# Estimation of Shear Wave Velocity, Ghadames Basin, Libya

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## Abstract

Estimation of shear wave velocity (Vs) plays an crucial role in amplitude variation with offset (AVO) analysis studies and rock physics. This paper introduces a method for superior estimation of shear wave velocity (Vs) from compressional wave velocity (Vp), bulk density (ρb) and gamma ray (GR/γ) logs, using multi-linear regression technique. Previously, Vp-Vs and Vp- ρb relationships are commonly used in order to extract AVO attributes which are influenced by lithology and fluid saturations. Due to the shortage and the availability of the log data, empirical equations used to calculate approximately shear wave velocity and bulk density logs. Empirical equations, (such as Castagna's relationship, 1985, which known as the Mudrock line equation), are derived from the linear relation between compressional wave velocity and shear wave velocity for worldwide rocks. The Ghadames basin is considered to be a Paleozoic basin, the main reservoirs' age are Paleozoic, thus applying aforementioned equations in order to estimate shear wave velocities provide relatively underestimated values at the reservoir zones while they predict overestimated values at the cap rock shales. An advantage of the new equations is that a new set of relationships to optimize the predicted shear wave velocity.


**Key words** : Shear Velocity, Compressional Velocity, Multi-linear regression


## الملخص

يلعب تقدير سرعة موجة القص (Vs) دورًا مهمًا في دراسات تحليل تغير السعة مع الإزاحة (AVO) وفيزياء الصخور. يقدم هذا البحث طريقة لتقدير أفضل سرعة لموجة القص (Vs) من سرعة موجة الانضغاط (Vp). في السابق، كانت تستخدم العلاقات Vp-Vs و Vp- pb بشكل شائع لاستخراج سمات AVO التي تتأثر بالليثولوجيا وتشبع السوائل . نظرًا لنقص وتوافر بيانات تسجيلات الابار، تستخدم المعادلات التجريبية لحساب تقريبا سرعة موجة القص وسجلات الكثافة الظاهرية. المعادلات التجريبية (مثل علاقة Castagna، 1985 ، والمعروفة باسم معادلة خط Mudrock) ، مشتقة من العلاقة الخطية بين سرعة الموجة الانضغاطية وسرعة موجة القص للصخور في جميع أنحاء العالم. يعتبر حوض غدامس حوضًا قديمًا، وعمر الخزانات الرئيسية هو حقب الحياة القديمة، وبالتالي فإن تطبيق المعادلات المذكورة أعلاه من أجل تقدير سرعات موجات القص يوفر قيمًا أقل من الواقع نسبيًا في مناطق الخزان بينما يتنبأ بقيم مبالغ فيها في صخور الغطاء الصخري. من مزايا المعادلات الجديدة أن هناك مجموعة جديدة من العلاقات لتحسين سرعة موجة القص المتوقعة.


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## Introduction

Seismic Rock Physics and Amplitude Variation with Offset/Angle (AVO/AVA) analysis studies depend essentially on shear wave velocity data. In the past the majority of the operator companies did not request dipole sonic log in their wireline logging program, which produces shear slowness logging data (Δts). Thus estimating shear velocity from the available monopole sonic data (Δtc) was an alternative solution for decades. The common empirical equations offer underestimated values of the shear velocities of the reservoir rocks in AlWafa Field, Ghadames Basin using only the compressional velocity log, fig 1. In 1985, Castagna build a direct relation between shear wave velocity and compressional wave velocity by plotting them against each other and draw the best regression line which known as Mudrock line equation, which can be mathematically represented in (eq. 1).

