Estimation of An isotropy Parameters Relationships on AVO Attributes in the Deep-Water Turbidite System: A Case Study from the West Africa Passive Margin

Anwar B. Daghdugh*[1], Ziyad Ali Ben Abdulhafied[2] and Abdurrazagh Ezzeddin[3]

*[1]Department of Geology, Faculty of Science, University of Tripoli
anwarhamuda1983@gmail.com

[2]College of Applied Sciences, Technology AL-Wata
z.benabdulhafied@gmail.com

[3]Department of Geophysics, Faculty of Science, University of Tripoli
aezzddin@yahoo.com

Abstract

Amplitude Variation Versus Offset or angle is one of the seismic related technologies that have been used by oil companies for decades in their search for hydrocarbon, particularly gas. AVO classes for different type of gas sands has been defined from Class I to IV, and case studies successes especially for Class III and Class II AVO. However, there are pitfalls in the implementation of the technology – for instance low gas saturated reservoir (also known as fizz gas) and highly porous wet sandstones can give strong AVO response which gives similar Class II or Class III responses. In addition, to the above-mentioned pitfalls, anisotropy and more specifically Vertically Transverse Isotropy (VTI) can also give false AVO response too. VTI is normally associated with shale whose mineral are platy in shape, thus giving horizontal direction of a planar bed to a faster velocity propagation direction as compared with the vertical direction. This research shines a light on the concept of the phenomena of anisotropy to see the different between two cases of reservoirs the gas sand (Yoyo-1) reservoir and wet sand (Trema-1) where the wet sand gives high response instead of no response seen in the seismic which reflected the same response of hydrocarbon such as gas sand. Anisotropic AVO gathering data were generated using the Aki & Richards equation to a highest angle of 50, and 70 degrees. As well as, demonstratingAVO attributes types that can be used to minimize or eliminate anisotropy effects, thus can be applied to future prospects in the case study vicinity.

Keywords: Anisotropy Parameters, AVO, VTI, Reservoir, Seismic Data, Velocity Log, Parameters Logs, Well Log

Introduction

Amplitudes variation versus offset or angle (AVO) or (AVA) is the most important techniques for seismic interpretation regarding to technologies that have been used by oil companies for long time in the exploration of hydrocarbon, in particularly gas sand. One of the factors that might distort AVO amplitudes is anisotropy that has only moderated influence on P-wave radiation pattern. Therefore, correction of AVO amplitude for radiation pattern is usually sufficient. However, understanding the phenomena of anisotropy is useful to see the different between the gas sand (Yoyo-1 well) reservoir and wet sand (Trema-1 well) where the wet sand gives high response instead of no response seen in the seismic which reflected the same response of hydrocarbon such as gas sand. Moreover, building up two curves of conventional AVO and VTI anisotropy can illustrate the difference of separation of two reservoirs. The isotropic and anisotropic PP (P wave up and down) can be determined the AVO gas sand type while the fractured gas reservoirs can be affected by PS (P wave and S wave), Adepelumi (2019).

Amplitudes of seismic waves propagation in a single layer with VTI (Vertical Transversely Isotropic) that has been determined by (Tsvankin, 1995). However, (Thomsen, 1986) expressed three parameters of anisotropic which are (γ, δ, and ϵ) where γ is the variation of s-wave velocity, ϵ is the variation of p-wave velocity, and δ is the relationship between p-wave and s-wave velocity. The most important of building AVO model and AVO-VTI model is to look for the angle on incidence that should we be wary of this effect. As well as how big is the epsilon and delta (VTI parameters) that can cause significant AVO response.

The parameters require of doing AVO blocky model and fluid substitution are Vp, Vs, ρ, Sw, Gr, and V-shale, by using these parameters to test the three kinds of fluids (water, oil, gas) for Yoyo-1, and Trema-1 reservoirs to look for possible tending of curves to compare with VTI-AVO model that can give evidence for possible fluid in reservoir. Extracting Thomsen's parameter from PSDM (pre-stack depth migration) processing to generate VTI-AVO, looking for the effect of anisotropy for angle stack (near, mid, far) that can be affected by anisotropy.

AVO attributes used for three kinds of attributes and the most suitable one that show good results is **A*B** product that minimize/eliminate anisotropy effects in the Trema-1 well, thus this kind of attribute can be applied to future prospects.

Location map and geological setting

The proposed Trema-1 exploration well is located within the Tilapia PSA and is designed to evaluate the Oligocene-aged Trema turbidity prospect. The Trema 1 well, is a deviated borehole with a surface location of X=544727.704m and Y=344709.005m, located approximately 365 meters from a modern-day slope channel. The well site is approximately 32 kilometers southeast of the Yoyo-1 Well and approximately 109 kilometers from Douala, Cameroon. The well was drilled to a total depth of 3340m.

The Trema-1 well fill amplitude anomalies are interpreted as a series of stratigraphic-trap, clastic-filled multiple story slope incised-channels. The channel fill sequences are expected to be amalgamated intra-slope channel and fan lobe deposits consisting of inter-bedded turbidity sands and bathyal shale. The equivalent stratigraphic interval was penetrated outside the anomaly by the Yoyo-1 and Bwabe-1 wells and encountered only shale. The Trema-1well feature is in close proximity to the paleo-slope feeder canyons. The primary sediment source direction appears to be from the southeast prograding to the northwest (Noble Energy). Interpreted depositional model for Trema-1wellanomaly comprising a multistory slope channel complex/canyon comprising multiple episodes of cut-and-fill.

The primary Tertiary source in the Douala Basin is the Eocene aged N'Kapa Shale. Seismically, the N'Kapa is recognized as an "opaque zone" due to a lack of internal reflectivity. The

N'Kapa is regionally extensive but with variable thickness. Moreover, Biomarker evidence confirms the presence of Tertiary source rocks and also suggests possible mixing with Cretaceous hydrocarbons while the Trema-1 well prospect is located during the Oligocene, the Trema-1 fill amplitude anomalies are interpreted as a series of stratigraphic-trap, clastic-filled channel.

The lower Miocene sediments working as seal (Figs 2 and 3). However, no hydrocarbon shows were observed in cutting samples collected of drilling the Trema-1 well. There is little variation in gas data recorded over this section, total gas readings staying within backgrounds levels of 1.0 %. At 3183.0m MD, gas readings.

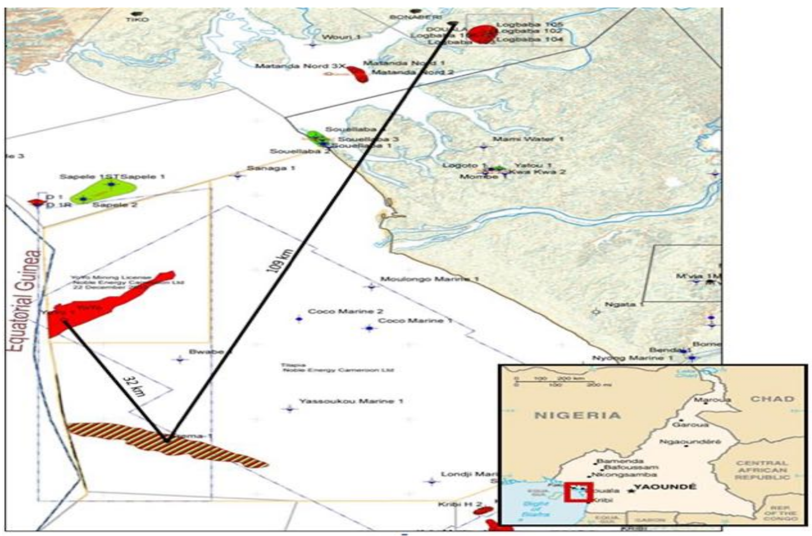

Figure 1: Map showing the locationof Yoyo-1 and Trema-1 wells in the Cameroon (Adopted from Noble Energy).

