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An Accurate Estimation of Shear Wave Velocity Using Well Logging Data for Khasib Carbonate Reservoir - Amara Oil Field

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ABSTRACT

Shear and compressional wave velocities, coupled with other petrophysical data, are vital in determining the dynamic modules magnitude in geomechanical studies and hydrocarbon reservoir characterization. But, due to field practices and high running cost, shear wave velocity may not available in all wells. In this paper, a statistical multivariate regression method is presented to predict the shear wave velocity for Khasib formation - Amara oil fields located in South- East of Iraq using well log compressional wave velocity, neutron porosity and density. The accuracy of the proposed correlation have been compared to other correlations.

The results show that, the presented model provides accurate estimates of shear wave velocity with correlation coefficient of about unity than other currently available methods.

Keywords: shear velocity, compressional velocity, well log data, dynamic modules, multiple regression, geomechanic.

تقدير دقيق لسرعة موجة القص باستخدام بيانات تسجيل الآبار لمكمن الخصيب - حقل نفط العمارة

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الخلاصة

تعد سرعات القص والموجة الانضغاطية ، بالإضافة إلى البيانات البتروفيزيائية الأخرى ، مهمة جدًا لتحديد حجم الوحدات الديناميكية في الدراسات الجيوميكانيكية وتوصيف مكمن الهيدروكربونات. ولكن نظرًا للممارسات وقيود التكلفة ، فإن قياسات سرعة موجة القص غير متوفرة في جميع الآبار نظرًا لارتفاع تكلفة تشغيلها. في هذه البحث ، تم تقديم طريقة انحدار إحصائية

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متعددة المتغيرات للتنبؤ بسرعة موجة القص لتكوين الخصيب - حقول نفط العمارة في جنوب شرق العراق من سجل الآبار لسرعة موجة الانضغاط ، المسامية النيوترونية والكثافة. تمت مقارنة دقة العلاقة المقترحة مع علاقات اخرى.
أظهرت النتائج أن النموذج المقدم يقدم تقديرات دقيقة لسرعة موجة القص مع معامل الارتباط يقترب من الواحد افضل من الطرق الأخرى المتاحة.

الكلمات الرئيسية: سرعة القص،سرعة الانضغاط ، بيانات تسجيل الابار ،وحدات ديناميكية ، انحدار متعدد المتغيرات ، جيوميكانيك.

1. INTRODUCTION

In many developed hydrocarbon fields, only compressional wave velocity (Vp) may be available through the borehole compensated sonic tool logs (BHC logs) or seismic survey. But shear wave velocity (Vs) may not available in all wells due to practical and investment restrictions. It is particularly essential to estimate the shear-wave velocity, especially for practical purpose such as seismic process as an aid for the evaluation of petrophysical and geomechanical properties and geophysical studies such as Amplitude Variation with Offset (AVO) analysis.
Shear wave velocity, compressional wave velocity and density are important parameters for determination of several elastic rock properties, such as Young's modulus, Poisson's ratio, Shear modulus, the rock compressibility factor, and Biot's coefficient, **(Widarsono, 2001)**. Shear and compressional wave velocities are vital to calculate the dynamic modulus, **(Garyet.al. ,1998**; **Liu and Chen, 2012**; **Li and Wong, 2013)**. The elastic rock properties are usually used to predict the stability of wellbore, select drilling fluid gravity, determining the critical production rate that minimizes sand production, optimize casing design, analyze subsidence, and forecast the height, width, length, and direction of hydraulic fractures, (**Economides and Nolte, 2000)**. Also, Vs could be applied in seismic technology used for reservoir characterization, (**Castagna, 1985)**.
Many research efforts have been made in investigating empirical relationships to estimate Vs prediction in previous decades, such as given by (**Carroll, 1969**;**Castsgna, et. al., 1993**;**Eskandari, et.al., 2004**;**Brocher, 2005**;**Ameen, et.al., 2009; Al-Kattan, 2015)**. All these Vs estimation models take Vp as input. The Vs equations are given below:

Pickett, 1963 (for Limestone) $$V_s = 0.526V_p \quad (1)$$

(for Dolomite) $$V_s = 0.556V_p \quad (2)$$

Carroll, 1969 (for different rock) $$Vs = 0.756090\, Vp^{0.81846} \quad (3)$$

Castsgna, et. al., 1993 (for Limestone) $$V_s = -0.05509\, V_p^2 + 1.0168\, V_p - 1.0305 \quad 4)$$

Eskandari, et.al., 2004 (for carbonate rock) $$V_s = -0.1236\, V_p^2 + 1.6126\, V_p - 2.3057 \quad (5)$$

Brocher, 2005 (for various lithologies)

$$V_s = 0.7858 - 1.2344\, V_p + 0.7949\, V_p^2 - 0.1238V_p^3 + 0.006V_p^4 \quad (6)$$

Ameen, et.al., 2009 (for carbonate rock) $$V_s = 0.52\, V_p + 0.25251 \quad (7)$$

Al-Kattan, 2015 (for various lithologies) $$Vs = 0.699\, Vp^{0.969} \quad (8)$$

However, most of previous attempts to predict the Vs of a field case consider the determination coefficient as a sufficient criterion to evaluate the accuracy of the empirical model, which may not always capture the total variation of rock independent variables.

