Predication of Shear Velocity at Shaly Sand Reservoir Rock

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Abstract: The magnitude of shear velocity (Vs) in geomechanical rocks properties leads many of petrophysics and geophysics to use and investigate simple and accurate technique for it, especially when this parameter is not measured by sonic tools. If there are no core samples available for calibration, empirical relations could be used, that based on measurable physical properties. The results emphasize the importance of local calibration before one utilizes any of the empirical relationships presented. During this study several trials, were carried out aimed to predicate shear velocity in shaly sand reservoir of late Jurassic to Late Cretaceous at southeast of Sirt Basin, Libya, by using gamma ray, compressional travel time and density logs. Therefore, a new approach by modified derived Poisson's Ratio Equation for shaly sand is introduced as an important part of shear velocity determination. This modified equation design upon deeper, highly compacted and cemented sandstone has a Poisson's ratio values range between (0.18 – 0.20), which is fairly similar to the studied reservoir condition.

Keywords: Gamma Ray; compressional travel time; porosity; bulk density.

INTRODUCTION

Several indirect methods have been used to estimate shear velocity (Vs) from full wave using acoustic logs. These methods include Stoneley wave velocity and inversion of refracted P-wave amplitude.

Historically, the primary use of the sonic log in reservoir engineering was identification of porosity, cement evaluation, mechanical properties, and formation velocities for seismic studies. This parameter Vs is an important tool to calculate rocks mechanical properties. Several techniques were published by many authors to estimate the shear velocity. Therefore, the enhancing, accuracy and reliability of the shear velocity was the main objective through this research.

Where the predication of shear velocity (Vs), for shaly sand reservoir were tested in southeast Sirt Basin, this reservoir is composed of shaly sand deposited during early rifting stages of basin formation in Late Jurassic to Late Cretaceous. The subdivided of upper part of studied (intervals) zone were subdivided according to the presence of shale layer and unknown distribution of shale contents through these zone(s). These determination and modification of the predication shear velocity depend on wireline log data, if the ultrasonic or dipole shear tools and core samples are not available. Consequently, by disclose method using shaliness index to compute Poisson's Ratio (PR) which is used to predicate shear velocity. In addition, application and comparative with published wireline log data were conduct to verify this approach. Finally, this technique is the most important requirements for an improved, accurate, simple, and economic process to determine this rock property.

There are many studies aimed to predicate the shear velocity for different rock type. Mason's (1984) introduced an approach for calculating formation S-wave velocity; was extremely dependent upon mineral composition and an idealized table of P-wave/S-wave velocity ratios. Castagna *et al* (1985) studied the relationships between compressional-wave and shear-wave velocities in elastic silicate rocks. They demonstrate simple systematic relationships between compressional and shear wave velocities. For water-saturated elastic silicate rocks, shear wave velocity is approximately linearly related to compressional wave velocity and the compressional-to-shear velocity ratio decreases with increasing compressional velocity. The results of the relationships established between Vp and Vs are

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then applied to calculations of rock dynamic module. The ratio Vp/Vs is used to determine petrophysical properties. It is normally a ratio ranges from 1.4 to 2.5, although examples exist of the ratio reaching values as high as 4.0 in unconsolidated sandstones. Brie *et al* (1995); proposed the same concept of (Vp/Vs) ratio versus ΔT cross plot was intended to describe the effect of the pore fluid on the acoustic properties of the rock.

Crain's (2000) through his publication presents the main equations of elastic constants of rocks which were defined by the Wood-Biot-Gassman equations. These equations depend mainly on wire line log data.

Widarsono *et al* (2001) developed a new approach for the estimation of the elastic properties of clastic rocks in boreholes with limited log suites.

In recent studies by Vernik and Bahret (2002) related the shear and compressional velocities to built petrofacies classification with 3-D seismic inversion in deepwater turbidities reservoir.

Statistical method is presented to predict (Vs) from wireline log data in carbonate rocks introduced by Eskandari *et al* (2003).

METHODOLOGY

Elasticity is a property of matter, which causes it to resist deformation in volume or shape. Poisson's Ratio is an important elastic constant, which depend on the Shear and Compressional waves. When shear travel time is not known, which is the case in the vast majority of older wells, a value for Poisson's ratio (PR) can be estimated in shaly sand by:

$$PR = 0.125 * Vsh + 0.2 \qquad (1)$$

(Crain's, 2000).

