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Prediction Rock Strength Properties for Southern Iraqi Field. Application of Petrophysical and Mechanical Properties Relationship, Using Wireline Log Data

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Abstract

Rock Strength Properties (Internal Friction Angle φ, Unconfined Compressive Strength UCS, Cohesion C_o, Tensile Strength T_o) are considered the significant parameters of geomechanics modeling affecting the rock failure criteria. Various researchers have developed rock strength for specific lithology to estimate high-accuracy value estimation without a core. Previous analyses did not account for the formation's numerous lithologies and interbedded layers. The main aim of the present study is to select which the suitable correlation to predict these properties for hole depth of formation without separating the lithology by using data from three wells along ten formations (Tanuma, Khasib, Mishrif, Rumaila, Ahmady, Maudud, Nahr Umr, Shuaiba and Zubair). The results revealed, after calibration with core test, that the Young's Modulus correlations are the best to predict UCS with RMSE equal to (53.23 psi). Furthermore, the result showed using the static Young Modulus as an input parameter in predicting UCS gives closer result to the laboratory test than using a sonic log. In this study, it was found that many of the previous equations were developed for only one type of rock and tend to generalize poorly to the broader database. This study further offers a more precise prediction of rock strength, hence improving the forecasting of operational strategies and the planning of hydraulic fracturing locations in oil well development. This is particularly beneficial in cases when geomechanical analysis must be conducted in the absence of core samples. Finally, the formation's strength and stability surrounding the wellbore may be inferred from the projected continuous rock mechanical profile.

Keywords: Unconfined Compressive Strength, Internal Friction Angle, Lithology, Cohesion.

التنبؤ بخواص قوة الصخور في حقل جنوب العراق، تطبيق العلاقة بين الخواص البتروفيزيائية والميكانيكية باستخدام بيانات مجسات الآبار

الخلاصة:

تعتبر خصائص قوة الصخور (زاوية الاحتكاك الداخلي φ، قوة الضغط غير المحصورة UCS، قوة التماسك Co، قوة الشد To) من المعلمات المهمة لنمذجة الجيوميكانيك التي تؤثر على معايير فشل الصخور. طور العديد من الباحثين قوة الصخور لخصائص صخرية محددة لتقدير قيمة عالية الدقة بدون اللباب الصخري. لم تأخذ التحليلات السابقة في الاعتبار العديد من خصائص الصخور والطبقات المتداخلة للتكوين. الهدف الرئيسي من الدراسة الحالية هو اختيار الارتباط المناسب للتنبؤ بهذه الخصائص للعمق الكلي للتكوين دون الفصل بين الصخور المختلفه باستخدام بيانات من ثلاث آبار على طول عشر تشكيلات (تنومة، خصيب، مشرف، رميلة، أحمدي، مودود، نهر عمر، شعيبة والزبير). كشفت النتائج، بعد المعايرة باختبار اللباب، أن ارتباطات معامل يونغ هي الأفضل للتنبؤ بـ قوة الانضغاط الغير محصورة مع نسبة خطأ (خطأ الذر التربيعي المتوسط) يساوي (53.23 رطل / بوصة مربع. وعلاوة على ذلك، أظهرت النتيجة أن استخدام معامل يونغ الثابت كمعامل إدخال في التنبؤ بـقوة الانضغاط الغير محصورة يعطي نتيجة أقرب إلى الفحص المختبري باستخدام بيانات المجس الصوتي. في هذه الدراسة، وجد أن العديد من المعادلات السابقة تم تطويرها لنوع واحد فقط من الصخور وتميل إلى التعميم بشكل سيئ على قاعدة البيانات الأوسع. تقدم هذه الدراسة أيضًا تنبؤًا أكثر دقة لقوة الصخور، وبالتالي تحسين التنبؤ بالاستراتيجيات التشغيلية وتخطيط مواقع التكسير الهيدروليكي في تطوير آبار النفط. وهذا مفيد بشكل خاص في الحالات التي يجب فيها إجراء تحليل جيوميكانيكي في غياب عينات اللباب الصخري. أخيرًا، يمكن استنتاج قوة التكوين واستقرار الحفرة المحيطة بالبئر من ملف تعريف الصخور الميكانيكية المستمر المتوقع.