Recentstudies have proved and shown the capability of using artificial intelligence modeling and fuzzy logic over empirical and statistical correlations to predict Vs from Vp and other well log data such as neutron porosity and bulk density as an input data, **(Zoveidavianpoor, 2017**; **Tariq, et.al., 2016**; **Bagheripour, et.al, 2015**; **Nourafkan and Ilkhchi, 2015**; **Maleki, et al., 2014**; **Tabari, et.al., 2011**; **Rajabi, et.al.,2010**; **Rezaee, et.al., 2007).**

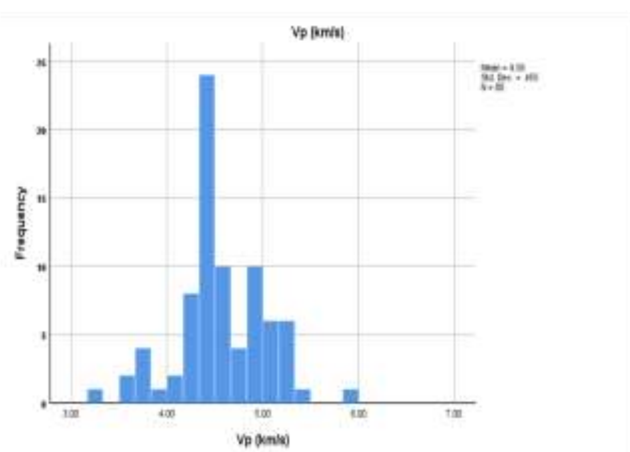
In this study, an attempt is made to predict accurate Vs for Amara oil field, this field is selective due to its drilling stability and production problem.

2. DATA ANALYSIS AND METHODOLGY:

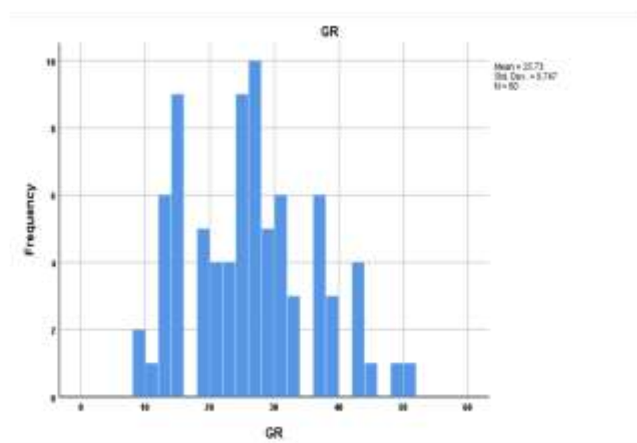
This study presents multivariate regression analysis using SPSS softwarethat is used to develop new correlation to predict shear waves and among effective petrophysical properties of a productive carbonate (limestone) section of South East Iraq (Amara field – Khasib formation). The Khasib Formation is considered one of the important reservoirs in the Misan oilfields. The development of empirical models in which the measurable well logs can provide an estimation of Vs will also be outlined.

Data analysis is used to ensure that the relationship between input data and the outcome function is logical. Sonic wave data can be determined using logs or core plugs,

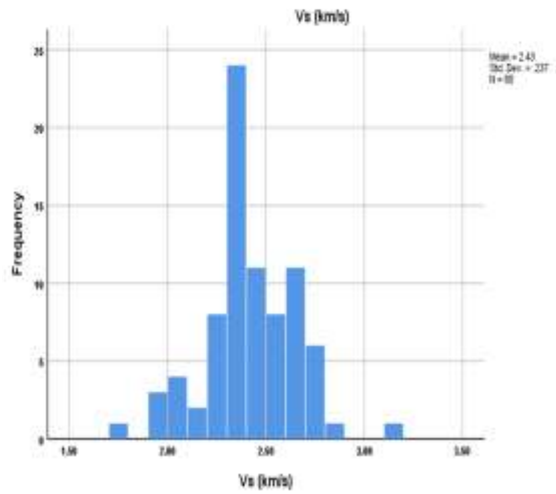
Fig. 1 shows the variation histograms with a statistical evaluation of the log dataset, which contains 80 data values for Vp, Vs, porosity, Resistivity and gamma ray, and 80 data points for bulk density. Figs 1a,1b, and 1d show the nearly symmetrical frequency histograms of Vp, Vs and GR. Whereas, these of NPHI and Rt (**Figs.1c** and **1f**) looked to be tilted to the left and frequency histogram for Bulk density (**Fig.1e**) skewed to the right.