Then, the shear velocity could be calculated by:

$$\mathbf{Vs} = \frac{Vp}{\sqrt{(1 - PR) \div (0.5 - PR)}} \qquad (2)$$

The two formulas are depending on the shale content and compressional sonic travel time (ΔTc). The shale content (Vsh) could be computed by many methods, through this reservoir, Gamma Ray log is the main data for its estimation.

Castagna *et al* (1985) and Han *et al* (1986) demonstrated linear relationships between compressional wave velocity Vp (km/s) and shear wave velocity Vs (km/s), see Fig. 1.

$$Vp = 5.81 - 9.42\,Ø - 2.21\,Vsh \qquad (3)$$

$$Vs = 3.89 - 7.07\,Ø - 2.04\,Vsh \qquad (4)$$

Where fractional porosity (Ø), and fractional clay content (Vsh) for elastic silicate rocks.

The shear wave velocity can be calculated from Christensen's equation as illustrated below; where Entwisled and McCann (1990) considered this equation in some detail and showed that it gives an over-estimate of the shear wave velocity in mud rocks and soft sediments. Indeed this equation gives over estimation of shear velocity values as illustrated in (Fig. 2).

$$\mathbf{Vs} = Vp\left[1 - 1.15\left(\frac{1/\rho + 1/\rho^3}{e^{1/\rho}}\right)\right]^{3/2} \qquad (5)$$

The popular sandstone and mud rocks equations by Greenberg and Castagna (1992) given (Vs) in km/sec as follows:

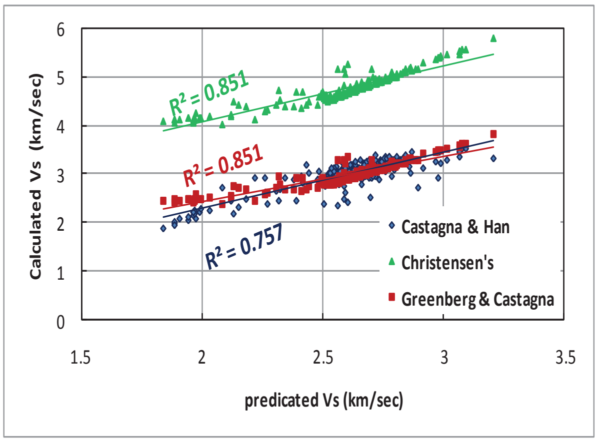

Fig. 1. Correlation between predicted Vs and calculated Vs.

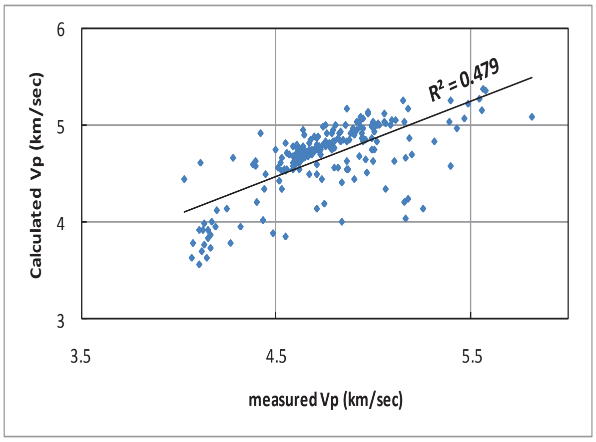

Fig. 2. Correlation between measured and calculated Vp.

$$Vs = 0.804\ Vp - 0.856 \quad (6)$$

This formula depends only on compressional velocity whereas, the other equations are depended on more than one physical parameter.

The interest of the shear interval transit time measurement has been exposed by Pickett (1963). He demonstrated that the ratio of the compressional to the shear velocities (Vp/Vs) can be used as a lithology indicator (Serra, 1984). While Crain's shown this cross –plot to indicate Poisson's ratio by lithology.