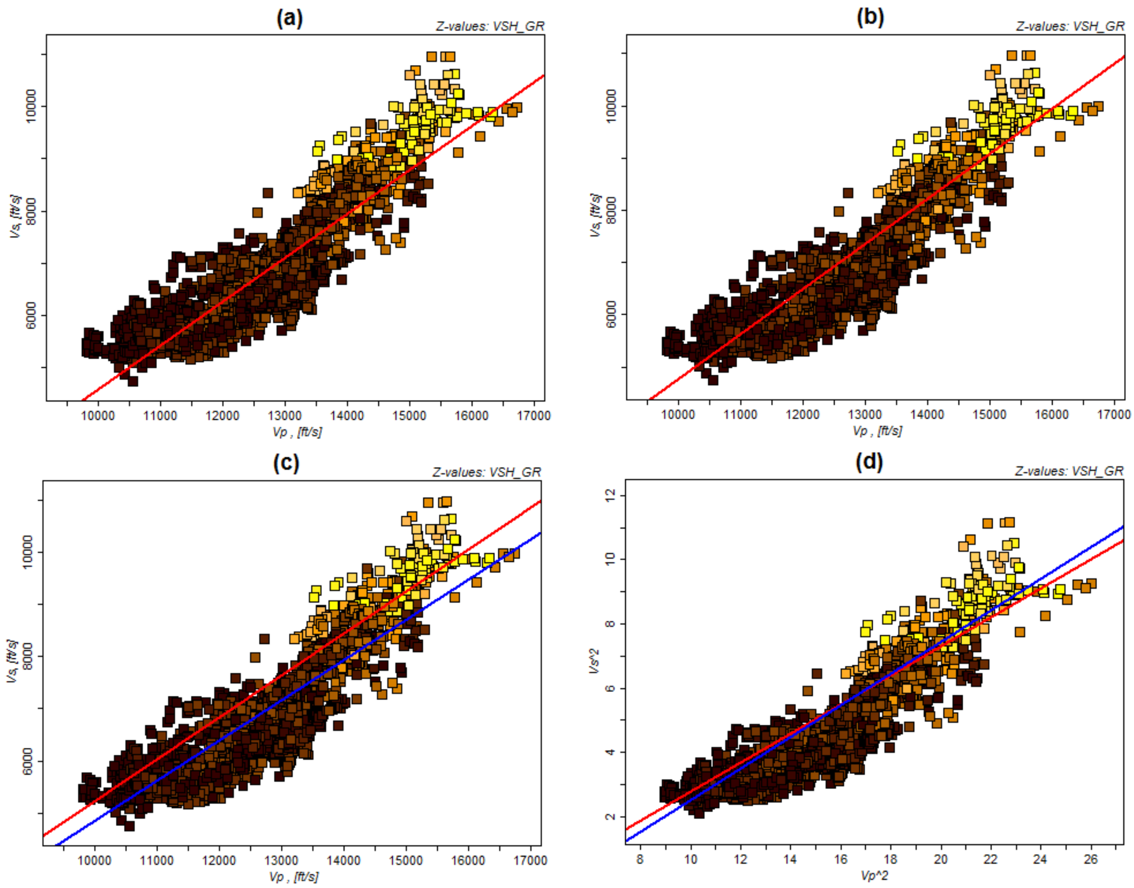


**Fig 1.** cross plot the real shear velocity log against the compressional velocity log colored by volume of shale (yellow = sand , brown = shale). (a) illustrate the best line fit among shear and compressional velocities. (b) the Mudrock line presented by Castagna et al, 1985. (c) Sand line (red) and Shale line (blue) presented by Greenberge and Castagna, 1992. (d) Sand line (red) and Shale line (blue) presented by Krief et al, 1990.

By comparison with the real shear wave velocity (Vs) and the estimated shear velocity using the Castagna's Mudrock line equation (eq. 1) which predicts underestimated values at the reservoir zone while creates overestimated values for the cap rock zone. General equation can be written as follow (Castagna, 1993):

$$V_s = aV_p^2 + bV_p + c$$

where velocities are expressed in km/s.

The coefficient values for the Mudrock line equation are

$$V_s = 0.862V_p - 1.172 \quad \ldots..(1)$$

*where velocities are expressed in km/s.*

For velocity unites in ft/s, divided the 'a' coefficient by 3281, multiply the 'b' coefficient by 1 and multiply the 'c' coefficient by 3281.