1. Introduction

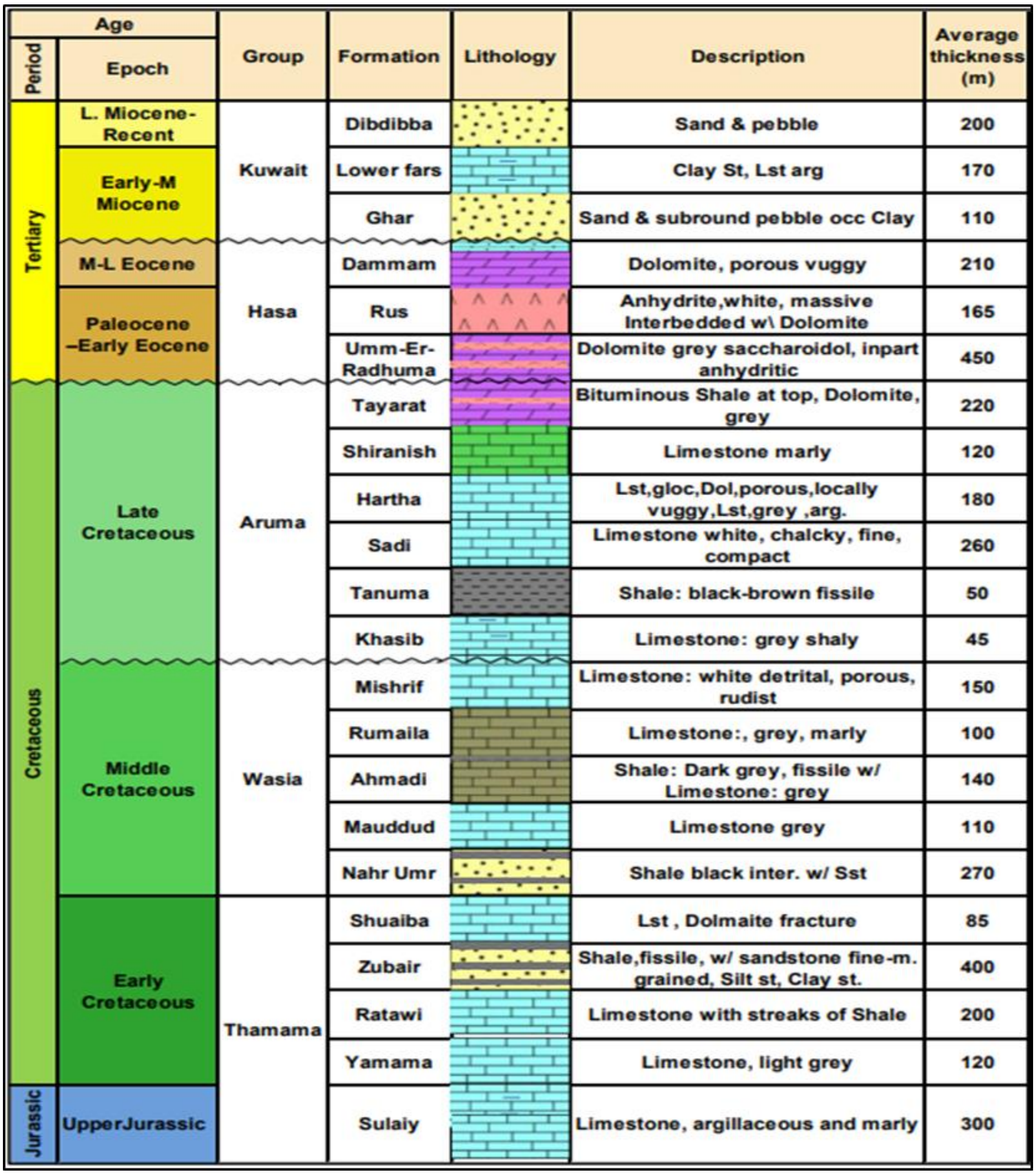
Rock elastic properties like Young's modulus and Poisson's ratio, as well as uniaxial compressive strength (UCS), are used to estimate in-situ stresses, examine wellbore stability, survey reservoir compaction, and determine the ideal mud pressure for drilling [1, 2]. According to [3], the elasticity of rocks may be evaluated with either dynamic or static techniques, while the unconfined compressive strength (UCS) of rocks can only be estimated by using static techniques and core tests. The dynamic approach allows for the measurement of compressional and shear velocities, which may be conducted either in a laboratory setting or in the field. By using this technique, it is possible to accurately calculate the elastic properties of the material. Empirical correlations have been presented to solve the problem of inferring mechanical parameters from wireline data [4-6]. These correlations estimate porosities or acoustic velocities by empirically correlating laboratory-derived rock mechanical characteristics with geophysical well logs [7]. The fact that many of the same elements that impact rock mechanical characteristics also affect porosity, velocity, and elastic moduli underlies these correlations [1]. To predict the UCS value when no core is available for laboratory testing, several notable previous publications studied the relationship between the UCS with the well log properties for specific formations and geological settings, creating different UCS equations at specific setting [8-10]. According to [11], there are a number of empirical correlations that estimate rock mechanical features using geophysical logging data. Case studies of geological features globally yielded these connections. Rock mechanical profiles may be accurately and efficiently obtained by correlating porosity with several rock mechanical characteristics. Rocks' strength and flexibility are influenced by their porosity, as stated by [12]. Rock strength characteristics may be derived from porosity wireline logs. In a study conducted by [13], the unconfined compressive strength was determined based on porosity in sedimentary basins worldwide, with a particular focus on well compacted sandstones exhibiting high cleanliness and porosity levels below 0.3. Rock porosity is shown to have a direct empirical connection with unconfined compressive strength [14]. Using laboratory research on sandstone core samples from the Germigny-sous-Coulombs structure in France, the relationship was discovered. After measuring the porosity and rock mechanics characteristics of North Sea sandstone cores, [15] found straightforward linear correlations between both, allowing them to predict the rock mechanical profile in a continuous fashion. Edimann et al., [16] used the power law function to suggest North Sea Tertiary shale transit time and UCS connection. Chang et al., [1] synthesized UCS and acoustic transit time data for worldwide, Gulf of Mexico, and Pliocene and younger shale. Onyia, [17] estimated the UCS from well logs for shale, sandstone, limestone, dolomite, granite, and mixed lithologies. (Horsrud, 2001) [16] developed the UCS estimation from compressional wave velocity for the North Sea area. Hareland and Nygaard (2007) developed the equation for calculating the UCS from sonic transit time for sandstone, shale, and mixed lithologies for onshore United Kingdom, offshore North Sea, and Norwegian Sea. The studied interval passes through complex formations (these formations contain limestone, dolomite, sandstone interbedded with beds of shale. The main advantage of the present study is to find suitable correlation to predict the Rock Strength Properties for longer well section, then, the operational cost can be decreased by minimizing the need to conduct core operations and laboratory measurements. In this study, many previous correlations were applied to the data of the three wells, and then the results are calibrated with the core data. Finally, statistical analysis done to detect the suitable correlation which get a good match with laboratory tests, and can use it to estimate the Rock Strength Properties for total depth of complex formations regardless the lithology.