RESULTS AND DISCUSSION

Shear Velocity Verification

Practical Application at SE Sirt Basin: Application of the discussed methodology is first part of the predication Vs, and comparative of these results is a second part which gives a main reason to acceptable the Vs estimation for the southeast Sirt Basin or there are requirements for adjustment. Therefore, we assessed the repeatability of the results and then impact it for future applications such as rock mechanical parameters.

Shale layers cross the studied reservoir were easy defined as shale intervals. While clean intervals contain undefined shale distribution type as clean intervals. Consequently, the cutoff value (20 %) of shale content takes from volume of shale, which calculated within the studied reservoir (southeastern Sirt Basin). Then 20% > Vsh > 20% filter was applied to identify clean sand and shale intervals.

Fig. 1 shows the plots of predicted Vs (equation 2) with the calculated Vs by the equation 4, 5 and 6 for the studied reservoir. Castagna *et al* (1985) and Han et al (1986) give a correlation coefficient (R2) of 0.76 less than Greenberg and Castagna (1992) which is equal to 0.85. The different of the R^2 due to these different relationships are included different physical parameters. In spite of the Christensen's equation also presents good regression but has an over estimate of the shear velocity. That what makes the Christensen's equation is not suitable for studied reservoir.

Note that (Fig. 2) illustrates weak relation between the Vp derive from sonic log data correlated with that derived by the Castagna *et al* (1985) and Han *et al* (1986) equation.

The same above procedure of the predicate Vs from PR (equations 1 and 2) is applied for well has package of wire line log data (GR, ρb, Øn, Rs, Rd, "shallow and deep Resistivity", ΔTc and ΔTs). The wire line log data of the tested well has the same rock type.

Cross plot between the predicated Vs and that measured by sonic travel time is done, instead of any equations, which they are used for the estimate Vs of studied reservoir. High regression coefficient of this cross plot (Fig. 3) utilized Crain's equation (1) to find PR which is the main parameter of the shear velocity. In addition, measured compressional velocity by sonic travel time correlated with the predicated and measured shear velocity and indicate good trend as shown in (Fig. 4).

Crain's Equation Modification: The Crain's (2000) equation (1) applied on US Gulf Coast formations, needs some adjustment in other areas as he reported. Although this equation gives best regression trend in the studied reservoir at southeast Sirt Basin, but to be generalized for the whole region it requires more investigation.

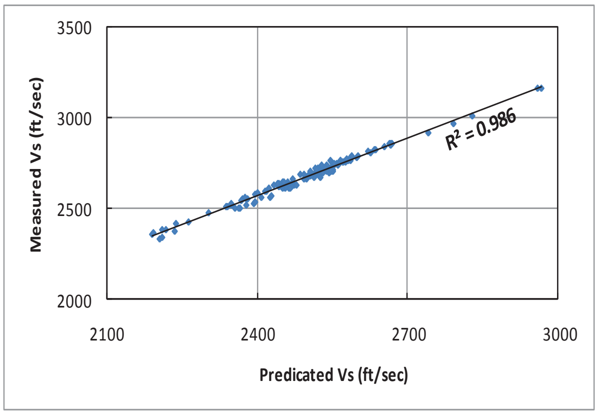

Fig. 3. Correlation between predicted and measured Vs for tested well.

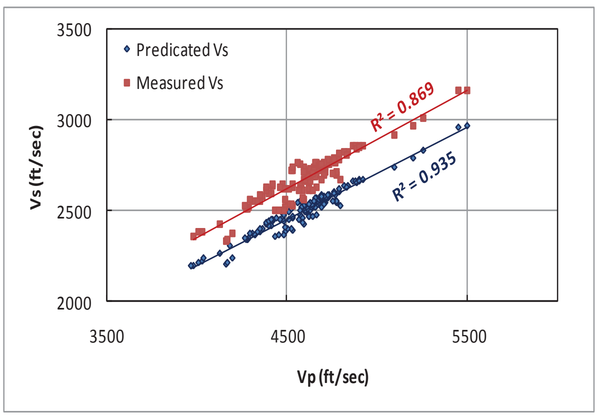

Fig. 4. Correlation between measured Vp and (predicated and measured) Vs for tested Well.