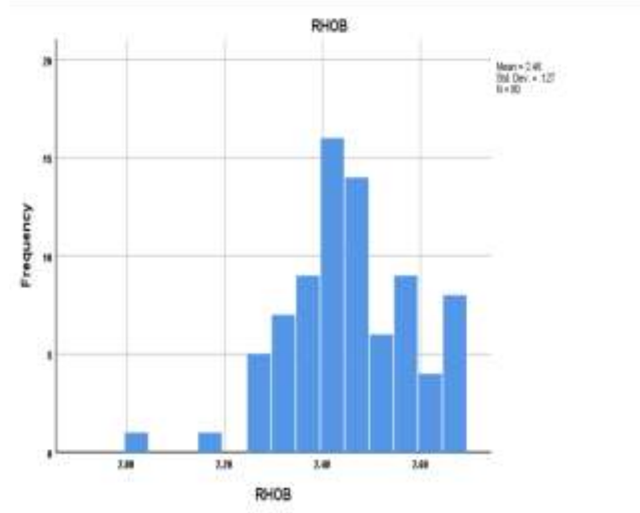
a) Vp



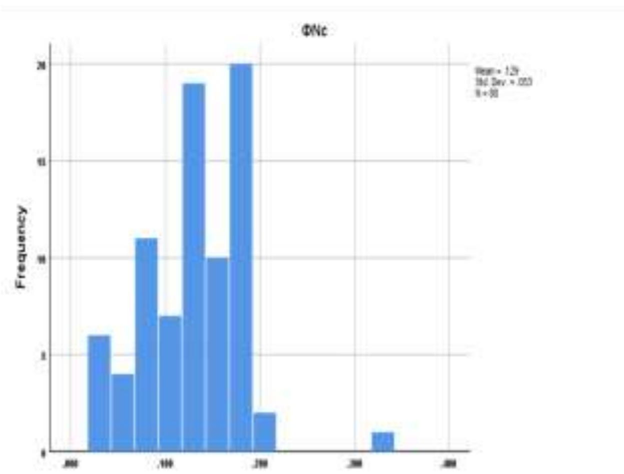
d) GR



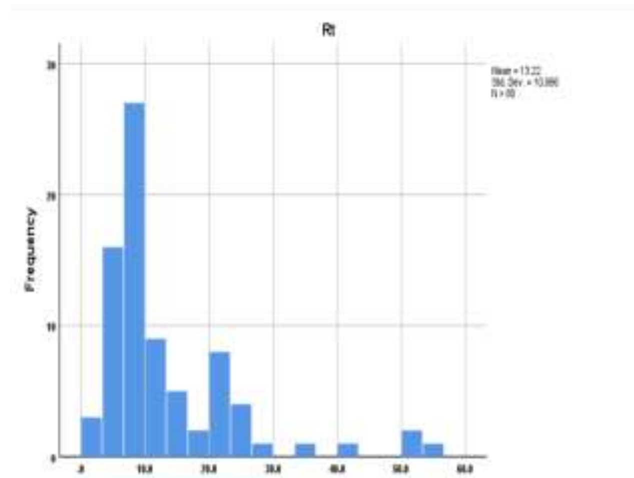
b) Vs



c) RHOB



d) NPHI



e) Rt

Figure 1. Histograms and statistical evaluations of the set data used a) compressional wave velocity b) shear wave velocity c) Neutron Porosity d) Gamma ray e) Bulk density and f) Rt for the 80 samples used in this study.

Table 1 showed the statistical summary for the data of petrophysical properties used in this study.

Table 1. Summary of statistical data used in this study.

Statistics

		Vp (km/s)	Vs (km/s)	ΦNc	RHOB	GR	Rt
N	Valid	80	80	80	80	80	80
	Missing	0	0	0	0	0	0
Mean		4.5585	2.4266	.12856	2.4561	25.73	13.225
Std. Error of Mean		.05085	.02649	.005893	.01424	1.090	1.1948
Median		4.5128	2.4033	.13200	2.4475	25.67	9.056
Mode		4.35	2.32	.120	2.41	27	7.0
Std. Deviation		.45485	.23697	.052706	.12738	9.747	10.6862
Variance		.207	.056	.003	.016	95.012	114.195
Skewness		-.063	-.080	.386	-.312	.362	2.127
Std. Error of Skewness		.269	.269	.269	.269	.269	.269
Kurtosis		.650	.655	2.009	.636	-.384	4.903
Std. Error of Kurtosis		.532	.532	.532	.532	.532	.532
Range		2.62	1.36	.310	.66	42	52.4
Minimum		3.24	1.74	.030	2.02	9	1.6
Maximum		5.86	3.10	.340	2.68	51	54.0
Sum		364.68	194.13	10.285	196.49	2058	1058.0
Percentiles	25	4.3216	2.3036	.09125	2.3767	17.77	6.914
	50	4.5128	2.4033	.13200	2.4475	25.67	9.056
	75	4.8615	2.5847	.16818	2.5500	31.00	16.500

3. SELECTION OF INDEPENDENT VARIABLES

Due to the complex effects of rock properties on (Vs) values, the order magnitude of several factors affecting Vs have been tested; while, the parameters of effective orders were used only in developing the model, keeping its significant accuracy on Vs predictions.