2. Available Data

All data in this work are collected from Southern Iraqi oilfield. The data includes both geophysical logging and mechanical properties and focused on formations consist of complex lithology (ex: shale interbedded with sandstone or limestone) [18]. In this study, three wells are used for UCS prediction analysis, which are S1, S2 and S3. There are core tests available in Tanuma, Mishrif, Nahr Umr and Zubair formations. Table (1) summarizes the well data used in this study, Figure (1) represent the lithology description for studied wells, while Figures (2) and (3) illustrated the available logs for each well.

Table (1) Well data summary.

Well Name	Data			
	Well Logs		Static Rock Properties	Core Data
	Density Log	Sonic Log		
S1	Available	Available	Not Available	Available
S2	Available	Available	Not Available	Available
S3	Available	Available	Not Available	Available



Age		Group	Formation	Lithology	Description	Average thickness (m)
Period	Epoch					
Tertiary	L. Miocene-Recent	Kuwait	Dibdibba		Sand & pebble	200
	Early-M Miocene		Lower fars		Clay St, Lst arg	170
			Ghar		Sand & subround pebble occ Clay	110
	M-L Eocene	Hasa	Dammam		Dolomite, porous vuggy	210
	Paleocene –Early Eocene		Rus		Anhydrite,white, massive Interbedded w\ Dolomite	165
			Umm-Er-Radhuma		Dolomite grey saccharoidol, inpart anhydritic	450
Cretaceous	Late Cretaceous	Aruma	Tayarat		Bituminous Shale at top, Dolomite, grey	220
			Shiranish		Limestone marly	120
			Hartha		Lst,gloc,Dol,porous,locally vuggy,Lst,grey ,arg.	180
			Sadi		Limestone white, chalcky, fine, compact	260
			Tanuma		Shale: black-brown fissile	50
			Khasib		Limestone: grey shaly	45
	Middle Cretaceous	Wasia	Mishrif		Limestone: white detrital, porous, rudist	150
			Rumaila		Limestone:, grey, marly	100
			Ahmadi		Shale: Dark grey, fissile w/ Limestone: grey	140
			Mauddud		Limestone grey	110
			Nahr Umr		Shale black inter. w/ Sst	270
	Early Cretaceous	Thamama	Shuaiba		Lst , Dolmaite fracture	85
			Zubair		Shale,fissile, w/ sandstone fine-m. grained, Silt st, Clay st.	400
			Ratawi		Limestone with streaks of Shale	200
			Yamama		Limestone, light grey	120
Jurassic	UpperJurassic		Sulaiy		Limestone, argillaceous and marly	300

Fig. (1): Lithology description for Southern Iraqi Fields (INOC, 1979).