Common diagram relates Vp (km/sec) and PR indicates lithology inside certain limit. Another quick look analysis used to estimate PR by ΔTs and ΔTc (Crain's, 2000). These two conventional methods are applied as shown in (Figs. 5 and 6) respectively for studied reservoir. Comparison with the standard two diagrams appear cluster point for clean intervals which include unknown distribution of shale as mentioned before, cause to shifting from clean sandstone range into sandstone, silt and carbonate range. While the shale intervals plot in the right region of shale. Whereas, the second figure present all the clean interval points are approximately close to 0.3 and the shale intervals at suitable range of PR. Therefore, the modification of the equation (1) to estimate accurate values of PR and consequently Vs for studied reservoir is the main task through this section.

The studied reservoir in southeast Sirt Basin, Libya is not clean sandstone due to changes in depositional environment conditions and burial history of this reservoir (Abdulghader, 1996; El-Hawat, 1992 and El-Hawat *el al.* 1996). In addition to different petrophysic characteristics of this reservoir were extracted from petrophysical study

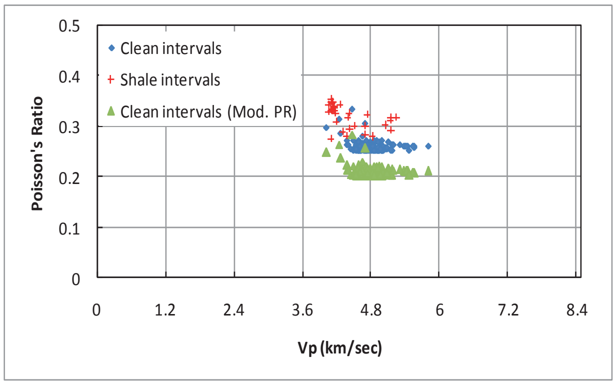

Fig. 5. Compressional velocity (Vp) versus Poisson's ratio (PR).

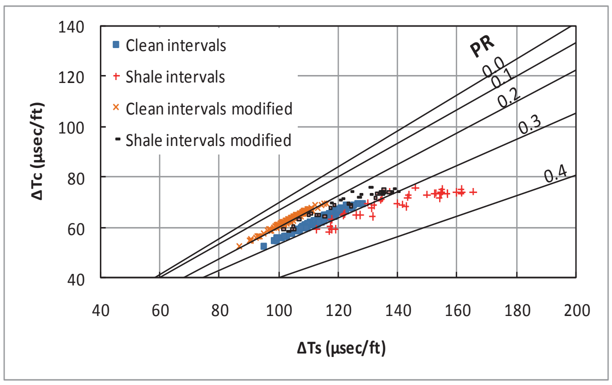

Fig. 6. Quick look analysis of Poisson's ratio (Modified after Crain's, 2000)

of this specific reservoir rock (unpublished study, 2007). Although the later result of PR (Figs. 5 and 6) is same as that observed at a common sandstone range of PR (0.2 - 0.3) (Allen and Allen, 1990), but it is unable to predicate Vs by this result (Crain's equation, 1).

Starting from a typical values of Poisson's ratio for deeper highly compacted, cemented sandstone ranging from 0.18 to 0.22 from most publications of mechanical properties of clastic rocks (Crain's, 2000). The selection of low limit (0.18) and high limit (0.22) of PR values as input constant values to calculate Vs (equation 2). The procedure worked for studied reservoir and test well data. However, comparison between the predicated Vs using variable shaliness PR with those calculated by constant values of PR are clearly noticeable in Figs. 7 and 8 respectively.

Shear velocity values through studied reservoir show conformity estimation even so the predication Vs has lower values than others. In other words, an increase in Poisson's ratio (from 0.18 to 0.22) cause decrease in shear velocity values. Consequently, the modification of Crain's equation (1) was necessary. Try and error technique used to get best modification (equation 7) of equation 1. Results of the new modified predicated Vs equation are plots with the results of equation 2, which is conduct constant values of PR. It is visible through the different Figs. 7 and 8 fitness of the Vs and located in normal range especially in clean intervals, but it couldn't reliable on the Vs results in shale intervals.

$$PR = 0.125 * Vsh + 0.2 \quad (7)$$

Repotting of the quick look diagram by the new Vs results (Fig. 6) indicates change of points toward PR line equal to 0.2.

