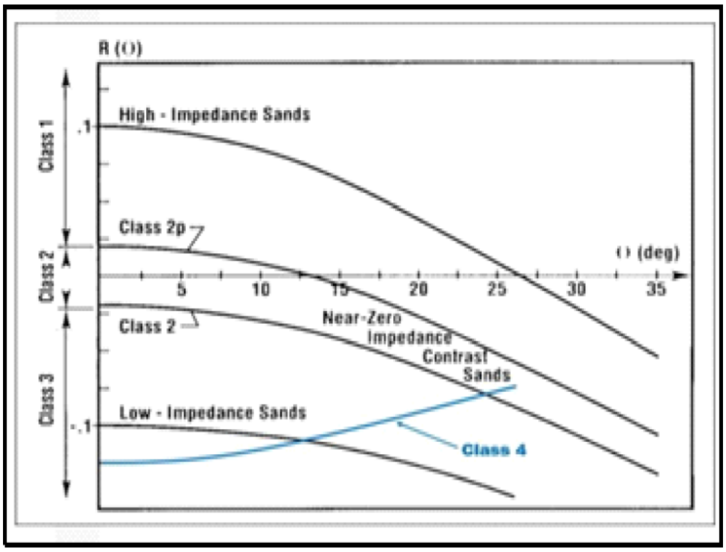

Figure 1 Classification of Modified AVO Class (Castagna and Swan,1997)

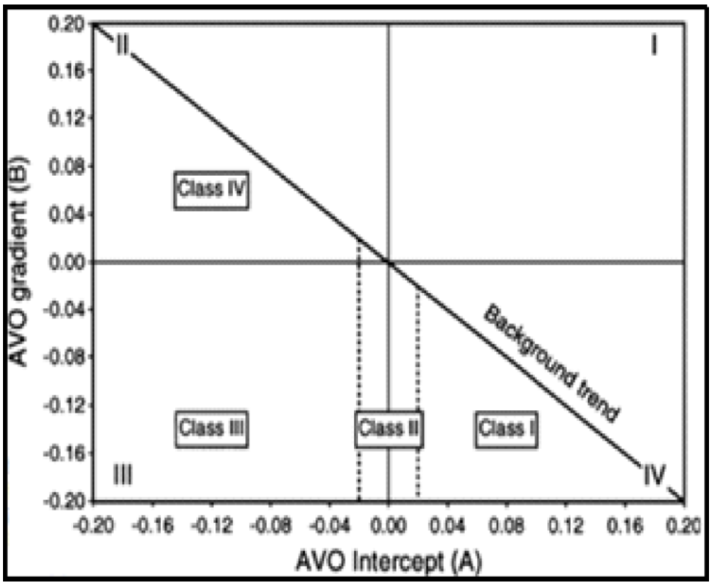

Figure 2 Crossplot Between Intercept Value (A) and AVO Gradient (B) for AVO Class Determination (Castagna and Swan, 1997)

Data Availability

The data used in this study are 3D Gather pre-stack data, Dip Moveout (DMO) velocity data and 17-WX-21, 48-X-28 and 41-2-X-3 well data. All well is vertical well and checkshot data is only available at 48-X-28 well. All this data can be found in Rocky

Mountain Oilfield Testing Center (RMOTC) dataset that can be accessed on the SEG WIKI website.

Normal Move Out (NMO) correction is used to eliminate the effect of distance (offset) on wave propagation time. The available velocity table is used to perform the NMO correction. The NMO process itself is performed on Super Gather data (Figure 3). Super gather is the process of adding multiple Common Mid Points (CMP) adjacent to seismic data with the aim of increasing the signal to noise ratio. The angle gather is then created using super gather data and the velocity table. The angle of seismic data ranges from 8^0 - 34^0. Figure 4 show the example of angle gather of study area.

Figure 5 shows the structure map of Lakota Formation. The orange colour indicates the high area associated with the reservoir area as evidenced by the well location in the orange zone. The time structure map also shows that the study area has two domes and a fault. The dome is visible with two high areas which are in the northern and southern part of the study area. Lakota Formation at two domes range from 840-860 msec TWT. There are two primary stages in this study; first is to analyze pre-stack seismic data to acquire amplitude response and AVO anomaly, as well as the distribution of AVO attributes. Secondly, well data is analyzed to obtain petrophysical parameters of target layer for AVO modelling which based on Aki-Richard equation.