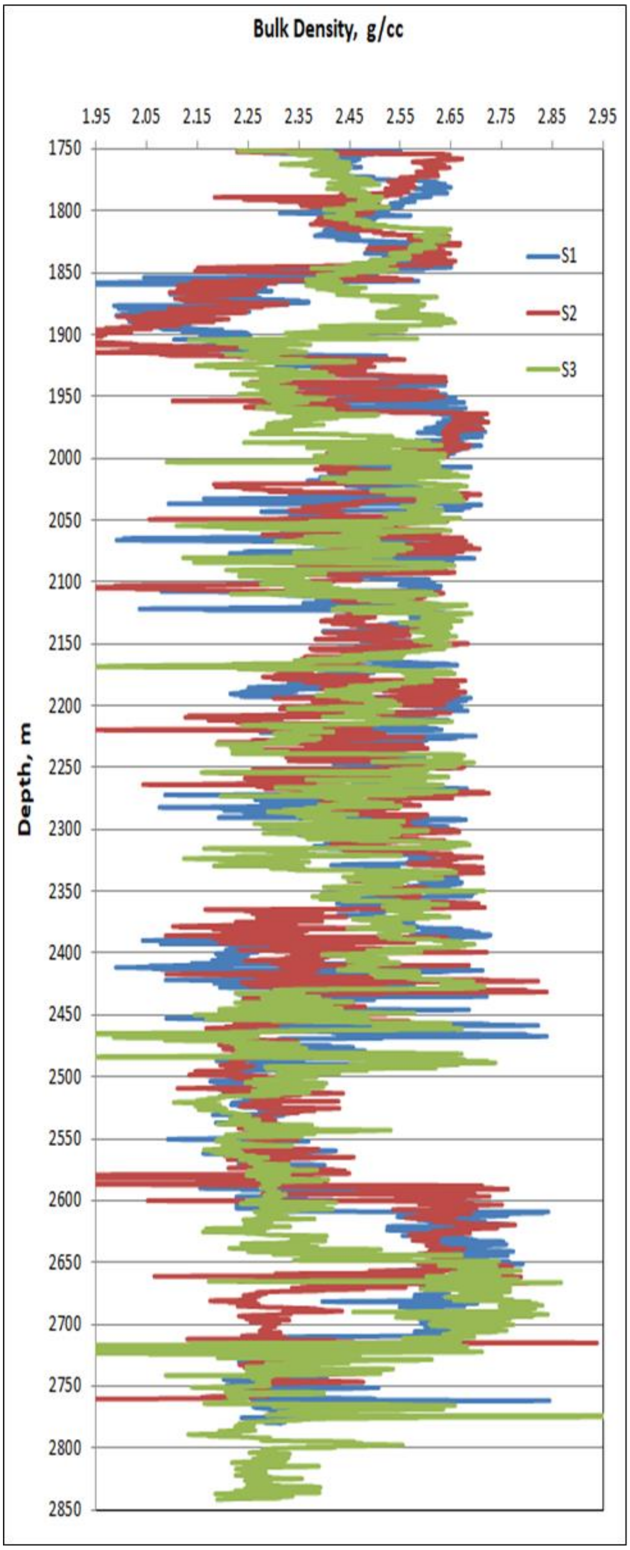


Fig. (2): Bulk density graph for studied wells.

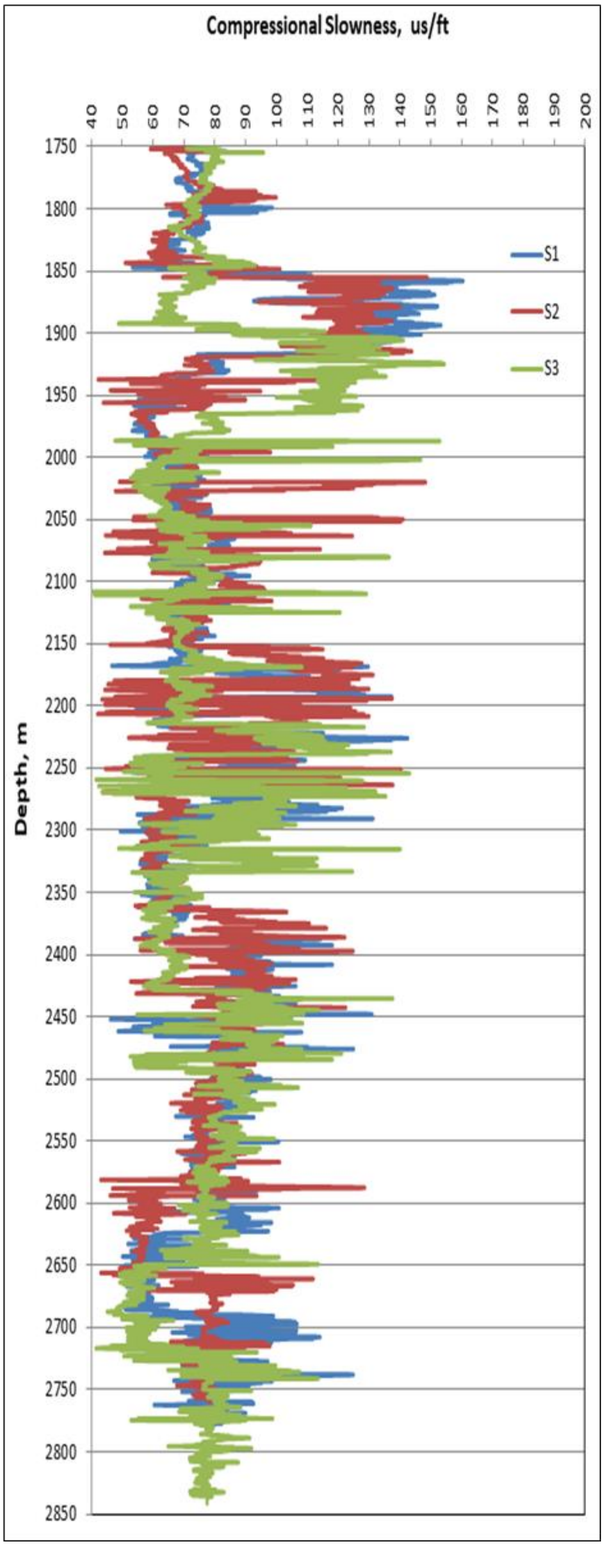
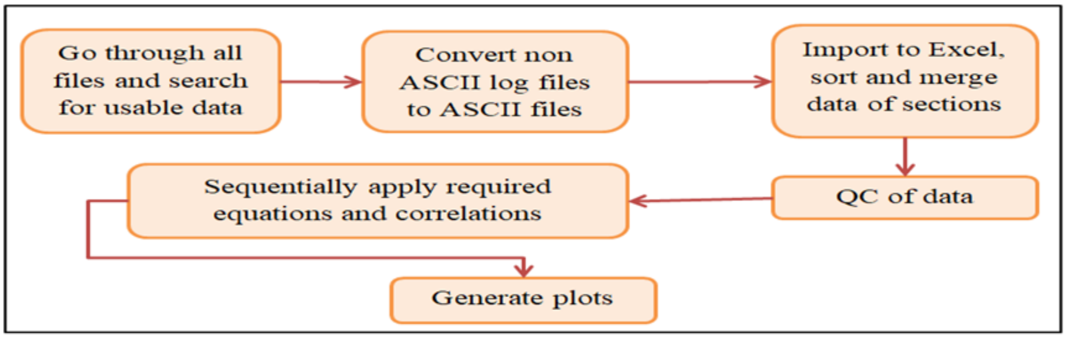