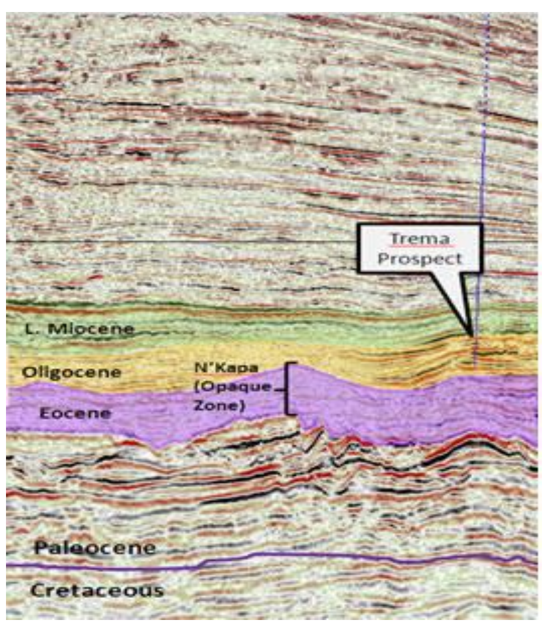

Figure 2: Seismic section through Trema-1 well showing canyon fill sediments in the Tilapia area, west region of Cameroon (Adopted from Noble Energy).

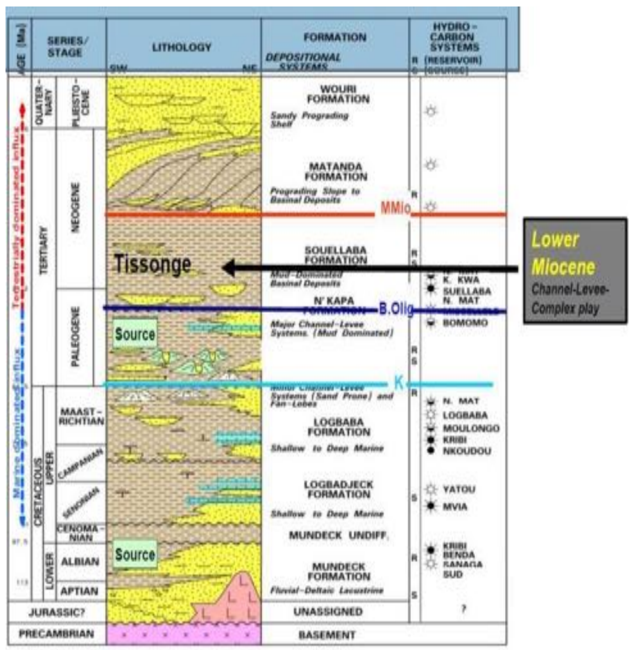

Figure 3: The stratigraphic sequence of the Douala sub-basin in the Cameroon (Compiled from Lawrence et al., 2002; Brownfield and Charpentier, 2006).

Materials and methods

The borehole compensated sonic logs for the two given wells represent the basic source of velocities, while the formation density compensated logs of the same wells exhibit the source of densities. In addition, the composite logs of these wells are available to define the lithology of their rock units and the depths of their formational tops. The parameters require of doing fluid substitution are Vp, Vs, ρb, Φ, and Sw to investigate of three cases (gas, oil, and water). However, extracting Thomsen parameters **(ε, δ)** from anisotropic Pre-stack depth migration processing by-product, in order to improve the positioning accuracy and the image quality and substituting in synthetic AVO modeling to calculate the VTI (vertical transverse isotropy) anisotropy. What is more, generating a synthetic seismogram for Yoyo-1 and Trema-1 wells.

Well log interpretation

The logs recorded for Yoyo-1 well from 1960 to 2700 m and target depth is 2570m, and Trema-1wellfrom 2625 - 3340 m and target depth are 3115 m. However, this section focuses on the interpretation of well logs for the intrinsic and induced properties of the rocks and their pore fluids. The both wells, Yoyo-1, and Trema-1 contain gamma-ray, P-wave velocity, S-wave velocity, gamma-ray, density, porosity, water saturation (Figs. 4 and 5) used in this research are described as following:

Gamma-ray log

Both wells consist of sandstones (deflection to the left) and shales (deflection to the right) as (Figs. 4 and 5). Not only the gamma ray can identify the lithology but also can predict the depositional environment and grain-size variations. For instance, the log pattern in Yoyo-1 well varies from blocky to fining upwards between 2650 m to 2560 m which may be amalgamated channels with sharp lower and upper contacts. On the other hand, Trema-1 well which is the sand unit coarsens upwards at the reservoir between 3140m to 3110 m, is characterized by a gamma ray pattern at the reservoir, characteristic of turbidities. The gamma-ray wireline-log stratigraphic correlations and depositional environment studies in similar sedimentary basins worldwide (e.g., Khalifa and Ward, 2010; Khalifa and Mills, 2020; Khalifa and Bottrill, 2021).

Density log

Based on Asquith and Krygowski (2004**)** that described the density log as a record of the formation bulk density (Rho) in g/cc; it is dependent on the matrix, porosity of the rock, and density of the fluid in the pores. Yoyo-1 well records a high density of about 2.47 g/cc in shale unit at depth 2560m and decreases to about 2.07 g/cc in the sand reservoir at depth 2580 m, while in theTrema-1 well has similar variation is observed.

P-wave sonic log

The P-wave sonic log measures the transit time (Δt in μs/ft) of an acoustic waveform between a transmitter and a receiver (Veeken, 2007)**.** As a result, Yoyo-1 log shows a general increase in velocity with depth, with a sudden decrease in the reservoir (Fig. 4). Furthermore, P-wave velocity in the overlying shale ranges at depth between 2560 to 2590m is3652 m/s, however it drops to below 2482 m/s in the reservoir at depth between 2590 to 2600 m, probably because of the presence of hydrocarbons before increasing hydrocarbon again in the underlying zone. On the other hand, Trema-1 well does not show a sudden decrease in p-wave velocity at reservoir depth, but still has variation in density (Fig. 5). This might because of anisotropy which can be predictable later in this research.

This is the fraction of the pore volume filled with formation water (Sheriff, 2002). It helps in quantifying the reservoir's hydrocarbon saturation and is calculated by using Archie's formula, equation: $\mathbf{Sw = \sqrt{F * Rw / \Phi * Rt}}$ **(1).**

Whereas F is formation factor, Rw is the resistivity of water, RT IS true resistivity of the formation, and Φ is porosity. Salley (1985) pointed out that this method is valid for clean, clay-free formations. In particular, a = 1 and m = 2; however, for unconsolidated sands (soft formations), a = 0.62 and =2.15 m from the Humble formula (Salley, 1985). From previous equation, the only unknown is Rw which has to be calculated from a brine-saturated portion of the log as shown below in equation.