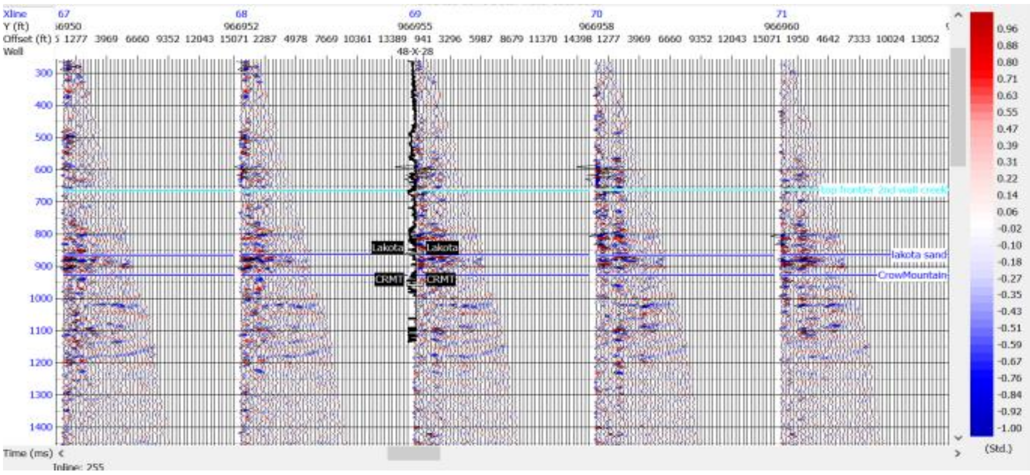

Figure 3 Super Gather Data

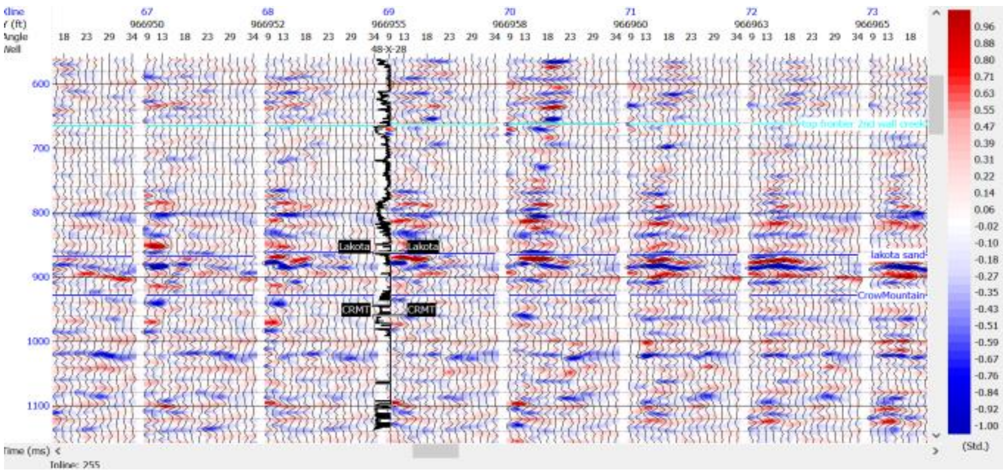

Figure 4 Angle Gather Data

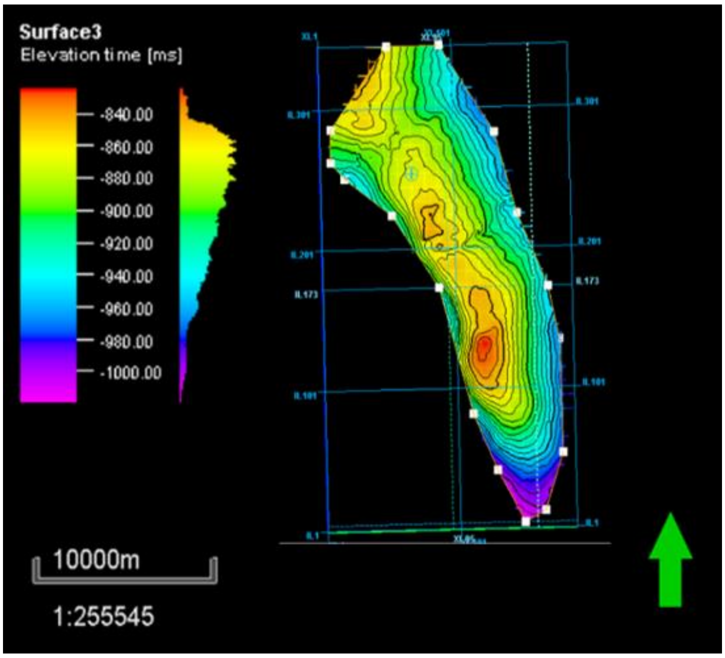

Figure 5 Lakota Time Structure Map

RESULT AND DISCUSSION

Log Data Analysis

Log interpretation is carried out to identify zones that could be hydrocarbon reservoirs using gamma ray, resistivity and neutron density. In this study, the main focus zone is at the Lakota formation, which is characterised by low gamma ray values, high resistivity and a visible overlay between the neutron density logs (Figure 6). Based on this analysis, Lakota is identified as oil reservoir.

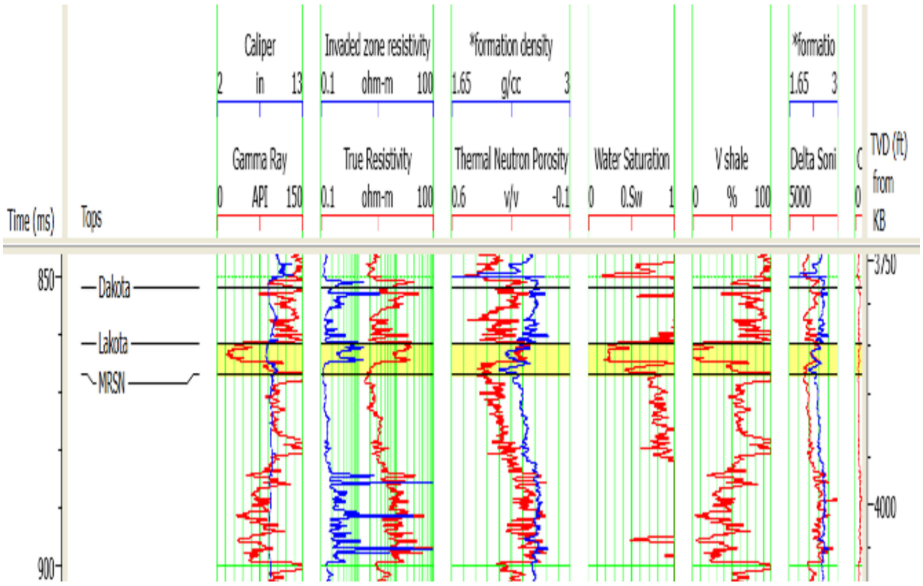

Figure 6 Interest Zone of 48-X-28

Shear velocity log is not available in all well, meanwhile the log is needed for AVO modelling. Therefore, shear velocity is estimated using Greenberg-Castagna's equation [10] for reservoir interval and Castagna's equation for the interval outside the reservoir [11.

AVO Modelling and Gradient Analysis

Shear velocity plays a crucial role in AVO modeling for reservoir characterization. By understanding the relationship between shear velocity and other seismic parameters, researchers can improve the accuracy of their analysis, which in turn helps in the exploration and development of hydrocarbon resources.