Fig. (3): Compressional Wave Velocity for studied wells.

3. Methodology

- Following the identification of all essential and usable data files, non-ASCII files were changed to ASCII files utilizing free software.
- The next step was to create a plot of the data to assess its accuracy.
- Once the log data has been loaded, rock may start doing property calculations.
- Estimate Dynamic and static Young's Modulus.
- The angle of internal friction was estimated using Equation (5).
- Several models have been investigated, including (Coates Denoo 1963, MCNally 1987, Vernic 1993, Plumb Sandstone Young Modulus 1994, Brad Ford 1996, static Young's Modulus 2002, Moos 2003 and Novel 2021) to predict UCS by using Excel program.
- The cohesion was calculated using Equation (6).
- Equation (7) is used to estimate the tensile strength.
- Calibration has been performed between the results and lab test data.
- Statistical analysis was used to detect which correlation gives a good match with core test.

Flowchart for building the model using Excel illustrated in Figure (4).



4. Result and Discussion

4.1 Determination of Dynamic and Static Young's Modulus

Young's modulus is the stiffness degree of the rock [19, 20]. Hooke's law defines the rules for the linear relationship that exists between stress (σ) and strain (ϵ)[21]. Some correlations that used to predict UCS depend on Young's Modulus, so the equations bellow are applied to predict the Young Modulus value. Figures (5) to (7) illustrate the results of Static Young's Modulus, which was calculated by Eq. 2, which appears a good match with laboratory tests.

$$E_{dyn} = \frac{9G_{dyn}K_{dyn}}{G_{dyn} + 3K_{dyn}} \tag{1}$$

$$E_{static} = 0.032 \times {E_{dyn}}^{1.632} \qquad (2)$$

Where:

$$G_{dyn} = 13474.45 \frac{\rho_b}{(\Delta t_s)^2} \qquad (3)$$

$$K_{dyn} = 13474.45 \frac{\rho_b}{(\Delta t_c)^2} - \frac{4}{3} G_{dyn} \qquad (4)$$

4.2 Determination of Internal Friction Angle

The angle of internal friction was estimated using Equation (5). This correlation maps Gamma Ray (GR) to the internal friction Angle with a linear relation, which getting the acceptable agreement to the laboratory results as shown in Figures (8) to (10).