Vs - Vp Relationship: The cross plot of the compressional and predicated shear velocities by Crain's equation (1) and the modified predicted equation (7) of Vs were compared with Vs estimation at standard PR values (0.18 and 0.22) for different studied reservoir intervals (Fig. 9). The enhancement is obvious about regression coefficient from 0.97 to 0.987 by new modified prediction equation. Therefore, an empirical relation between Vs and Vp for the studied reservoir (southeast Sirt Basin, Libya) could be:

$$Vs = 0.602\ Vp + 89.90 \quad (8)$$

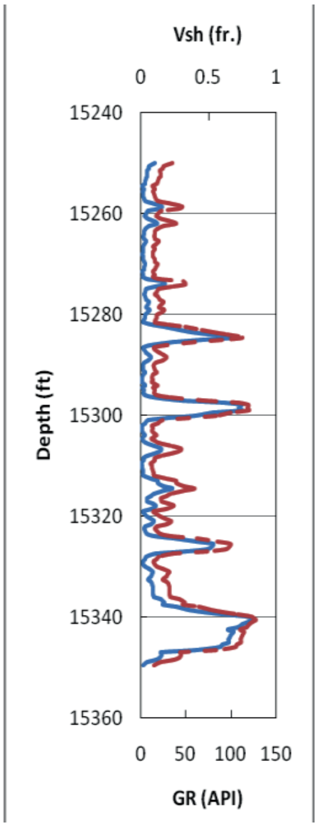

Fig. 7.a. Gamma Ray and shale content of the studied reservoir rock.

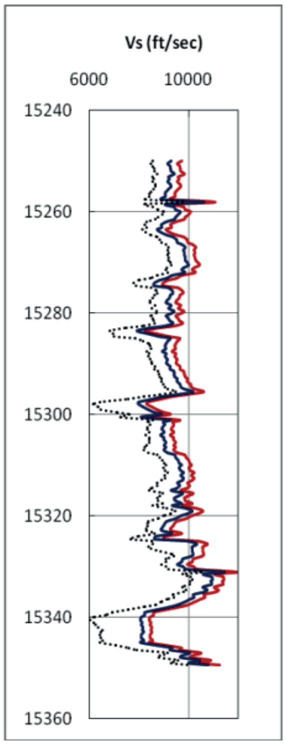

Fig. 7.b. Vs by equation no. 1 of studied reservoir.

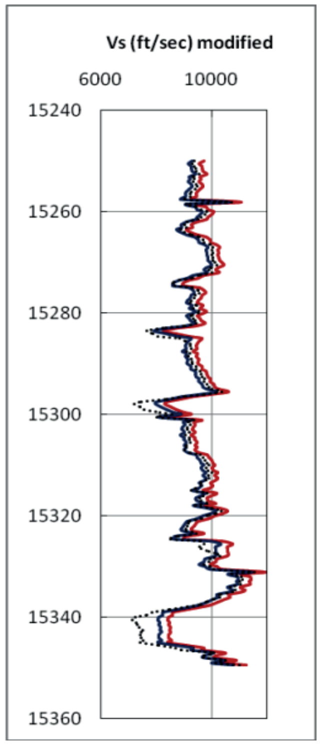

Fig. 7.c. Vs by modified equation no. 7 of the studied reservoir.

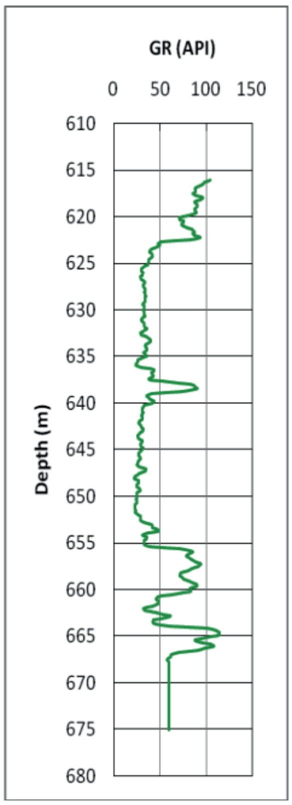

Fig. 8.a. Gamma Ray of the tested well.