In this experiment, lithology control equations have been used which enhanced the estimated shear wave velocity at the reservoir interval while the overlain shales interval overestimated the shear wave velocities. The lithology control equations introduced by Greenberge and Castagna, 1992, and Krief at el, 1990, see fig 1. The used techniques can be described as follow:

First of all separating sandstone intervals from shale intervals based on the volume of shale or gamma ray cut offs. Secondly, plotting the shear wave velocities versus the compressional wave velocities for the sandstone intervals only, and do the same step for the shale intervals. Finally, illustrate the best line fit (using linear regression method) among the sandstone velocity values were (eq. 2a and 2b).

$$V_s = 0.804V_p - 0.856 \quad \ldots..(2a)$$
$$V_s = 0.770V_p - 0.867 \quad \ldots..(2b)$$

where velocities are expressed in km/s.

Krief et al, 1990, have done the same technique but the different was plotting the squared shear velocity versus the squared compressional velocity. The output equations were (eq. 3a and 3b).

$$V_s^2 = 0.438V_p^2 - 0.395 \quad \ldots..(3a)$$
$$V_s^2 = 0.492V_p^2 - 2.407 \quad \ldots..(3b)$$

where velocities are expressed in km/s.

**Methodology:**

Optimizing the prediction of shear wave velocity data are required in order to avoid any pitfalls in AVA analysis and rock property studies. Understanding the age of the reservoir, the depositional environment and the pore space fluid provide an indication of the case and what the suitable procedures should be taken.

The study well is considered to be an oil produced well. Basically, the density, shear and compressional velocities are variously affected by the presence of hydrocarbon and the previous equations were applied on brine bearing reservoirs. Reverse fluid substitution was used to eliminate the effect of the oil presence, therefore the reservoir became water bearing. Gassmann's equation, 1951, was utilized to obtain new set of logs. The prospective reservoirs in Ghadames basin are Paleozoic age which more burial and compaction occurred, so the sandstone rocks are harder than the shale rocks, in terms of acoustic impedance.

In terms of deposition environment, the reservoir sandstone was deposited in deltaic environment so it is vary from medium to fine grain material in order to sort this issue out another variable factor need to add in our equation, thus gamma ray or volume of shale integrated with the compressional wave velocity and density logs.

Taking into account the previous factors, ending up with build a recursive equation using multi-linear regression relation, which vary with the changes in the elastic properties represented in compressional velocity and density and not ignoring the variation of lithology with represented by gamma ray (volume of shale can be used instead of gamma ray).

One well utilized in this experiment with 2322 samples, covers the upper section of Devonian which consists of the reservoir layer. The four mentioned logs were plotted in 4D visualization view to model these variables using a multi-linear method, fig 2.