AVO modelling is performed on well data based on P-wave log, S-wave log, and density log data to estimate the AVO class at Lakota Formation. Gradient analysis is performed on angle gather data at well location. This analysis is performed on the pay zone at Lakota Formation. The comparison of AVO classes is made between the result of well modelling with gradient analysis from seismic data.

AVO modelling at 17-WX-21 well (Figure 7) shows that the resulting reflectivity has a small positive number close to 0 and decreases with increasing angle. Therefore, the Lakota Formation pay zone is an AVO Class IIP based on well data modelling. AVO analysis using seismic data is conducting by crossplotting amplitude vs angle and intercept (A) and gradient (B). Amplitude vs angle at Lakota pay zone reflector is shown in Figure 8 (above). It shows a decrease in amplitude that becomes increasingly negative with increasing offset or a Class II AVO. Figure 8 (below) is a crossplot of A and B (A-B plane) for entire interval at 17-WX-21 location which shows two different trends. The first trend is called the background trend usually shows the shale lithology and/or wet sands. Meanwhile other trend shows a hydrocarbon trend. These two different trends show that AVO analysis may be work in this area. The pay zone of Lakota formation is shown as red box which fall within Class II. However, the red box is fall both in the hydrocarbon and background trend. This show that it will likely be difficult to differentiate oil and water/shale in Lakota Formation in this well.