The selected powered parameters were (Vp, NPHI, RHOB, GR, Rt) **Fig.**(**2**&**3**) shows a good relation between Vp and Vs in well No.2 for the measured samples.

However, (**Figs. 2**, **3**, 4) illustration the effect of Vp, NPHI on Vs.

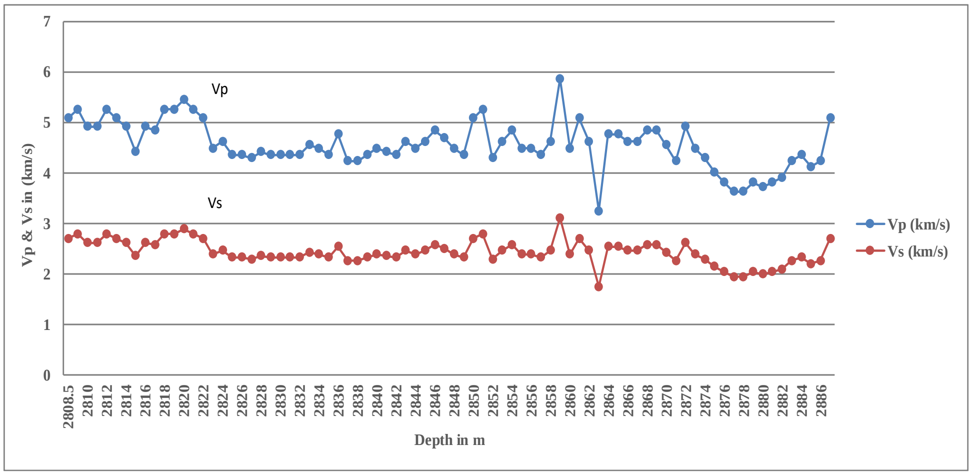


Figure 2. A good relation between Vp and Vs in well No.2 for the measured samples.

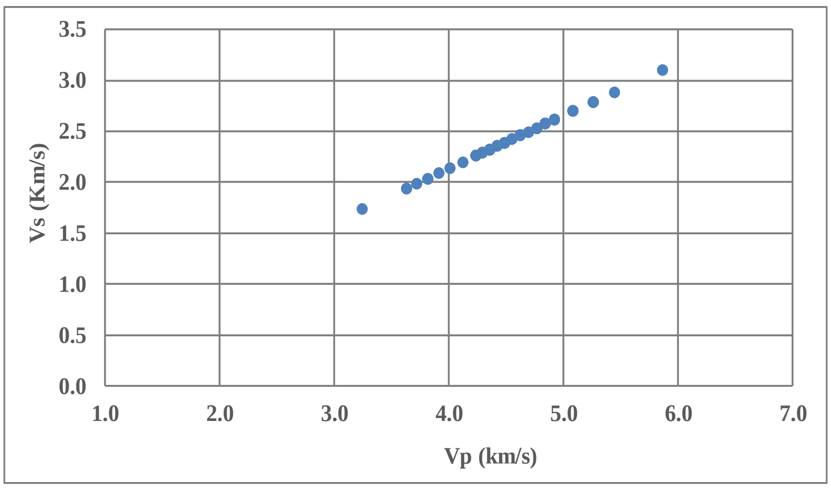


Figure 3. Vs versus Vp for all data used in the study.

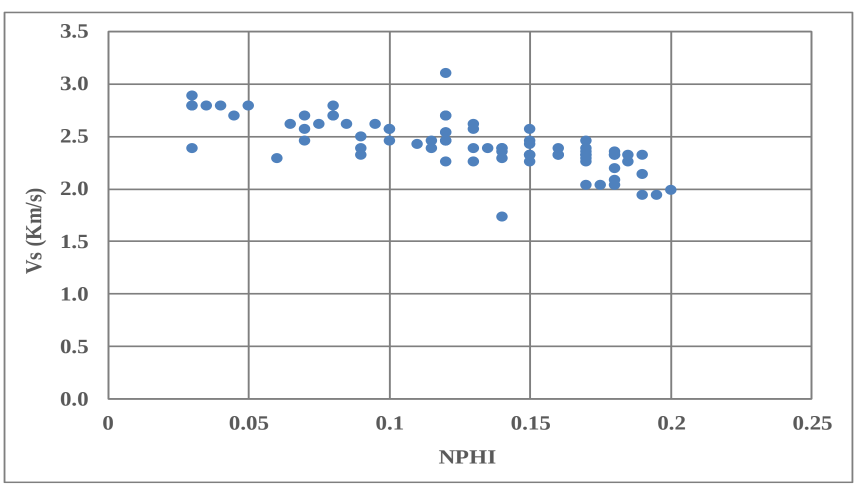


Figure 4. Effect of NPHI on Vs.

4. MODEL DEVELOPMENT

This work done in one reservoir of the South- East Iraq, Amara field – Khasib formation, where, shear wave velocity available. Dipole Sonic Imagers (DSI) run in wells 2 for measuring the shear wave velocity.