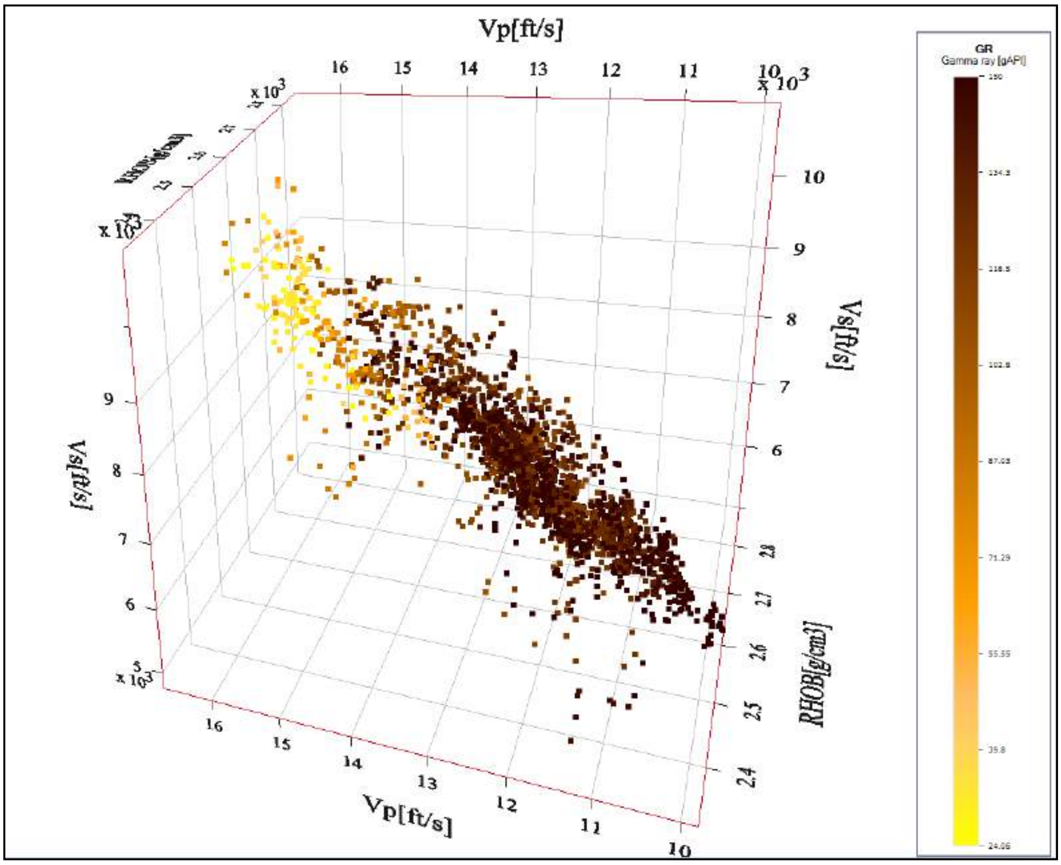


**Fig 2.** illustrates the input data for one well. X axis represents Vp, Y axis represents Vs, Z axis represents Density and colored by gamma ray.

At the first glance, fig 2, the sandstone points have high velocities than shales, while the density values are vice versa.

This method does not have any iterations and offers only one result that reduces the quadratic errors for the least mean square. The resultant equation can be described as follow, table 1:

**Table 1. Vs verses Vp-ρb-γ multi-linear regression coefficients**

Coefficients are for velocities in ft/s and the general equation $V_s = aV_p + b\rho_b + c\gamma + d$

where:

$V_s$ = shear wave velocity (ft/s)

$V_p$ = compressional velocity (ft/s)

$\rho_b$ = bulk density (g/cc)

$\gamma$ = gamma ray (API)

a, b, c, d = coefficients

| Coefficient | |
|---|---|
| a | 0.790 |
| b | -4256.673 |
| c | 0.659 |
| d | 7924.809 |

$$V_s = 0.790V_p - 4256.673\rho_b + 0.659\gamma + 7924.809 \quad \ldots\ldots(4)$$

Comparing the predicted shear velocity logs with the real shear velocity log, see fig 3. All the modeled shear velocity logs excluding the multi-linear method produce underestimated values at the reservoir zone and overestimated values at cap rock layer. The lithology control equations provide better modeled curves of shear velocities than the Mudrock line equation at the reservoir interval.

Essentially, AVA anomalies depend on the variation and the contrast of the elastic properties above and below any interface (top reservoir), the contradictory output values may generate pitfalls in AVO analysis. This topic will be discussed next.