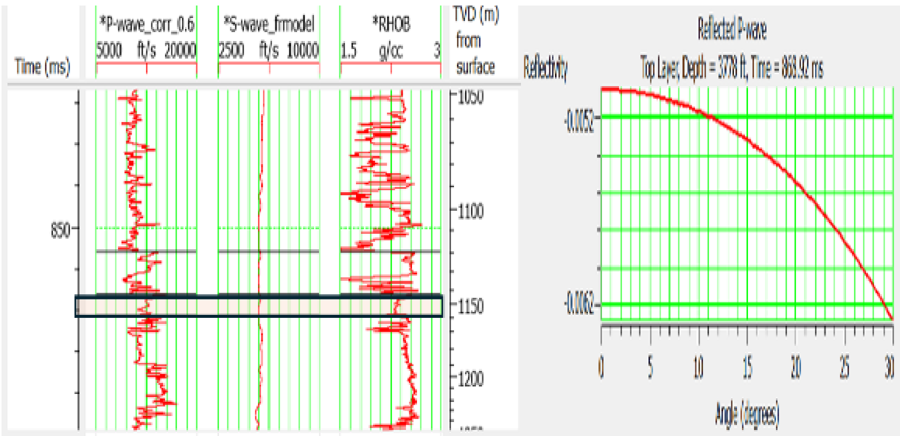

Figure 7 AVO Modelling for 17-WX-21

Vol.7 No. I 2024, 33 – 45
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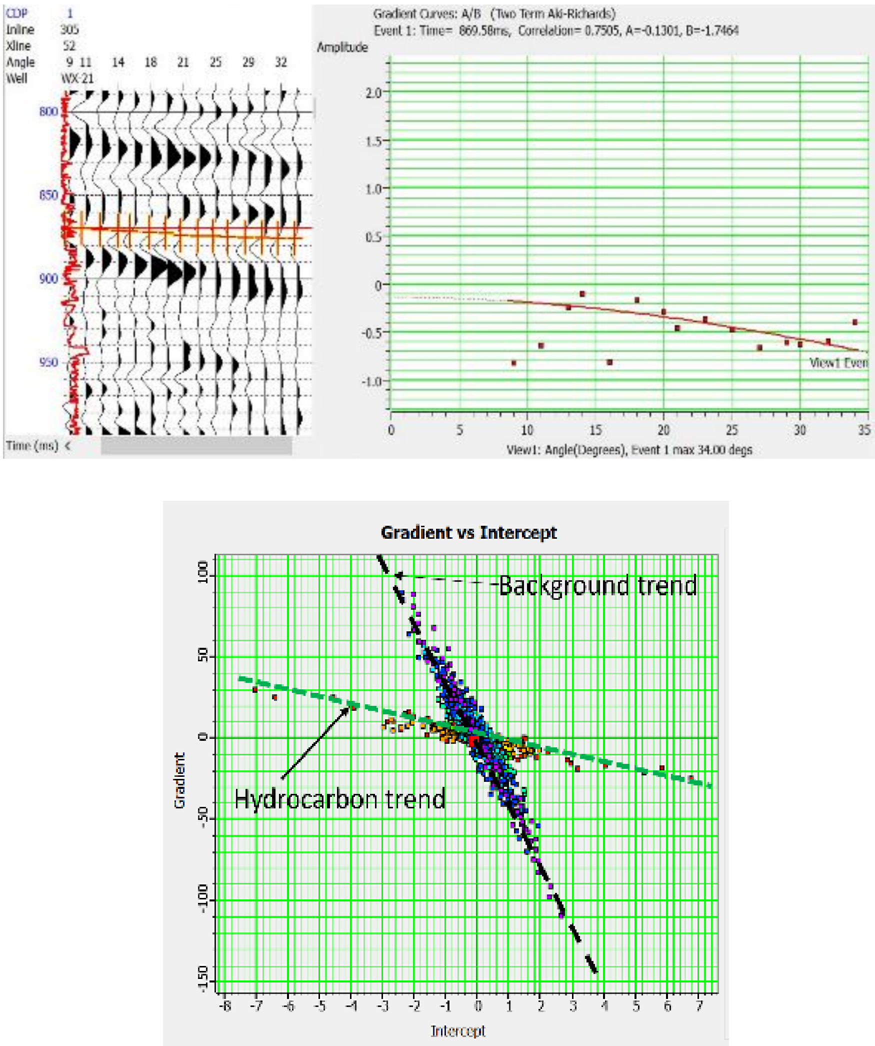