The main lithology of Amara field – Khasib formation is carbonate rocks "Limestone". Therefore, the ability of the introduced equation to predict the shear wave velocity is a check in interest reservoir.

5. USE OF RELATION BETWEEN S – WAVE VELOCITYAND P- WAVEVELOCITY

By using the Simple regression, the calculated Vs can be described as a linear model with Vp as shown in Eq. (9):

$$V_s = aV_p + b \tag{9}$$

So as, Statistical method was used to obtain an equation to calculate Vs with better correlation coefficient. At first, only Vp from sonic log was used as input data. In this way the best equation is as follow:

$$V_s = 0.5198\ V_p + 0.0574 \tag{10}$$

UsingEq. 10, the shear wave velocity has been predicted and compared with the real values of shear wave velocity as shown in **Fig.5**. **Eq. 10** has one input parameter (Vp) and R^2 for this equation is approximately 1.

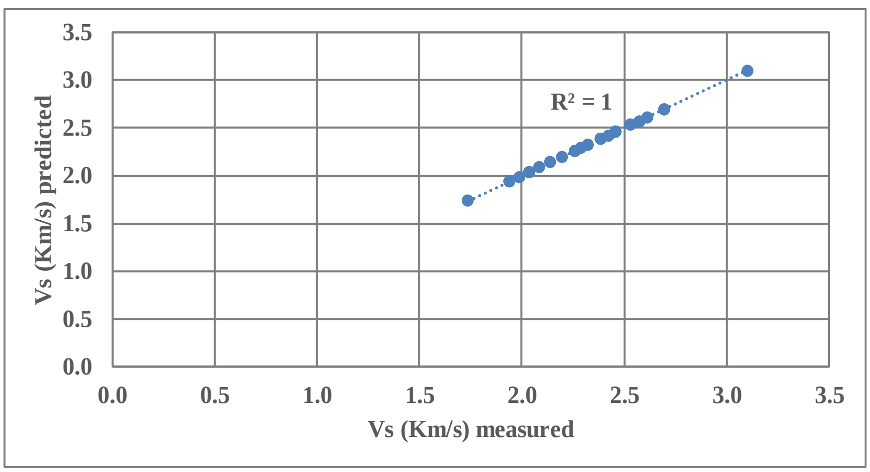


Figure 5. The relation between measured and predicted Vs in AM-2 using Eq. 10.

6. MULTIPLE REGRESSION METHOD

Regression analysis is a statistics process used to develop a mathematical correlation for determinate the unknown variables based on known variables, **(Pallant, 2013, Salal and Khudair, 2019)**. In this study, multiple regression method in SPSS software was used to predict Vs from well logs data, such as, NPHI, RHOB, GR, Rt and P- wave velocity. So that, first, investigate the relation between shear wave velocity and input parameters (NPHI, RHOB, GR, RT and Vp). Then, find the coefficients equation (a, b, c, d, e and f) in follow equation:

$$\mathrm{Vs} = \mathrm{a} + \mathrm{b} * \mathrm{Vp} + \mathrm{c} * \mathrm{NPHI} + \mathrm{d} * \mathrm{RHOB} + \mathrm{e} * \mathrm{GR} + \mathrm{f} * \mathrm{R_t} \quad (11)$$

Where, NPHI is neutron porosity expressed as a fraction, RHOB is bulk density in gm/cc, Vp and Vs are compressional and shear wave velocity, respectively in km/s, GR in API and Rt true formation resistivity in ohm.m. In multiple regression model, the use of available wells data could be useable in other wells.

The magnitude of the input variables affecting on Vs are given by their degree of contribution to the Vs, which is determined by the multivariate regression analysis. Contribution factors are (0.05, 0.520, 0.003, 0.0001, 4.401E-6, and -9.114E-6 respectively.). It can be seen that the essential affecting variables in the presented correlation are the Vp, NPHI, and RHOB that play significant roles in Vs accuracy. The weakest variables are GR and true formation resistivity, which means that they must be taken out of the model. The new model was fitted again and the following equation was obtained:

$$\mathrm{Vs} = \mathrm{a0} + \mathrm{b} * \mathrm{Vp} + \mathrm{c} * \mathrm{NPHI} + \mathrm{d} * \mathrm{RHOB} \quad (12)$$

Eq. 12 became as:

$$V_s = 0.055 + 0.52\, V_p + 0.002\, NPHI + 0.0001\, RHOB \quad (13)$$

The suggested equation could beas follow:

$$V_s = a + b * V_p + c * NPHI + d * (NPHI + e)^2 + f * \rho\mathrm{bc} + \mathrm{g} * (\rho\mathrm{bc} + \mathrm{h})^2 \quad (14)$$

The statistical process made by SPSS software, shows that Eq. (14) can be written using the coefficients of dependent parameters as follow:

$$\mathrm{Vs} = 0.093 + 0.520\,\mathrm{Vp} - 0.092\,\mathrm{NPHI} - 0.083\,(\mathrm{NPHI} - 0.672)^2 + 0.001\,\rho\mathrm{bc} - 0.0002(\rho\mathrm{bc} + 1.273)^2 \quad (15)$$

Where Vs and Vp in (km/s).