Sw = [C * (√Rw/Rt)] / Φ (2)

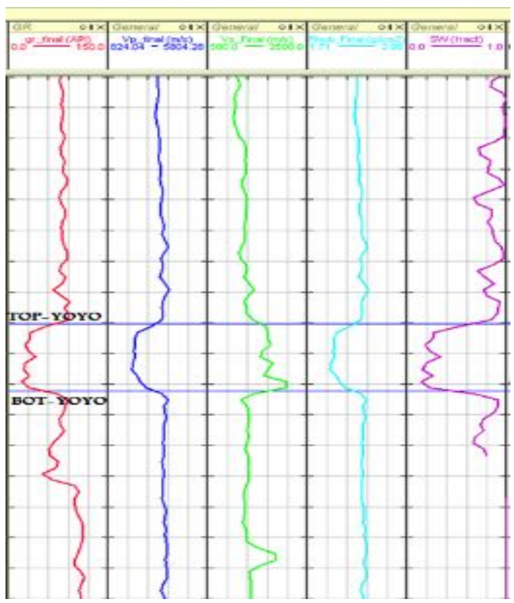

Figure 4: Illustrates the elastic parameters logs with Sw, and porosity log for Yoyo-1 reservoir.

Water saturation (Sw)

At the depth 3140m to 3110 m, Trema-1 is assumed to be approximately 100 % water saturated in the sand unit; Rt = Ro (Resistivity of rock with water) ≈ 0.27; Porosity ≈ 0.24; C = 0.9 for sands; Sw = 1; therefore, Rw = 0.2633 ohm-m. By substituting the value of Rw in previous equation, once can calculate Sw. However, water saturation in the reservoir is almost 100%, while Sw for Yoyo-1 well is 23% (Fig. 4).

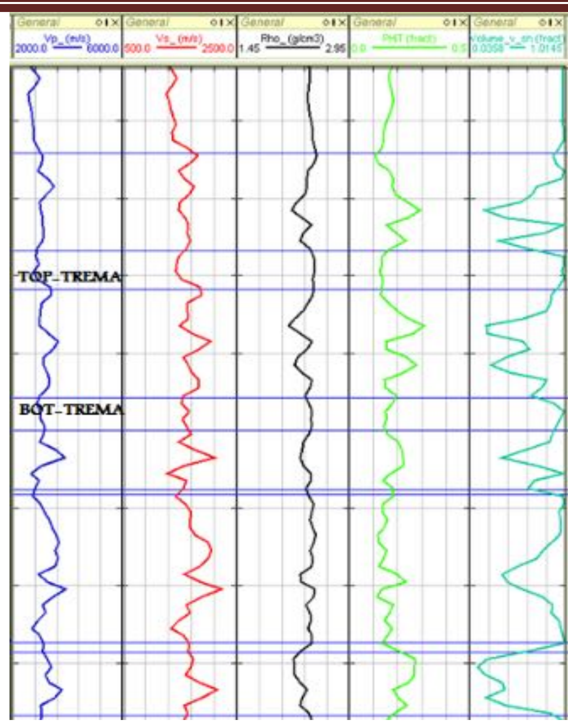

Figure 5: shows the elastic parameters logs, and porosity log for Trema-1 well.

AVO blocky model and fluid substitution

AVO has been used extensively to identify hydrocarbon accumulations. However, some examples of false positives and false negatives exist in fields around the world. The beneficial of blocky AVO modeling and Gassmann equation (Gassmann, 1951) to see the potential effects of hydrocarbon on reflectivity at the top reservoir interface for Trema-1 reservoir (wet sand) comparing with Yoyo-1 reservoir (gas sand). This part of research focuses on how the anisotropy can affect AVO synthetic in three cases of fluids by using Thomsen's parameters Blangy (1994) for both cases. The parameters require of doing fluid substitution are Vp, Vs, ρb, Φ, and Sw Charles (2009) by taking the average of reservoirs interval for both and over lying shale. As a result, 3 new logs (Vp, Vs, and ρ), and used to create a new AVO synthetic. However, the processes of getting the three cases of fluids as following:

Case 1: In-situ fluid: (Gas, brine) - Trema-1 reservoir has proved as wet sand, while the Yoyo-1 reservoir has proven as gas sand. However, Using the So 80% to be 20 % oil model as the input and So 0% to be 100 % brine model as the output forTrem-1 well, and Sg 23% to be 77 % brine model as the input and Sg 77% to be 23 % brine model as the output for Yoyo-1well (Figs. 6 and 7).

Case 2: Oil - Using the So 0% to be 100 % brine model as the input and So 8o % to be 20 % oil model as the output for Trem-1 well, and So 0% to be 100 % brine model as the input and So 80% to be 20 % oil model as the output for Yoyo-1well (Figs.6 and 7).

Case 3: Gas-Using the Sg 0% to be 100 % brine model as the input and Sg 8o % to be 20 % gas model as the output for Trem-1 well (Figs. 6 and 7), but for Yoyo-1 well the output needs to be brine in this case.

Synthetic modelling of AVO

Seismic rock properties are directly responsible for seismic wave propagation and seismic responses, which are (P- and S-wave velocities and density, and *VP/VS* ratio and Poisson's ratio), acoustic impedances, modulus rock properties (bulk modulus K, shear modulus μ, Lame's constant λ), and anisotropic rock properties. Anisotropic synthetic modeling produces the best suited to CDP gathers than isotropic synthetic model Ehirim (2017). However, the blocky modelling is a fast, first-look technique which uses average values over intervals to get a response to a changing set of properties. According to Chiburis (1993) stated that "the key to use AVO for fluid identification is comparison of real data with a synthetic seismogram". Moreover, the RokDoc software is used in the generation of AVO synthetic seismograms for fluid-saturated rocks (oil, brine and gas) with input density and velocity logs (P-wave and S-wave) coming from Yoyo-1, and Trema-1 wells.

The Synthetics are generated for angles 0º - 40º where we are interested in, at near and far angle stack by using Zoeppritz and elastic wave equations (Zoeppritz, 1919), and analysis results compared for both reservoirs (Figs. 6 and 7) that done for both reservoirs to three cases of fluids ricker wavelet 50 and 70 HZ. As the blocky sands are the main reservoir target it is logical to develop an AVO interpretation strategy based on the blocky sands. An AVO half space model is created by averaging the elastic parameters for the blocky sand and for the cap rock shale, and using this as input to the Zoeppritz equation. Setting the average of fluid substitution effect that done in previous part with the average of overlaying shale for both reservoirs to see the potential effects of oil, gas, and water saturation on the reflectivity at the top reservoirs' interfaces. As a result, the three curves of fluids have displayed (Figs. 8 and 9).

The estimation of Thomsen parameters (ε, δ)

Usually extracting Thomsen parameters from anisotropic Pre-stack depth migration processing by-product (PSDM). Pre-stack depth migration and velocity model analysis for isotropic media have been widely used to image the complex structure area. In order to improve the positioning accuracy and the image quality, seismic anisotropy is needed in most places of the world. The challenge is to estimate and build the anisotropic model for depth migration Jun Cai*, Yang He (2009). However, import these values of parameters (by using petrel software) to make distribution of whole the horizon formations to get the exact values of Thomas parameters at the top of reservoir to calculate VTI vertical transverse isotropy Ruger (2001)**.** Therefore, the result shows Figures 10 and 11for delta (δ) distribution forYoyo-1 reservoir, the exact value is equal 0.15. Based on the distribution of delta (δ) for Trema-1 reservoir is 0.16 (Figs. 10 and 12). In addition, the distribution of epsilon (ϵ) at the top reservoir or around the target reservoir is 0.3 for yoyo-1 reservoir, and Trema-1 reservoir is almost 0.32 (Figs. 11 and 13).