$$\varphi = 70 - 0.417 \ \times GR \qquad (5)$$

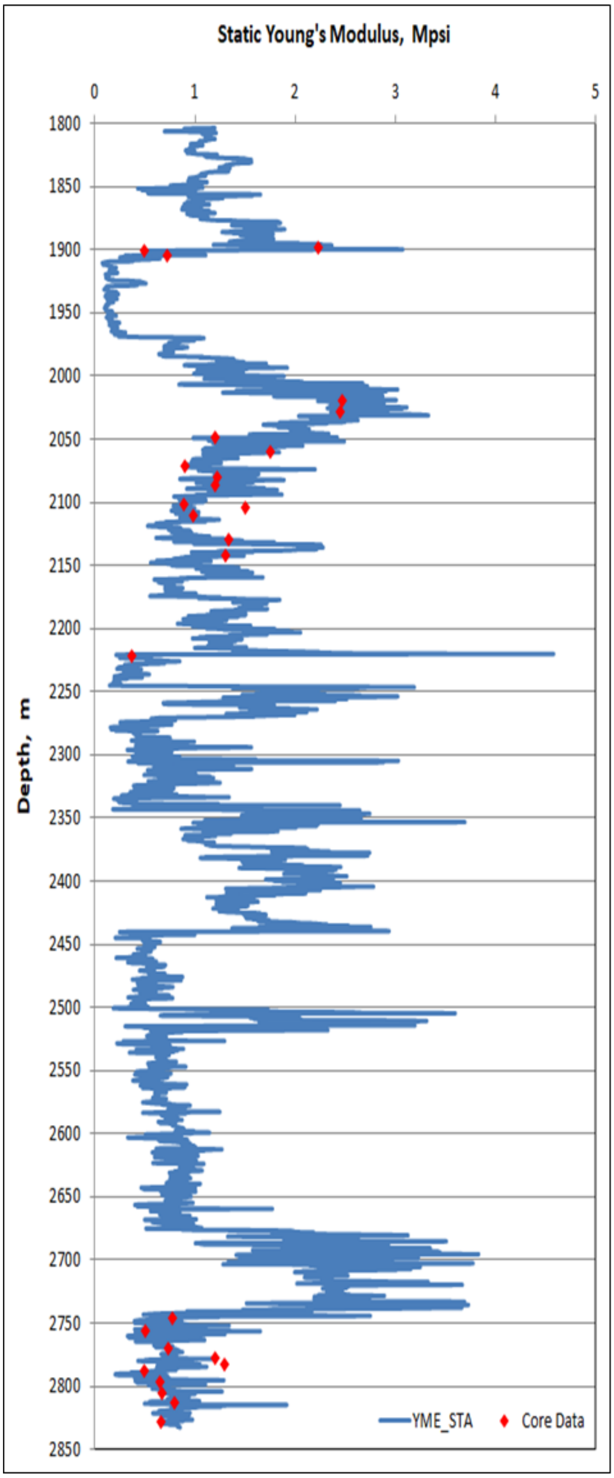


Fig. (5): Static Young Modulus for well S1.