Figure 8 Gradient Analysis for 17-WX-21

For 48-X-28 well, AVO modelling based on log data show that Lakota formation is AVO Class II. This well shows a increasingly negative reflectivity value as the offset increases (Figure 9). Based on seismic data, the pay zone of the Lakota Formation for this well is also in Class II AVO, indicated by a small negative amplitude value close to 0 and continuing to decrease as the offset increases (Figure 10). Figure 10 (below) is A and B plane for entire interval at 48-X-28 well location. It shows that pay zone of Lakota formation (red box) are in within hydrocarbon trend and fall within Class II. The pay zone is fall near the zone where the background and hydrocarbon are crossing each other.

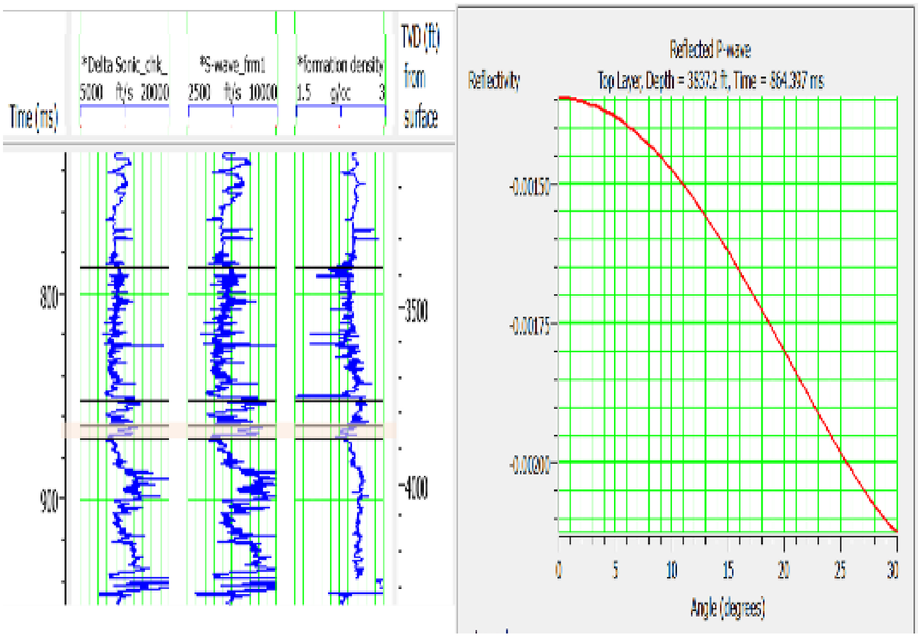


Figure 9 AVO Modelling for 48-X-28