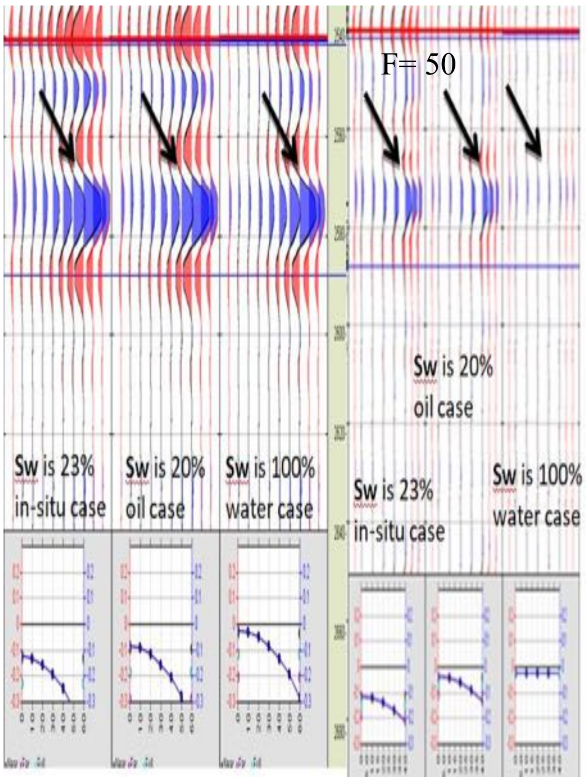

Figure 6: shows synthetic AVO modeling and fluid substitution for Yoyo-1 reservoir, one with ricker wavelet of 50 Hz, and the other of 70 Hz of three cases (in-situ case, gas case, and oil case).

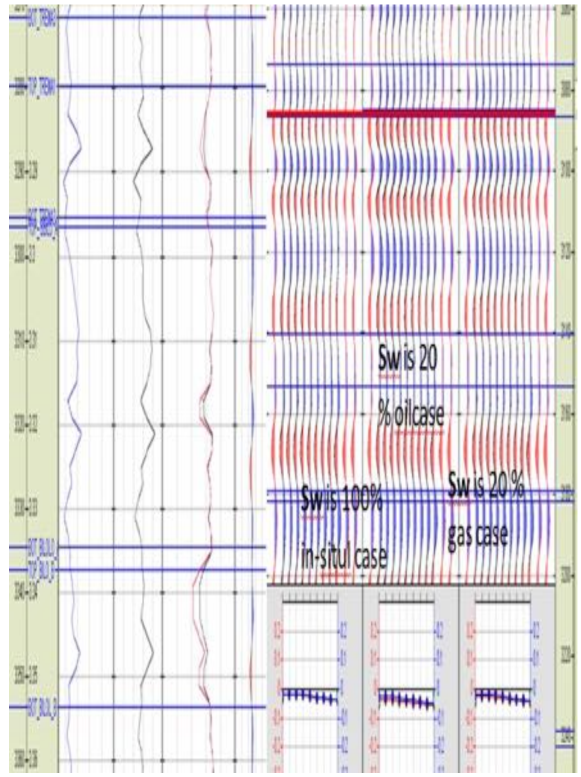

Figure 7: shows synthetic AVO modeling for Trema-1 reservoir, one with ricker wavelet of 50 Hz of three cases (in-situ case, gas case, and oil case).

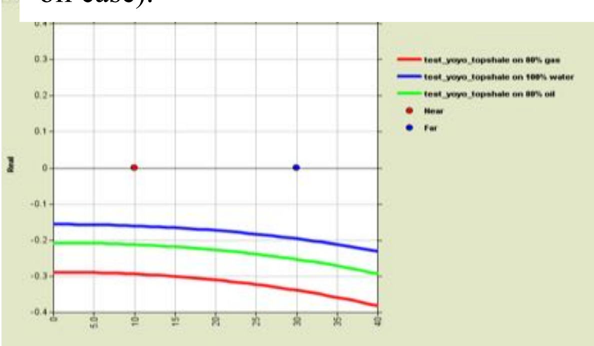

Figure 8: shows AVO blocky model for Yoyo-1 reservoir for three cases.

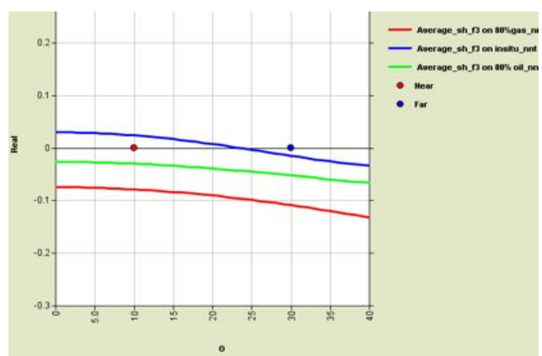

Figure 9: shows AVO blocky model for Trema-1 reservoir for three cases.

Result and discussion

Anisotropy and synthetic gathering of AVO

In particular, taking the real values of Thomsen's parameters that we got in previous part and substituting in synthetic AVO modeling to calculate the VTI anisotropy. As a result, the curves of the fluids (water, oil, and gas) have no big differentiation(Figs. 1 and 4) if we compare these parameters with the values in case of Yoyo-1 reservoir, while the Trema-1 reservoir shows the big differentiation (Fig. 15).In particular, being more accurate of having anisotropy, we need to display and calculate the anisotropy Rüger,(2001) along the well to build up a synthetic model of anisotropy, and comparing with the three cases of fluid (brine, gas, oil) for both reservoirs. Therefore, calculating anisotropy log requires the parameters of epsilon (ϵ), and delta (δ) as well as Gamma (γ) along the well.

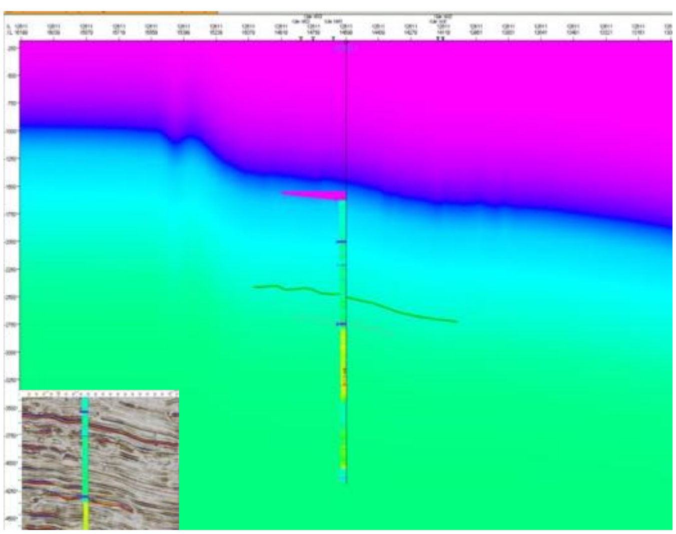

Figure10: shows the distribution of delta (δ) in vertical section (interpretation window) for Yoyo-1 reservoir

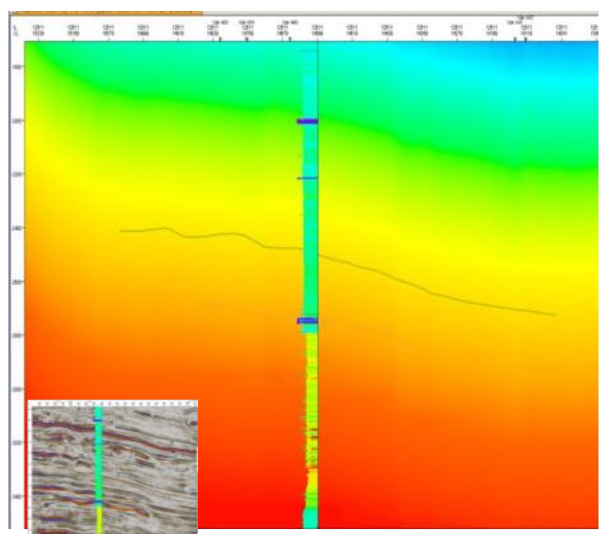

Figure11: shows the distribution of epsilon (ϵ) in vertical section (interpretation window) forYoyo-1 reservoir.