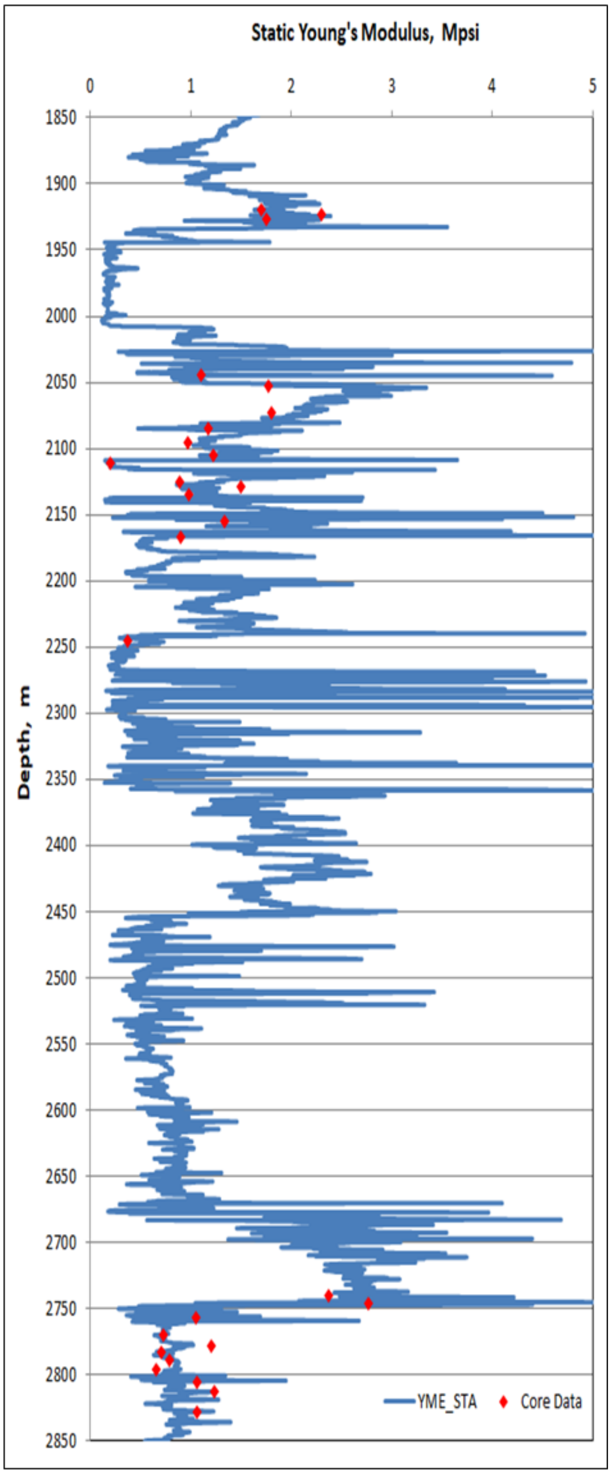
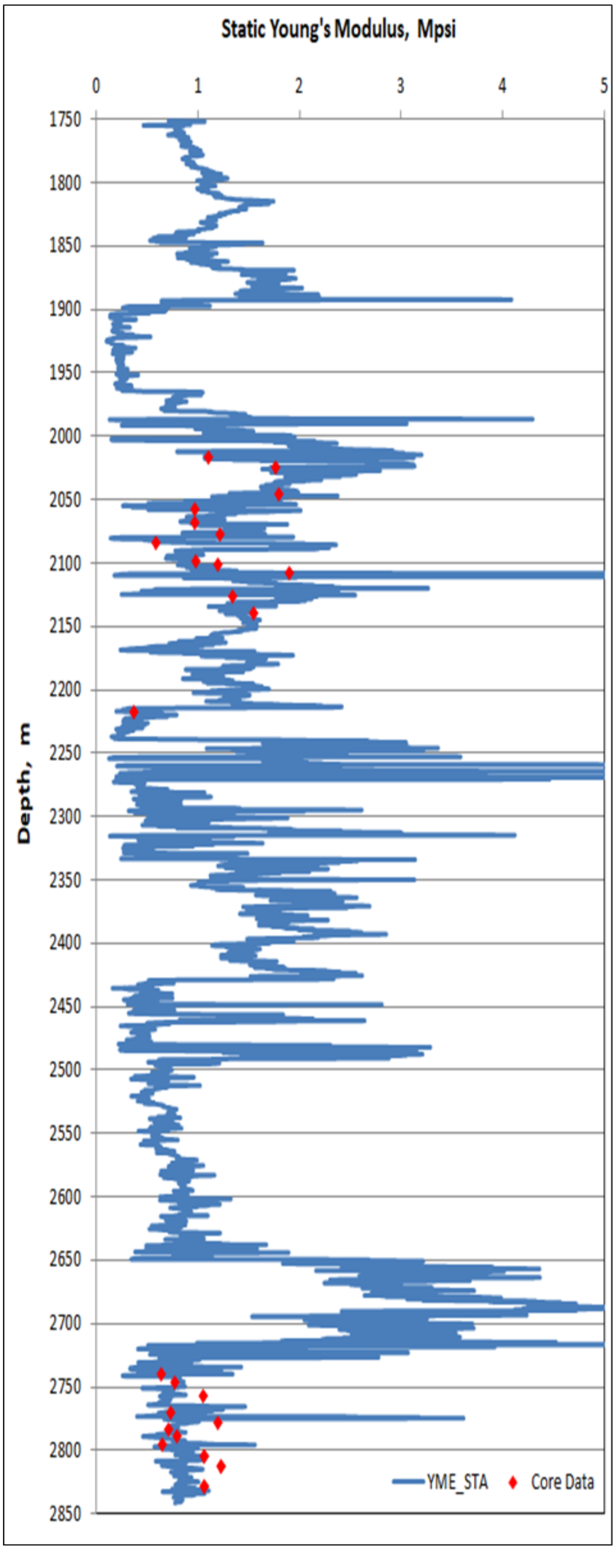


Fig. (6): Static Young Modulus for well S2.