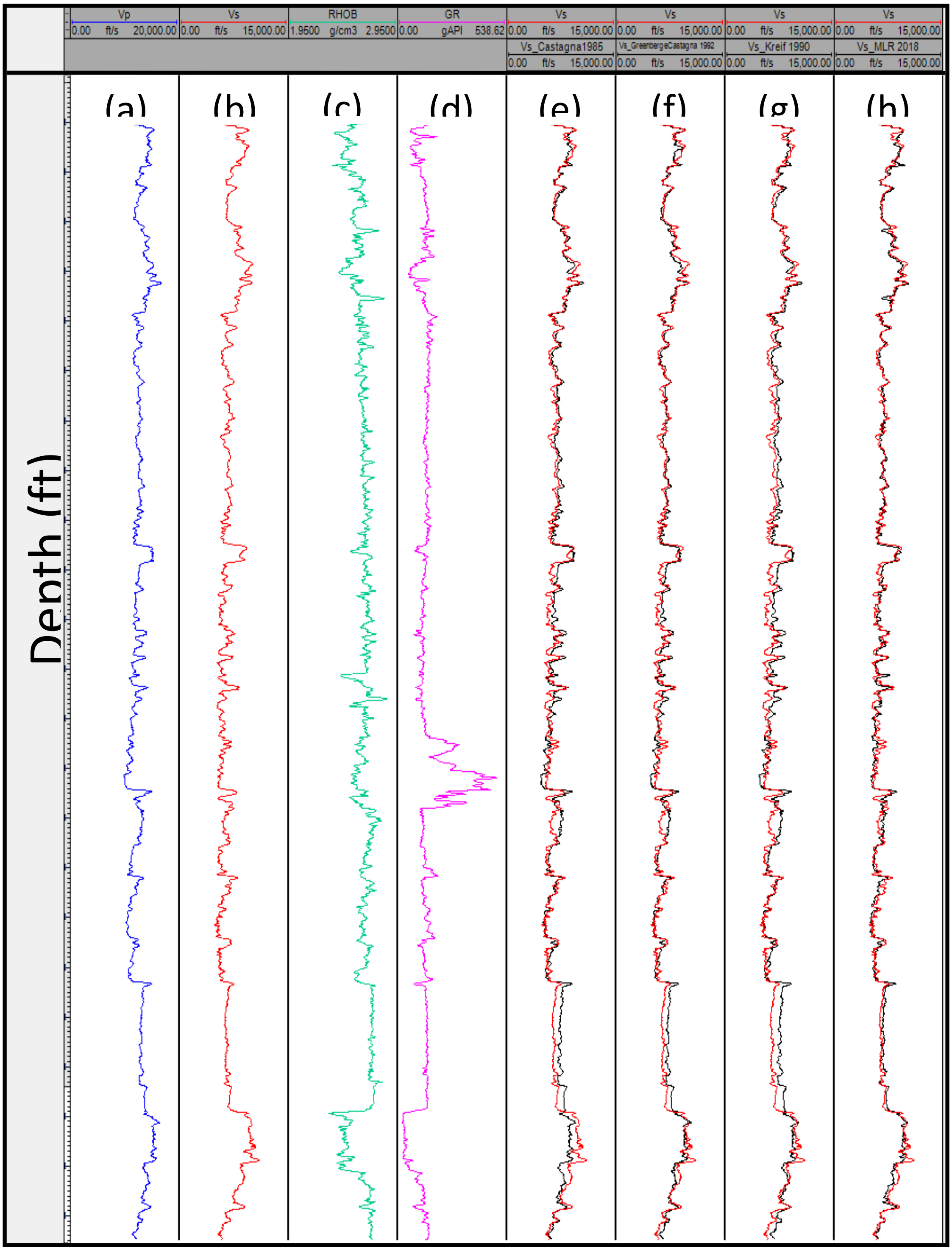


**Fig 3.** shows the input and output data logs for one well. (Track a) compressional velocity log Vp, (Track b) shear velocity log Vs, (Track c) density log ρ, (Track d) gamma ray log γ, (Track e) estimated shear velocity log using Mudrock equation, 1985 (black) and real shear velocity log (red), (Track f) estimated shear velocity log using Greenberg & Castagna, 1992 equations (black) and real shear velocity log (red), (Track g) estimated shear velocity log using Krief et al, 1990 equations (black) and real shear velocity log (red), (Track h) estimated shear velocity log using multi-linear regression equation (black) and real shear velocity log (red), note all the velocity logs unit is ft/s.