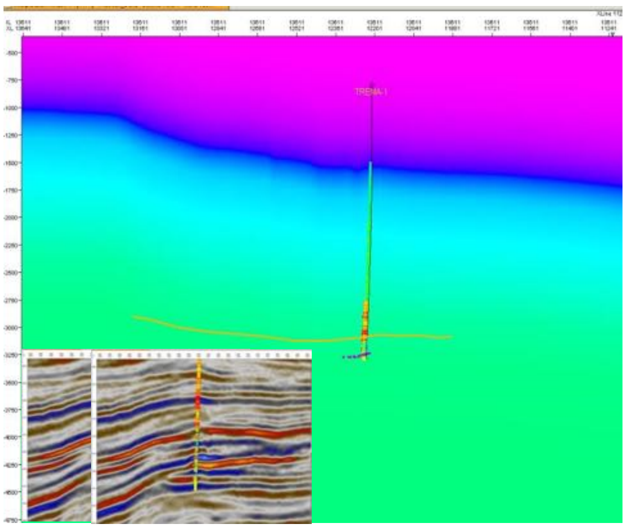

Figure 12: shows the distribution of delta (δ) in vertical section (interpretation window) for Trema-1 (wet sand).

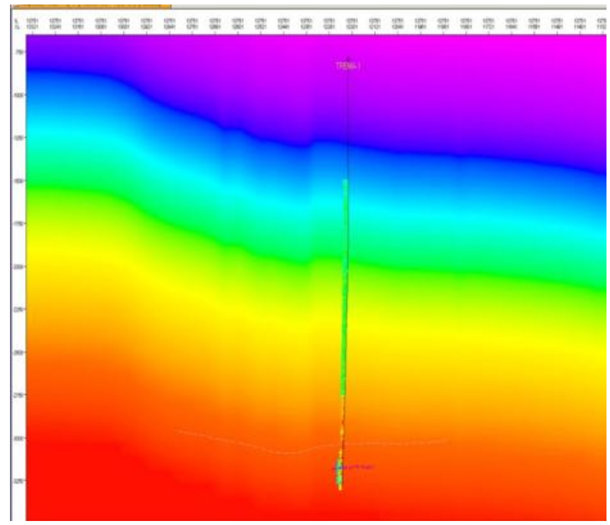

Figure 13: shows the distribution of epsilon (ϵ) in vertical section (interpretation window) for Trema-1 wet sand.

Generating VTI-AVO model at angle stack (near, mid far)

Using Thomsen parameter from a PSDM processing to generate VTI-AVO and use it to match the gather at (near, mid, far stack) seismic for both reservoirs (Yoyo-1 and Trema-1 wells). However, this processing is done by Hampson software, by import the Thomsen's parameters as well as the angle stack to convert them at near, mid, and far angle stack (Figs. 16 and 17). Moreover, making the gathering of seismic data at near, mid and far requires to do scaling for three angle stacks, and setting the angle at near = 12, mid = 24, far = 38. As a result, the three-angle stack displayed (Figs. 18 and 19) for both reservoirs. The results illustrate that the slightly increasing of offset at near, mid, and far at the top of Yoyo-1 reservoir (Fig. 18), while the Trema-1 reservoir shows that far angle stack has strongly increasing of offset (Fig. 19), which is the reason of having false class 2 response.

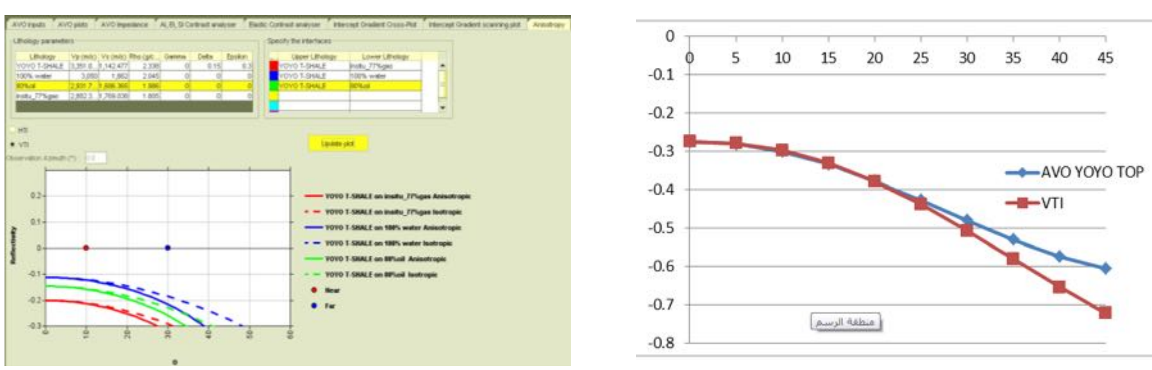

Figure 14: shows the calculating of blocky model for Yoyo-1 reservoir by using a Thomsen's parameters values.

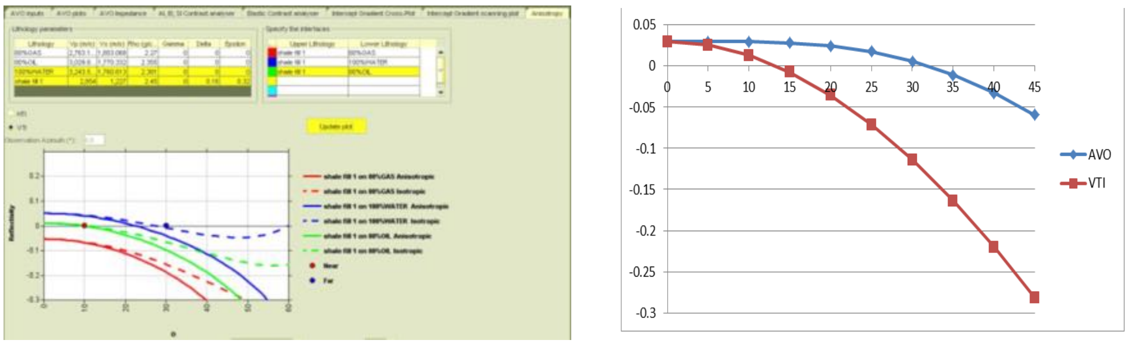

Figure 15: shows the calculating of blocky model for Trema-1 wet sand by using a Thomsen's parameters values.

AVO attributes

AVO attributes are used to analysis large volumes of seismic data, looking for hydrocarbon anomalies. However, the most important of this part is how can AVO attributes used to minimize/eliminate anisotropy effects, thus can be applied to future prospects. Two primary attributes, gradient and intercept, are extracted from the generated synthetics because we need to combine to form a single attribute such as AVO product (A x B) and other attributes. However, the Aki-Richards equation predicts a linear relationship between A, B amplitudes and $\sin^2\theta$ (Aki and Richards, 1980) which is result in positive or negative amplitude. ***Scaled Poisson's Ratio Change :(A+B attribute).***

This combination is derived from Shuey's $A+B = 9/4\ \Delta\sigma$ **(3).** The sum A+B is proportional to the change in Poisson's Ratio. As a result of calculating AVO sum (A+B) shows a negative response at the top of the reservoir (decrease in σ) and a positive response at the base (increase in σ) (Fig. 20) for Yoyo-1 reservoir, while Trema-1 well shows a positive response at the Top of the reservoir (increase in σ), and a negative response at the top (decrease in σ) (Fig. 21).