7. ERROR ANALYSIS

Two criteria were used to evaluate the accuracy of this correlation compared to five correlations. These criteria are, **(AbdulMajeed, 2014):**

a. The average absolute relative error, Eq.16:

$$AARE = \frac{1}{N}\sum_{i=1}^{N}\left[\left|\frac{X_{measured\,(i)} - X_{calculated\,(i)}}{X_{measured\,(i)}}\right|\right] * 100\% \quad (16)$$

b. The standard deviation error given by Eq. 17:

$$SD = \sqrt{\left(\frac{1}{N-1}\sum_{i=1}^{N}\left[\,\left|\frac{X_{measured\,(i)}-X_{calculated\,(i)}}{X_{measured\,(i)}}\right|\,\right]-AARE\right)^{2}} \tag{17}$$

8. PRESENT WORK APPLICATIONS

The estimated shear wave velocity using the model given in Eq.15 has been compared with the actual field data and other five well known correlations available in the literature**, (Pickett, 1963**; **Carroll, 1969**; **Brocher, 2005**; **Ameen, et.al., 2009**; **Al-Kattan, 2015)** as shown in **Fig. 6.**

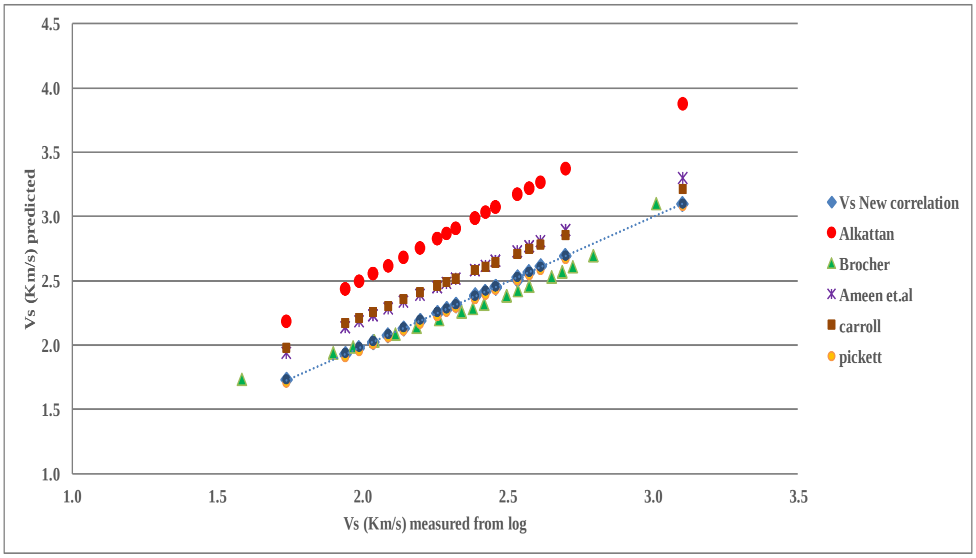


Figure 6. Comparison between new correlation (Eq. 15) and other correlation with the actual data for AM-2.

9. RESULTS AND DISCUSSION

Estimated Vs using the Eq. 18 shows excellent match with measured Vs (**Fig. 7**) with R^2 about 0.9997. **Fig.8** presents the computed shear wave velocity using Eq. 15and core shear wave velocity versus depth for AM-2. Multiple regression method presents robust correlation to predict shear wave velocity from well log data. The multiple regressions of the presented variablesshow a strong correlation among (Vs) values predicted from well logging data.

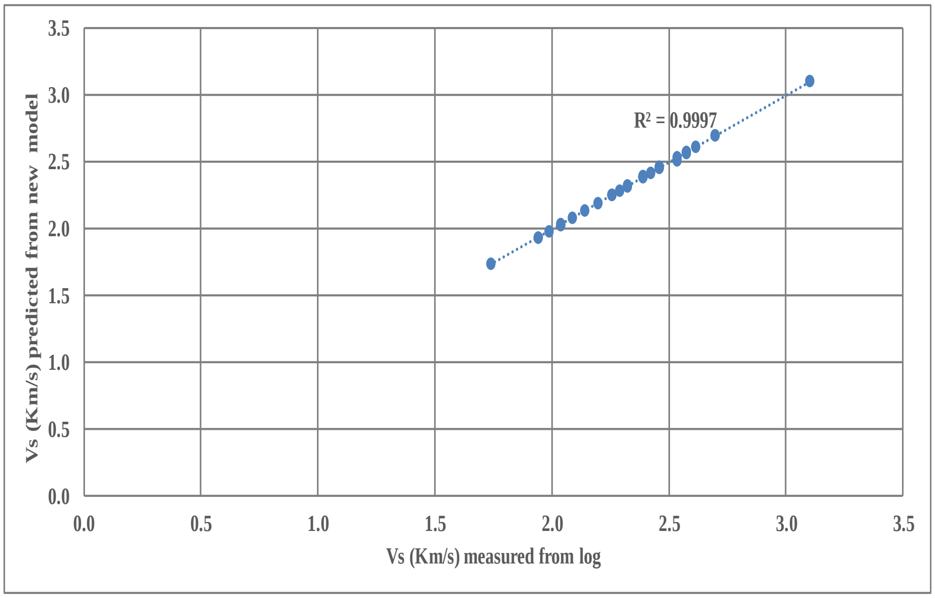


Figure 7. Plots of predicted Vs using Eq. 15 versus measured Vs from log.