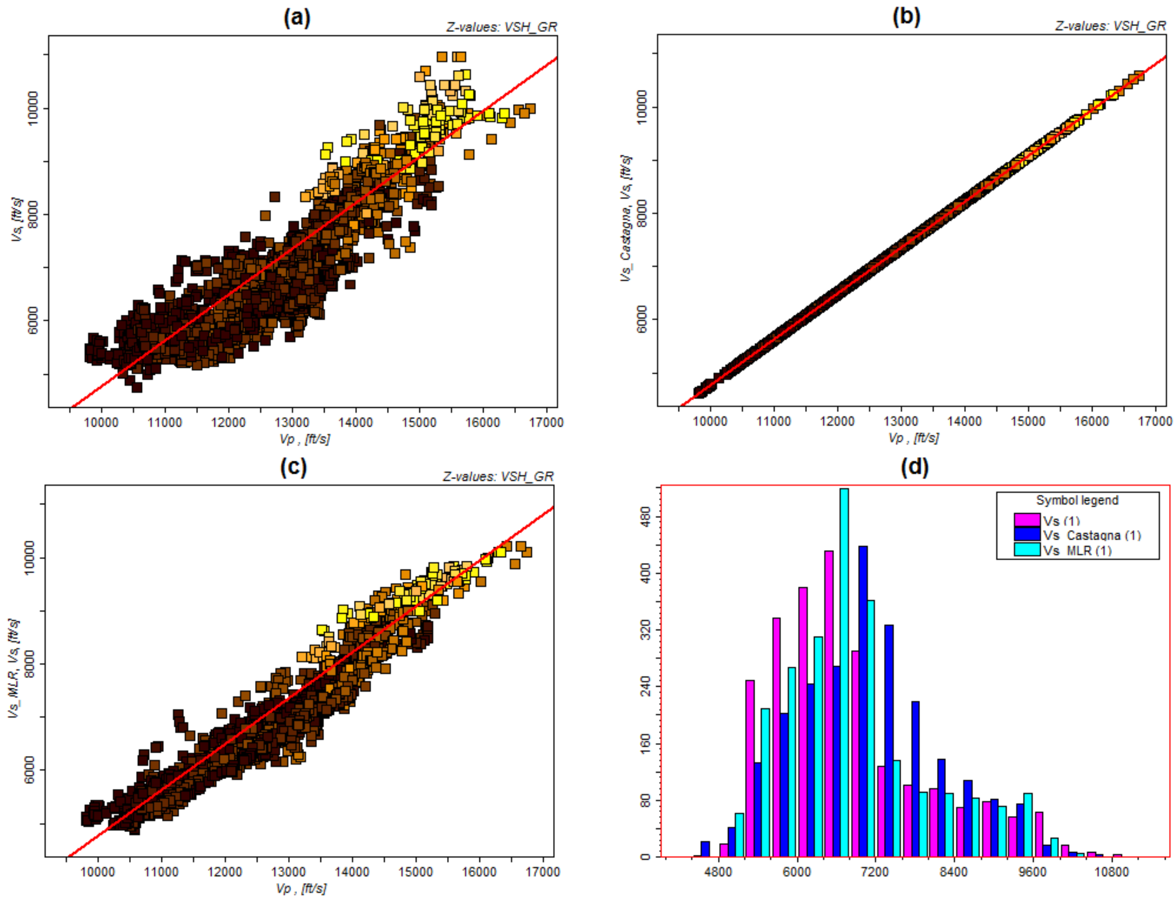


**Fig 4.** illustrates cross plots of the shear wave velocity logs against the compressional velocity log colored by volume of shale (yellow = sand , brown = shale). (a) the real shear vs. compressional velocities values. (b) the estimated shear using Mudrock line eq. vs. compressional velocities values. (c) the estimated shear using multi-linear regression eq. vs. compressional velocities values. (d) histogram of the three shear logs mentioned above show the best match between real Vs and MLR Vs.