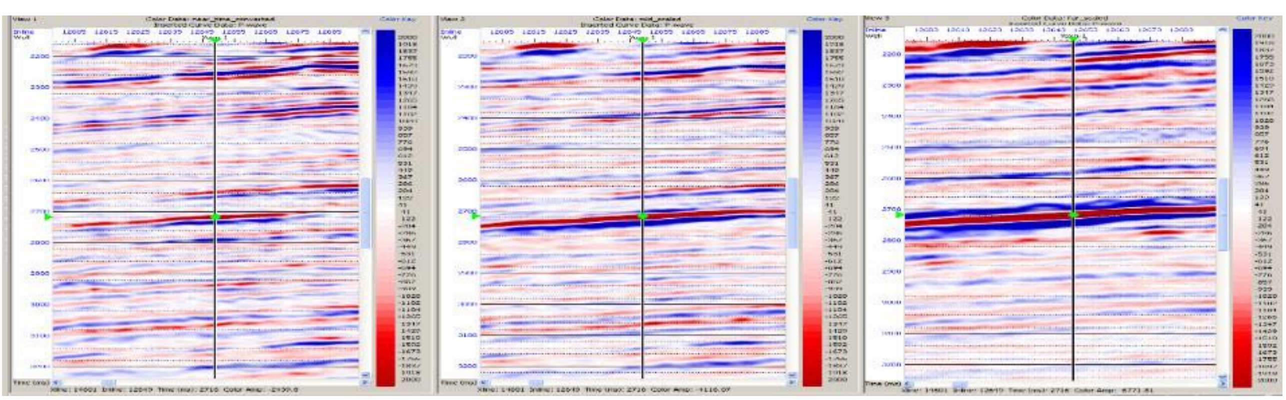

Figure 16: shows the scaling section of three angle stack for Yoyo-1 reservoir.

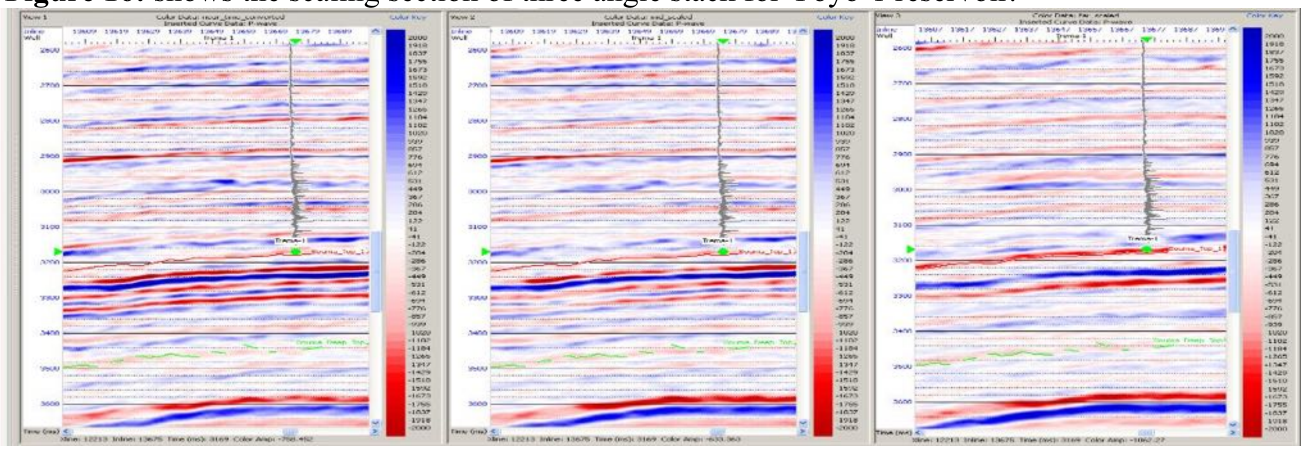

Figure17: shows the scaling section of three angle stack for Trema-1 wet sand.

The second combination is derived from the Aki& Richards equation

This combination is derived from Aki and Richards equation: **Rs = ½ (A- B)(4).** The difference A-B is proportional to the Shear Reflectivity. As a result of calculating this type of attribute, the AVO difference (A-B) shows an increase in Shear Impedance at the top of the reservoir for both reservoirs (Figs. 22 and 23).

AVO product: A*B

Many AVO anomalies have the form of positive and negative reflector as shown below. In this case, both the intercept (A) and the gradient (B) are large numbers or "bright". Also, they have the same sign. For instance, Yoyo-1 reservoir has shown class 3 anomaly. As forming the product of A and B, we get: Top of sand: **(-A) *(-B) = +AB (5).** Base of sand: **(+A) *(+B) = +AB (6).**

In general, the most of calculations have done for the top of reservoir only, where we are interested in. However, the result shows a positive "bright" response at both top and base (Fig. 24), while the Trema-1 reservoir does not have any response (Fig. 25) because the forming product of A and B gives a negative response as following:

Top of sand: **(+A) *(-B) = -AB (7).**

Therefore, depend on the results, the most important attribute that can eliminate anisotropy is A*B product, comparing with other attributes that have a false response of "bright spot" that indicate on hydrocarbon. However, comparing the angles gathering with the suitable attribute (A*B to notice that Yoyo-1 well (gas sand) indicating on slightly increasing in offset at near, mid, and far (Fig. 26), while Trema-1 well (wet sand) does not show any increase in offset at near, and mid angle stack except shows an increasing at far angle stack (Fig. 27).

The findings of the study are being implemented successfully in the blocky AVO and Gassmann equation to see the potential effects of hydrocarbon on reflectivity at the top reservoir interface (Gassmann, 1951) for Trema-1 reservoir (wet sand comparing with Yoyo-1 reservoir (gas sand). One of the most steps of anisotropic effect is to make AVO blocky model and fluid substitution for two reservoirs to check the probability of three fluids and compare them with the location of Rutherford and Williams classes of AVO anomaly. The blocky modeling is a fast, first-look technique which uses average values over intervals to get a response to a changing set of properties. Moreover, the output can be used to construct models which help us to understand fluid behavior of reservoir, and blocky modeling gives a good steer on how useful AVO modeling will be in a given situation. However, the blocky model of Yoyo-1 reservoir testing by (100% water, 80% oil and 77% in-situ gas) (Fig. 6), while the Trema-1 reservoir testing by (80% gas, 80% oil, and in-situ 100% water) because has been proven as wet sand (Fig. 7). However, the results of yoyo-1 reservoir are more likely to behave as a gas sand reservoir comparing with the in-situ curve (Fig. 8), while the Trema-1 reservoir has different behavior tending to be as wet sand reservoirs comparing with in-situ curve, even though the AVO anomaly indicator on class IIp rather than class II (Fig. 9).

Anisotropy and synthetic gathering of AVO illustrates that behavior of anisotropy leads to have false class 2 “bright spot” for Trema-1 well (wet sand) comparing with gathering angle stack (Fig. 19) for Yoyo-1well that shows high response of three angles stack (Fig. 18). However, the most important attribute that can be applied for future study is A*B product to eliminate the anisotropy. As a result, the only A*B product that show no response for Trema-1 reservoir while the two other attributes show the false response of Trema-1 (wet sand) (Fig. 26), even though they show the response of gas sand (Yoyo-1 reservoir) (Fig. 27).