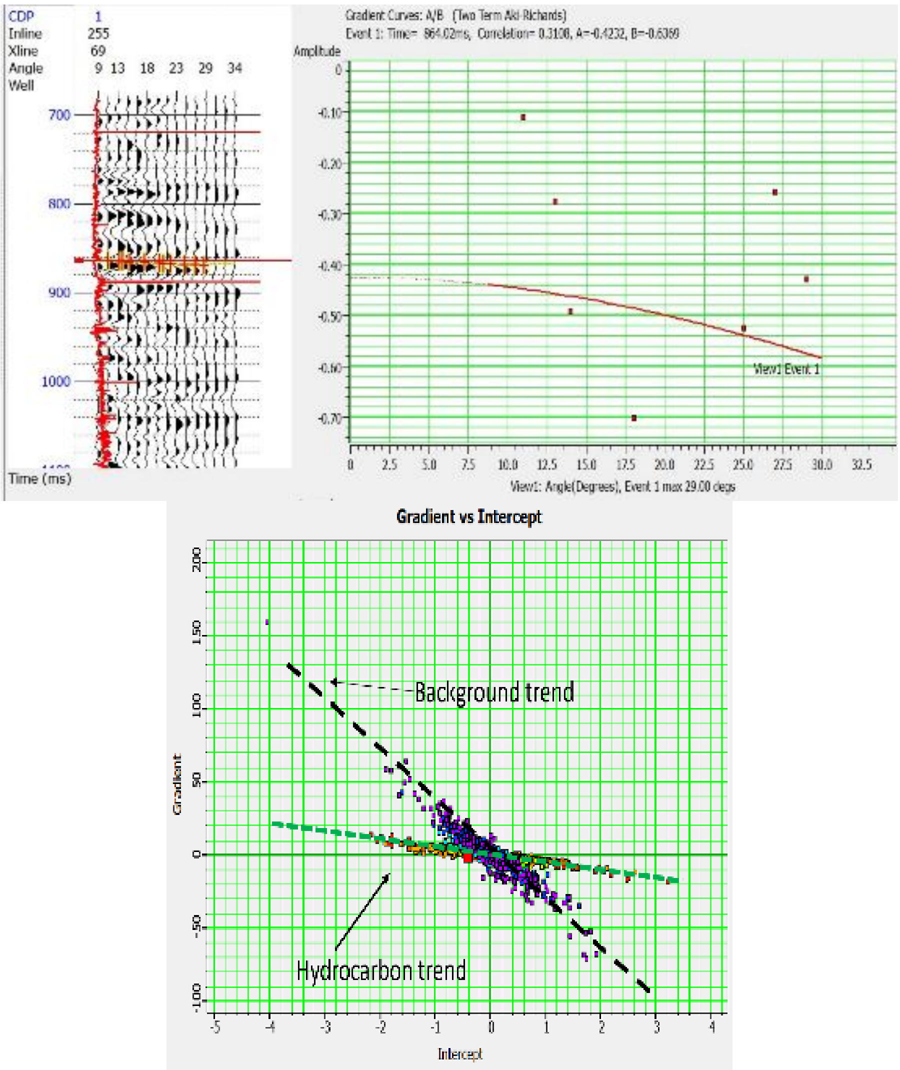


Figure 10 Gradient Analysis for 48-X-28

For 41-2-X-3 well, AVO modelling from well data shows reflectivity value has a small positive number close to 0 and decreases with increasing angle. Therefore, the Lakota Formation pay zone is an AVO class IIP as shown in Figure 11. AVO analysis using seismic data shows a decrease in amplitude that becomes increasingly negative with increasing offset which shows a Class II AVO (Figure 12). A-B plane for entire interval shows two different trends, where the pay zone of Lakota shows in red box and fall within Class II. In this well, the pay zone is more clearly at hydrocarbon trend rather than at background trend.

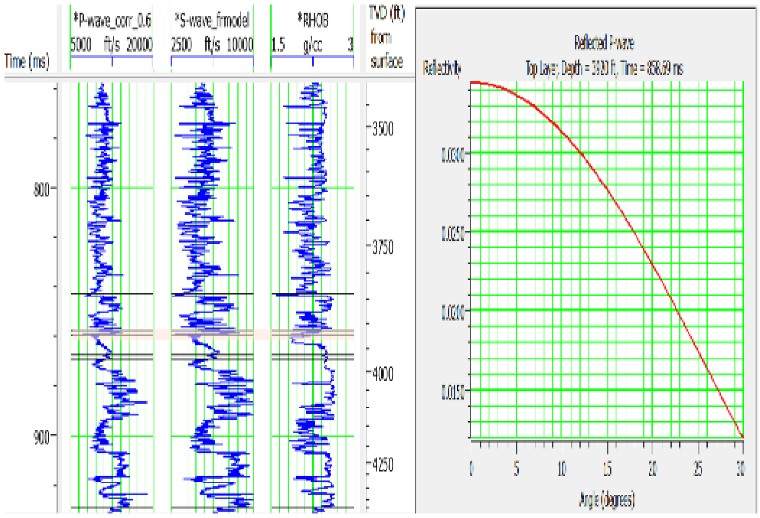
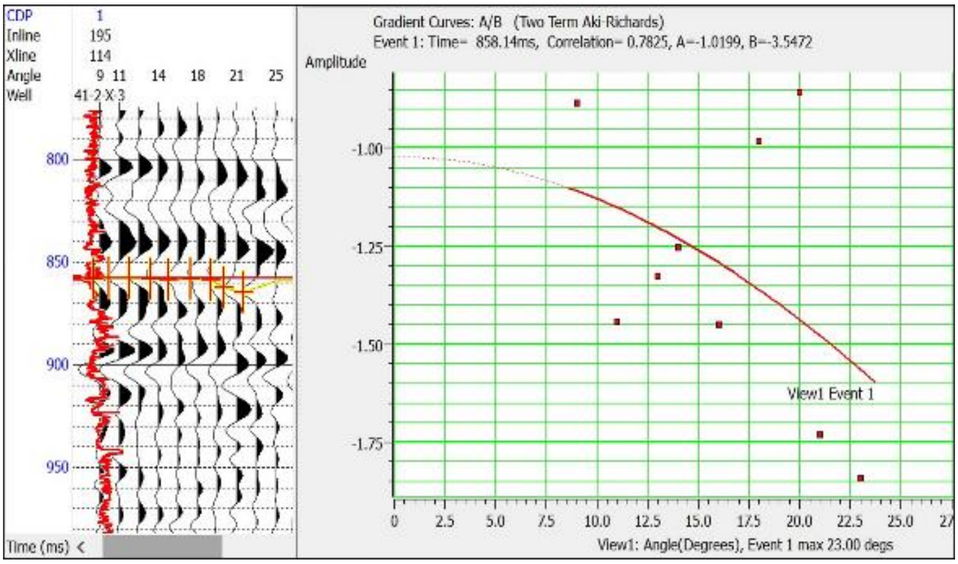