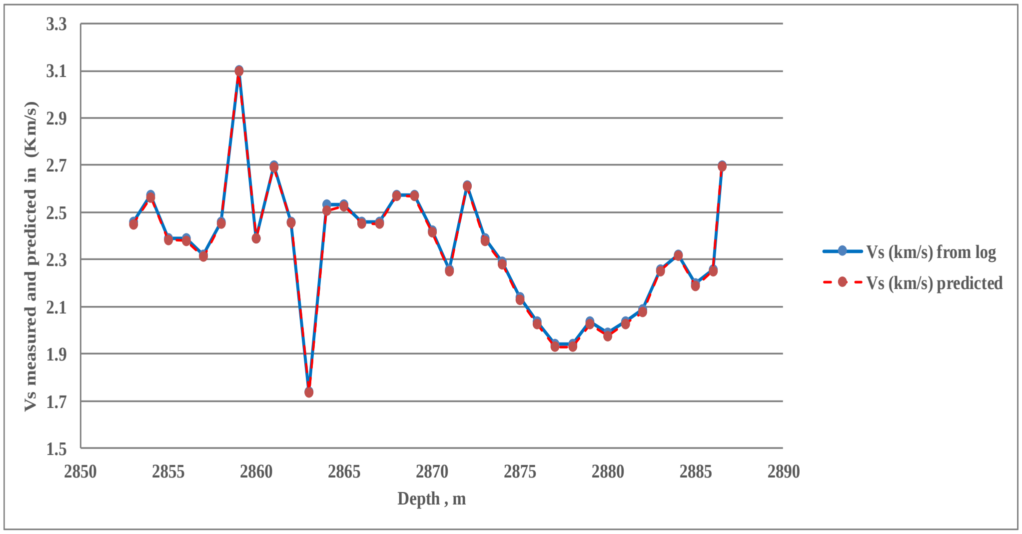


Figure 8. Measured and predicted Vs using Multivariate Regression Eq. (Eq. 15).

The results show that statistical method performs better estimates than empirical models, which can be used only to obtain an order of magnitude for shear wave velocity.

Checking the relation between the output parameter (Vs) and input parameters (RHOB, NPHI and Vp), shear wave velocity predicted in well Am-3. **Fig. 9**shows the relation between measured and predicted S-wave velocity values in well Am-3.

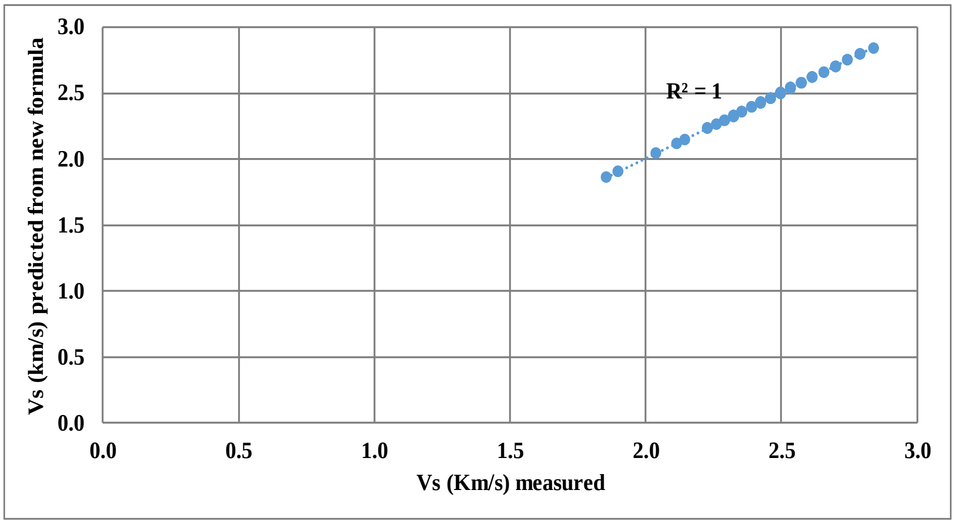


Figure 9. Plots of predicted Vs using Eq. 15 versus measured Vs from log for well Am-3.

Fig. 10 shows that the new correlation provides the most accurate results than the other correlations. It gives (0.01092%) standard deviation error compared with the other correlations which give at least double standard deviation error. While the new correlation gives also lower average absolute relative error than the other correlations as shown in **Fig. 11**. Notice that the present model works for various reservoir conditions.