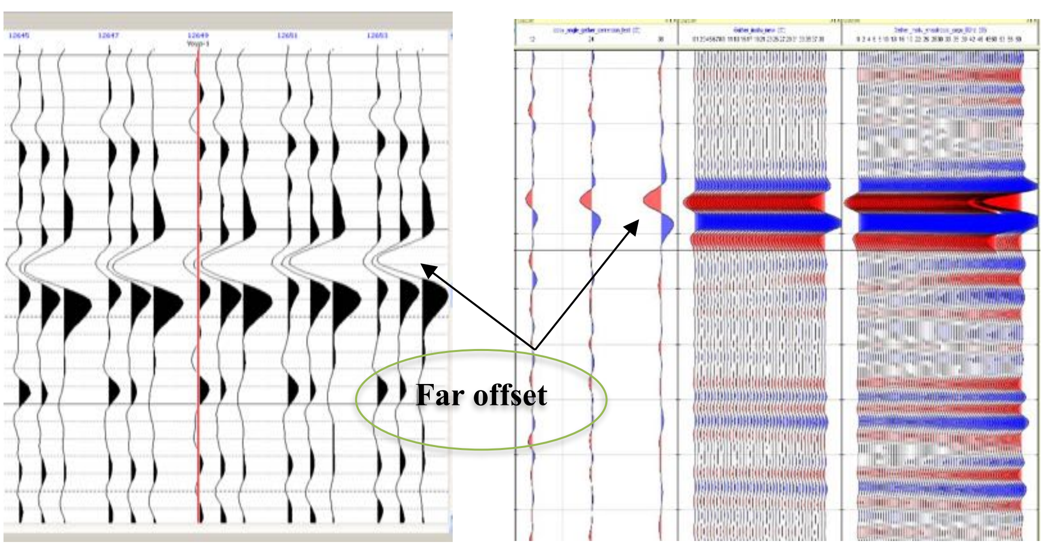

Figure 18: Illustrates the gathering of angle stack of seismic comparing with in-situ AVO conventional and anisotropy for Yoyo-1 gas sand.

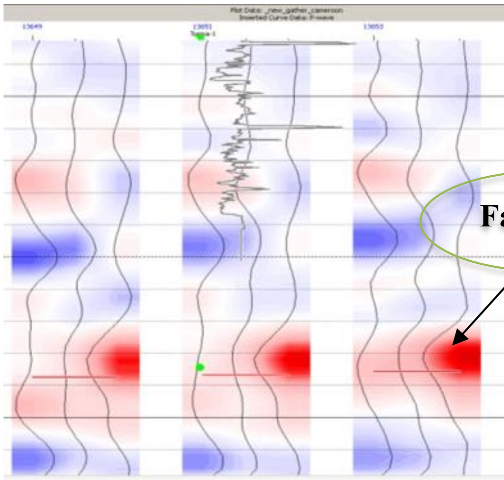
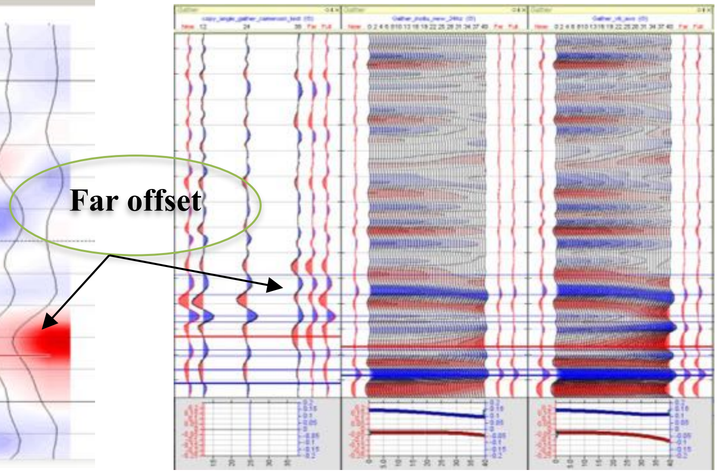

Figure 19: Illustrates the gathering of angle stack of seismic comparing with in-situ AVO conventional and anisotropy for Trema-1 wet sand.

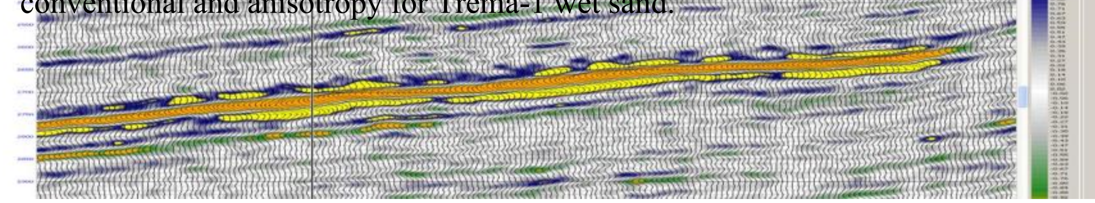

Figure 20: Shows the result of (A+B) volume attributes for Yoyo-1 reservoir (gas sand).

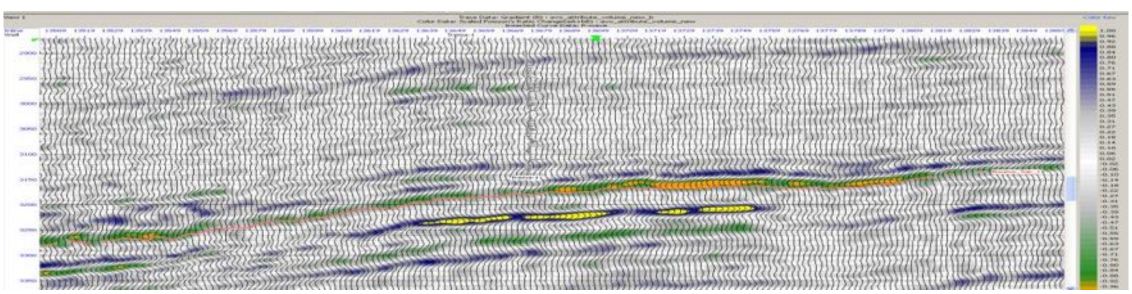

Figure 21: Shows the result of (A+B) volume attributes for Trema-1 (wet sand).

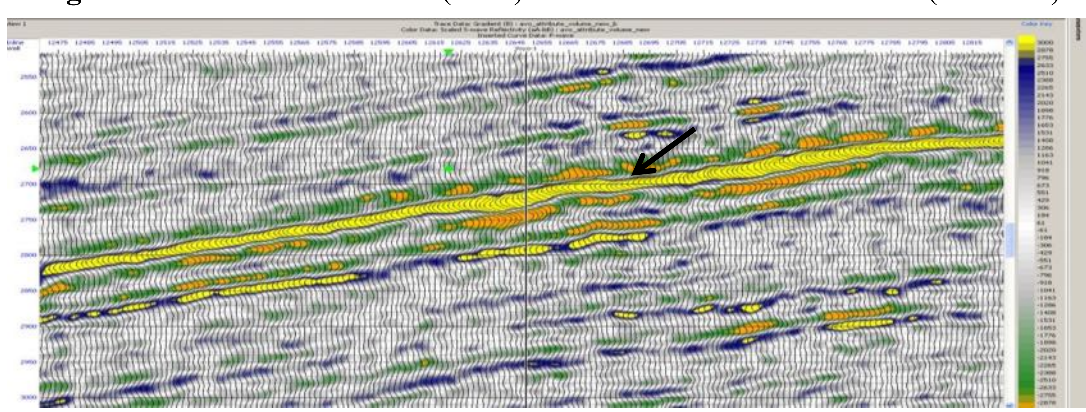

Figure 22: Shows the result of (A-B) volume attributes for Yoyo-1 reservoir (gas sand).