Figure 11 AVO Modelling for 41-2-X-3



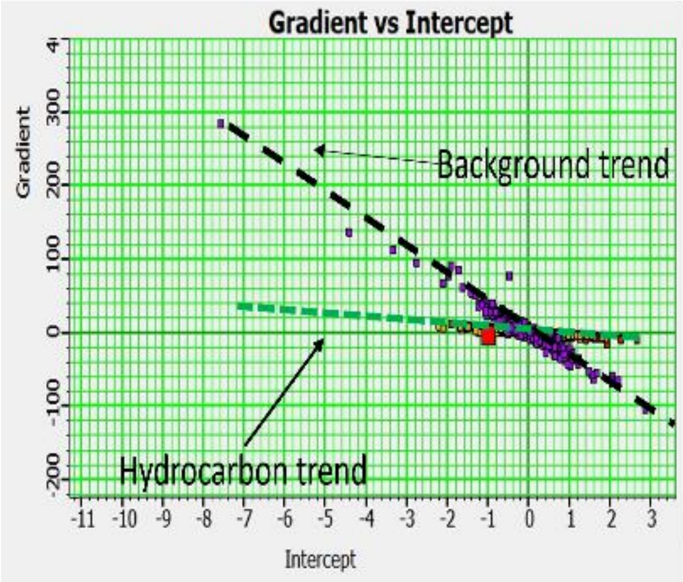


Figure 12 Gradient Analysis for 41-2-X-3

For those three wells, the AVO class of Lakota Formation is Class II and Class IIP based on well data modelling. Meanwhile based on A-B plane, Lakota pay zone is in Class II and fall within hydrocarbon trend. However, the A-B value is very close to background trend which is usually defined as shale and/or wet sand.

In addition to performing gradient analysis on the Lakota Formation pay zone, gradient analysis is also performed on water bearing layers. This work is done to see the difference in AVO class between hydrocarbon bearing zones and water bearing zones. The gradient analysis indicated that the water-filled zones in the three wells were in AVO Class II, as indicated by the increase in amplitude value becoming negative with increasing offset. The comparative results of the gradient analysis of the Lakota Formation pay and water-filled zones for each well are shown in Table 1. The A and B value for water and oil zone show negative value.

Table 1 Gradient Analysis Result Value of Each Well in the Lakota Formation Pay and Water Content Zones

Well	Fluid type	Time (msec)	A	B	AVO Classes
17-WX-21	Oil	869.58	-0.1301	-1.7464	2
	Water	952.59	-0.9362	-1.8592	2
48-X-28	Oil	864.02	-0.4232	-0.6369	2
	Water	1087.51	-0.3863	-6.4098	2
41-2-X-3	Oil	858.14	-1.0199	-3.5472	2
	Water	982.22	-0.4098	-0.6535	2

AVO Attribute

The AVO attribute used in this study is Product A*B. The result of product A*B can be used as a Direct Hydrocarbon Indicator (DHI), where a high positive value indicates the presence of hydrocarbons [2]. However, the result of the product A*B in Table 1 shows that value of A*B is also positive either for hydrocarbon saturated zone or water saturated zone. So therefore, most likely A*B attribute cannot distinguish between the hydrocarbon zone and the water zone.