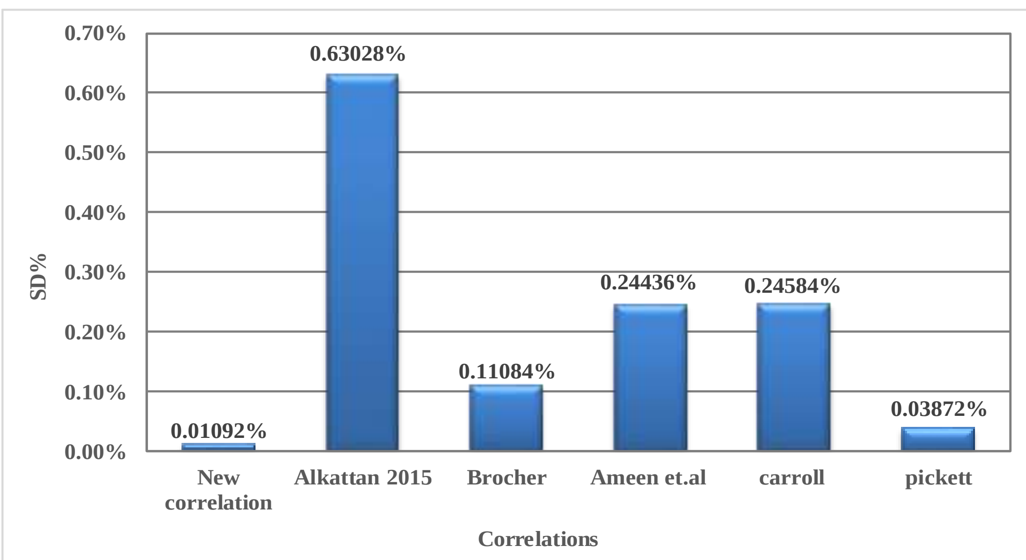


Figure 10 . SD% for the new and the other five correlations for Am-2.

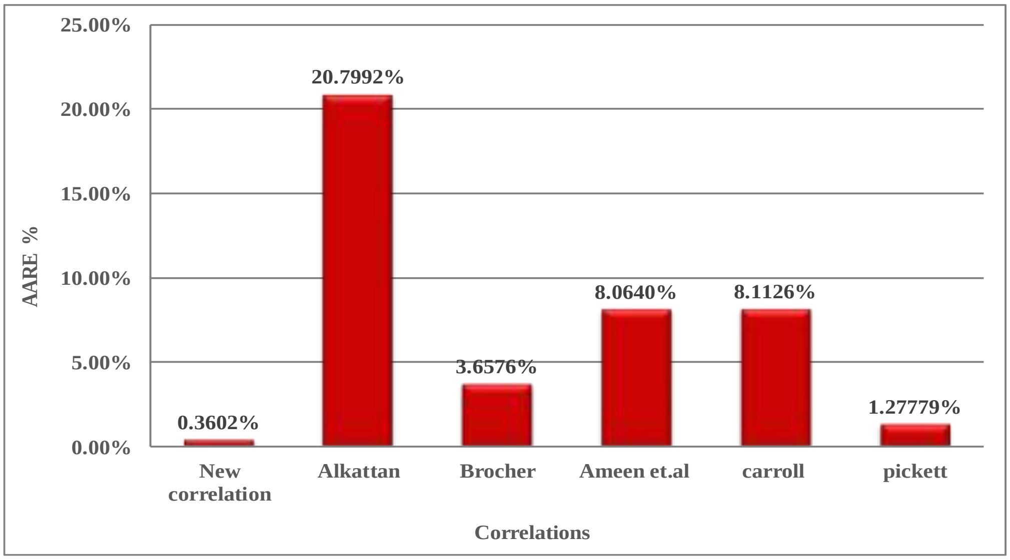


Figure 11. AARE % for the new and the other five correlations for Am-2.

10. CONCLUSIONS

1- Presents more accurate correlation to estimate shear wave velocity in Khasib reservoir Eastern South of Iraq Amara oil field using conventional well log data.
2- It is validated that well logging data are useable to predict the shear wave velocity, due to continuous and actual values of these parameters.

3- The sonic log is a major input data of regression. It is observed that the most important variable to this regression, which considers as intrinsic properties of rock such as the P-wave velocity (Vp), NPHI, and RHOB that play significant roles in the statistical model.

4- It has been clearly demonstrated that the shear wave velocity can be estimated from P-wave velocity, porosity and density if the dipole sonic log is not available.

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11. NOMENCLATURE

Vp : compressional wave velocity.
Vs : shear wav velocity
ρ : density in gm/cc.
GR : Gamma ray log.
NPHI : Neutron porosity.
R_t : true formation resistivity.
a, b, c, d, e and f : the coefficients of statistical equation.
AARE : Average absolute relative error.
SD : standard deviation error.