## AVO Analysis Pitfalls

Generating Amplitude versus Angle (AVA) gathers is one of the important steps during AVA analysis study, which can provide a direct hydrocarbon indication (DHI). For example, reverse polarity can be observed at the top of the reservoir, in terms of AVA classifications, it is also can be classified as class IIp AVA, fig 5a.

In many wells the real shear wave velocity would not be available. So applying the common predicted equations to get shear wave velocity data is the solution. The AVA gather form the multi-linear modeled shear velocity illustrates reverse polarity or class IIp as well, while The AVA gather form the Mudrock modeled shear velocity demonstrates dim out anomaly or class I AVA was introduced at the top of the reservoir, fig 5a.

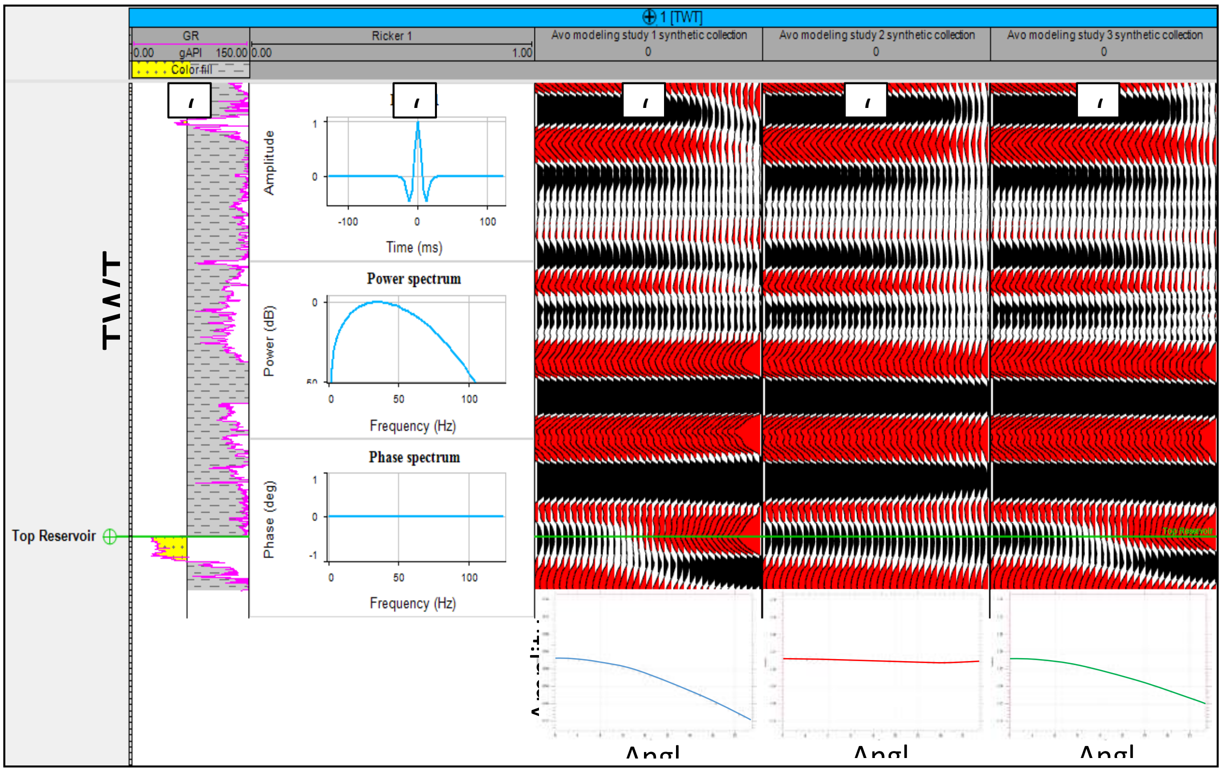


**Fig 5a.** shows AVA gathers and AVA classification of the top reservoir interface. (Track a) gamma ray log γ , (Track b) estimated source wavelet, (Track c) AVA gather via the real shear wave velocity, (Track d) AVA gather via estimated shear wave velocity using Mudrock equation, 1985, (Track e) AVA gather via estimated shear wave velocity using multi-linear regression equation.