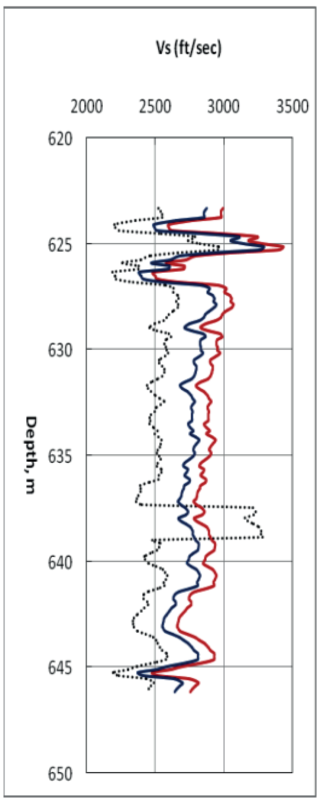

Fig. 8.b. Vs by equation no. 1 of tested well.

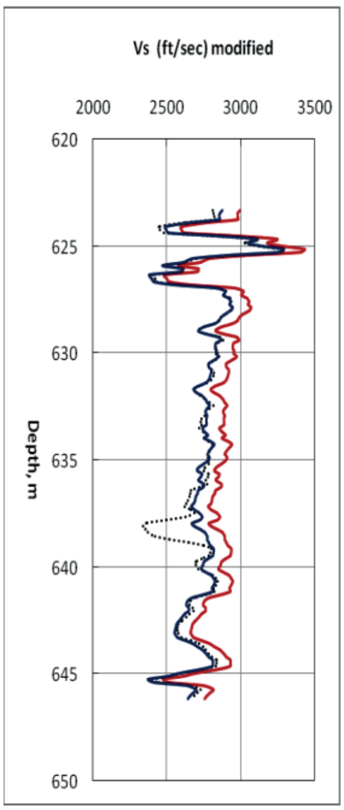

Fig. 8.c. Vs by modified equation no. 7 of tested well.

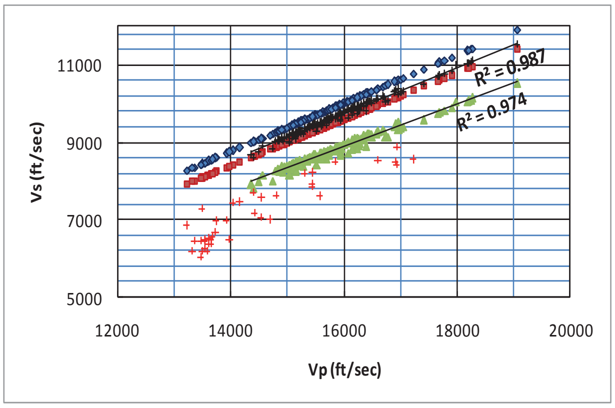

Fig. 9. Cross correlation between Vp and predicted Vs.

The application of this relation indicates good agreement in shale intervals, where as equation (7) still gives over estimation of Vs (Fig. 7c).

CONCLUSION AND RECOMMENDATION

Shear velocity (Vs) could be estimated from the popular equations if the studied rock has the same petrophysics conditions. However, presence of shale content above 20% with unknown distribution throughout the studied reservoir, cause heterogeneous of elastic reservoir rock properties (shear velocity). Therefore, the predication of the Vs of this reservoir rock type subject to some error. A present approach provides a Poisson's ratio; as one of the mechanical property, which is subsequently used to calculate Vs. This technique has been applied for selected reservoir rock in southeast Sirt Basin, Libya. Good agreement of calculated shear velocity by popular equations for sandstone rocks, except that derived from Christensen's equation.

Crain equation can be used to estimate PR for sandstone rock which has the same petrophysic characteristic. In other words, shear velocity as a function of PR could be used and gives good results at clean intervals. This equation of PR according to shale content subjected to modify for confirmation of the petrophysic studied reservoir conditions. Shear velocity by new modification of equation gives better estimation in both clean and shale intervals. According to this result, this new equation of Vs for studied reservoir can be applied without requirements to distinguish a shale intervals within the reservoir.

This approach to estimate the shear velocity within a productive part of shaly sand reservoir is strongly recommend and preferred if there are any core samples to verify an empirical equation results, in addition to study another important mechanical rock properties for this reservoir rock in the study area.

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