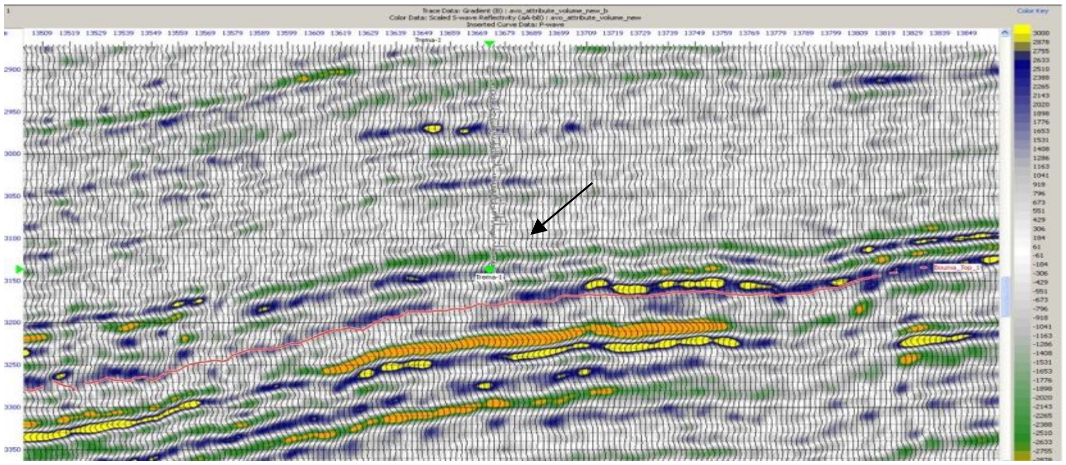

Figure 23: Shows the result of (A-B) volume attributes for Trema-1 (wet sand).

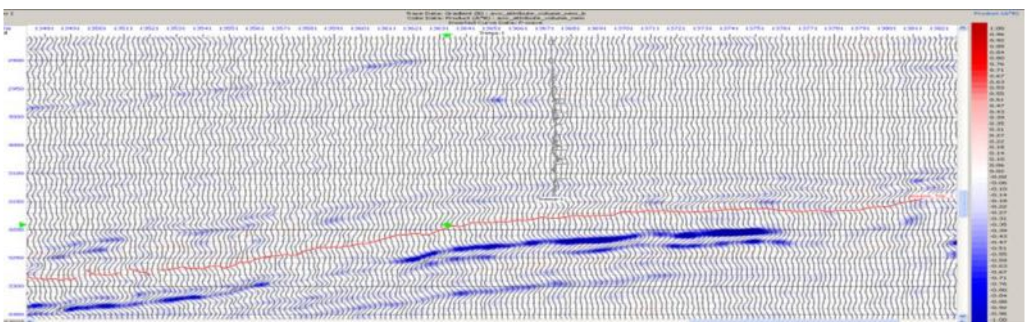

Figure 24: Shows the result of (A*B) volume attributes for Yoyo-1 reservoir (gas sand)

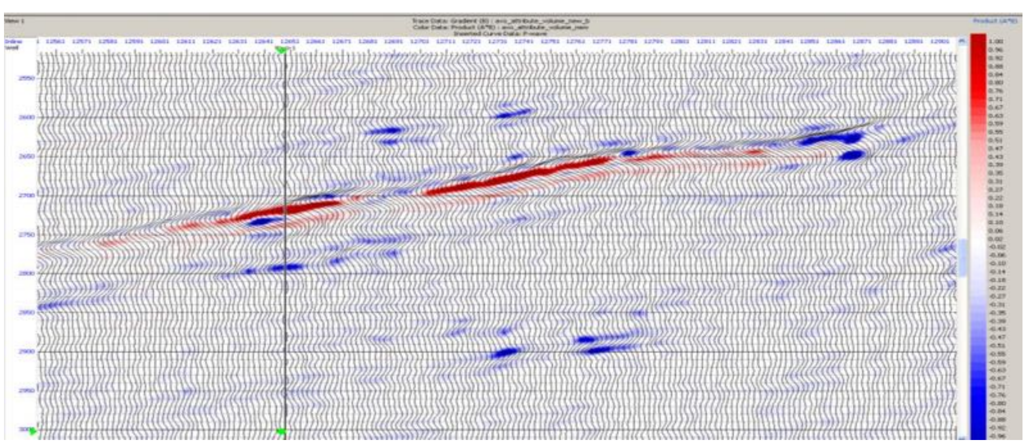

Figure 25: Shows the result of (A*B) volume attributes for Trema-1 (wet sand).

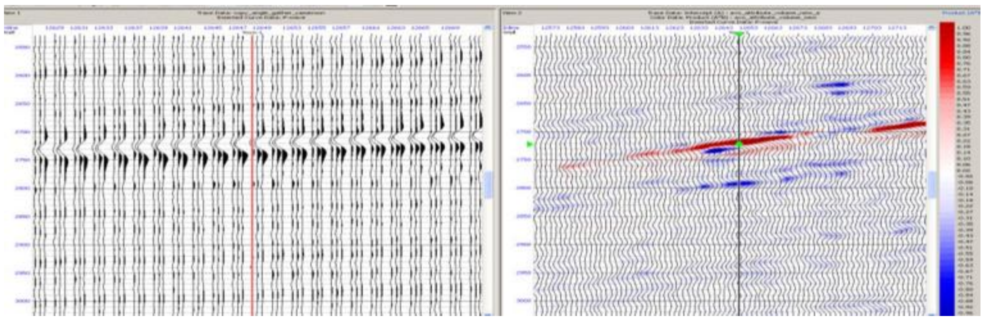

Figure 26: Shows the result of (A*B) attributes for Yoyo-1 reservoir (gas sand), comparing with angle stack.

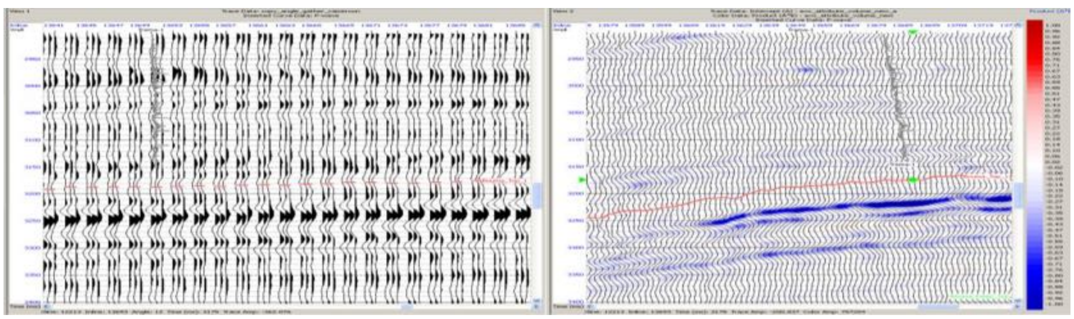

Figure 27: Shows the result of (A*B) attributes for Trema-1 (wet sand), comparing with angle stack.

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Figure (24): shows the result of (A*B) volume attributes for Yoyo-1 reservoir (gas sand)

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