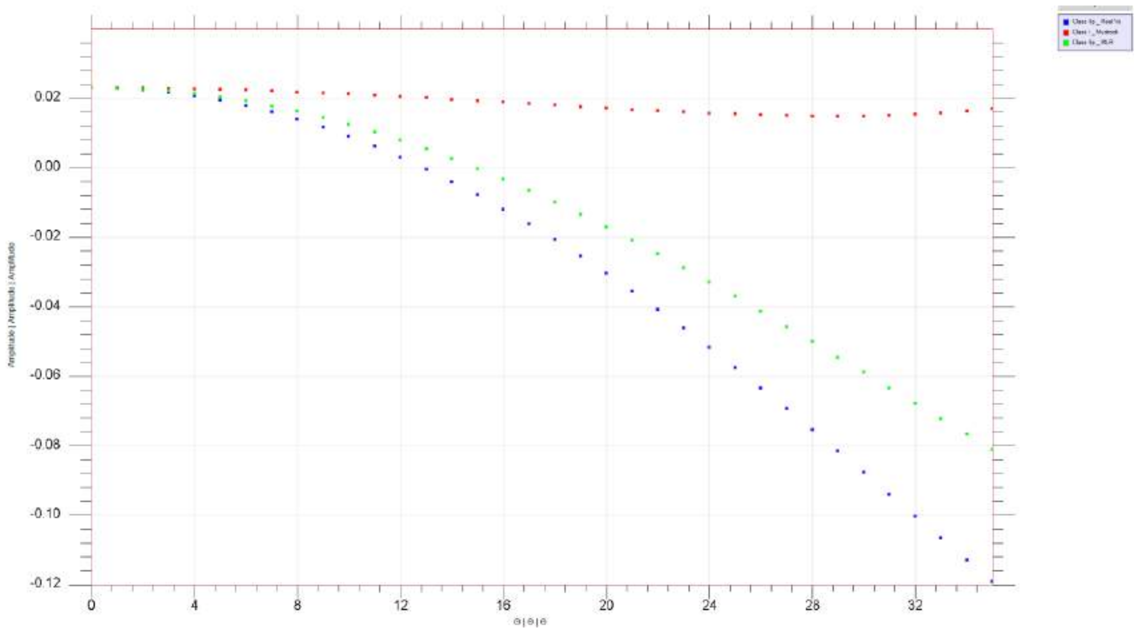

**Fig 5b.** shows AVA classification of the top reservoir interface, (Blue) using real shear velocity produces Class IIp AVA, (Red) using estimated shear wave velocity from Mudrock line equation generates Class I AVA, (Green) using estimated shear wave velocity from the Multi-linear regression equation generates Class IIp AVA.

## Recommendations

If the used well in the study is not water bearing, Gassmann fluid replacement modeling should be applied on the hydrocarbon bearing zones to improve the estimation of the shear-wave values at the reservoir zone. If the available software packages do not capable to do multi-linear regression, local linear regression between Vs and Vp is recommended.

## Conclusions

The multi-linear regression technique showed superior prediction for shear wave velocity. The residual errors among the different methods influenced the result of AVO anomaly. The AVO modeling results from the multi-linear estimated shear wave velocity demonstrate AVO reverse polarity in amplitude at the top of reservoir the same as the real shear wave result target whereas the Mudrock relationships do not exhibit this anomaly.

## Acknowledgement

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