The absence of bright spot anomalies in the product AVO cross sections at well location (Figure 13) indicates that in Lakota Formation, the AVO method is not sensitive to fluid type.

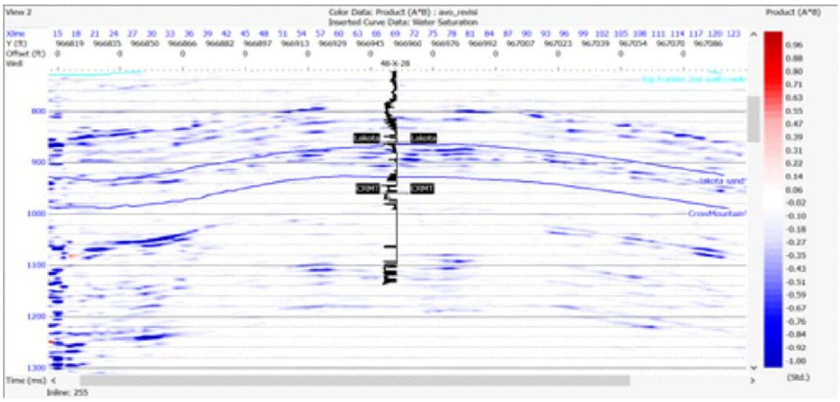


Figure 13 Cross Section of A*B of Well 48-X-28

Another AVO attribute, Scaled Poisson Ratio (Aa+bB) is also estimated. The expected response is a high contrast value to detect the presence of hydrocarbon fluids in the Lakota Formation. However, this attribute also shows the same result as product (A*B). The zones with water content and zones with oil content is not distinguishable (Figure 14).

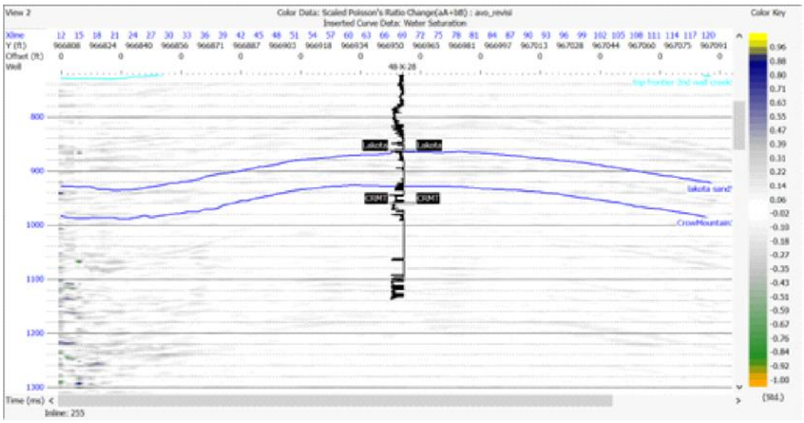


Figure 14 Cross Section of Scaled Poisson Ratio of Well 48-X-28

CONCLUSION

Based on AVO analysis, the pay zone at Lakota Formation is AVO Class II for each well. Intercept (A) and Gradient (B) attributes which extracted from seismic data at each well location shows two trends. The two different trends; background and hydrocarbon trends show that AVO analysis might be work in this field to differentiate the fluid content. The oil zones at Lakota Formation fall in the hydrocarbon trend but close to shale/wet sand trend. Therefore, oil zone at Lakota Formation is difficult to differentiate from water zone. The A and B values are extracted in both oil and water zone at Lakota Formation, and the product, A*B, has the same sign (positive value) for oil and water. The other AVO attribute, scaled Poisson Ratio also does not give strong anomaly related to oil response at well location. Therefore, it is difficult to predict distribution of oil zone at Lakota Formation.

Since AVO analysis does not work in determining oil potential in the Lakota Formation, it is suggested to apply other seismic inversion methods. The AVO method may still work in this area for other reservoirs. In addition, to obtain the correct amplitude continuity, further work in normal moveout correction is required.

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