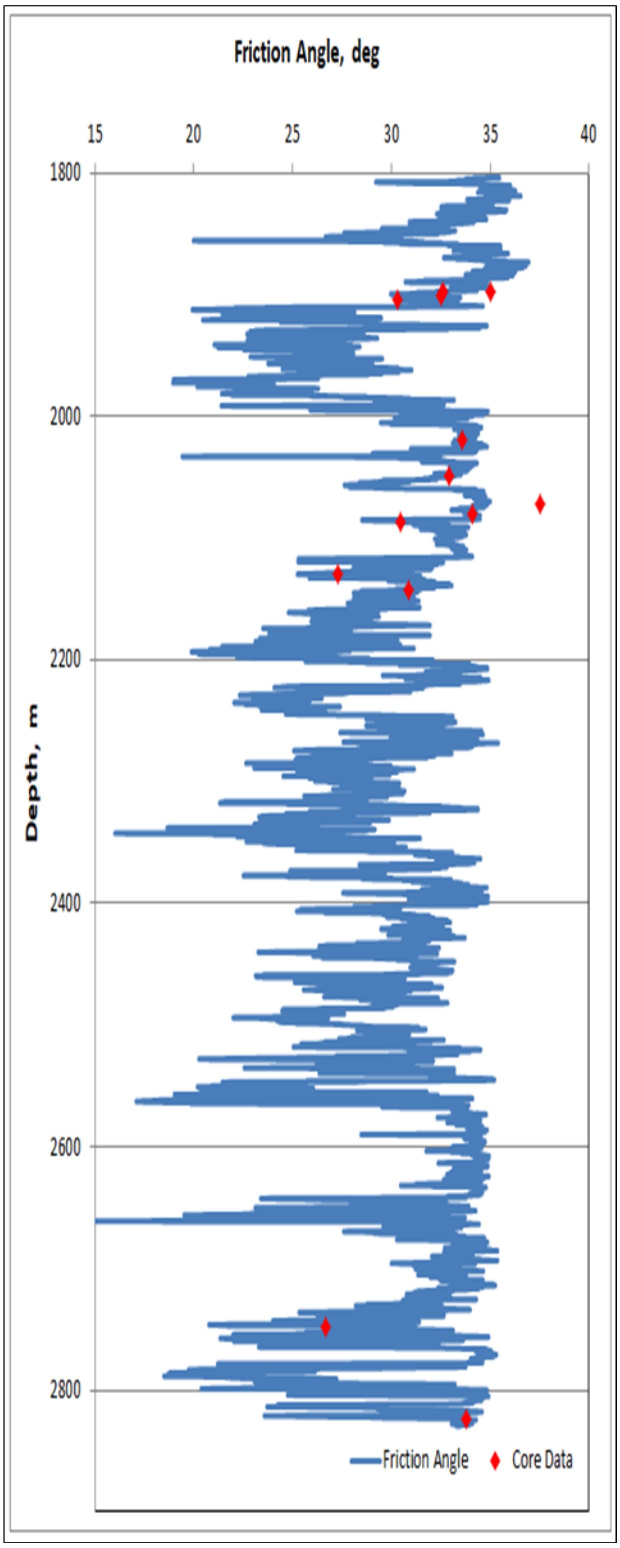
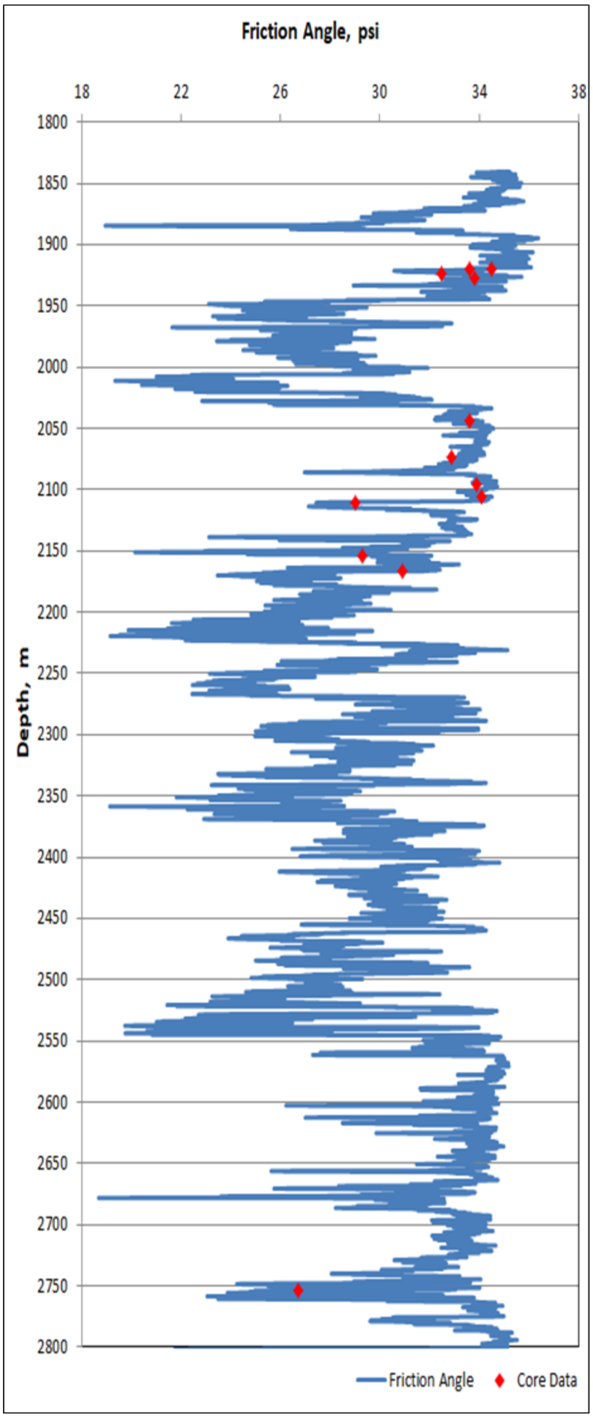


Fig. (7): Static Young Modulus for well S3.

Fig. (8): Internal Friction Angle for well S1.



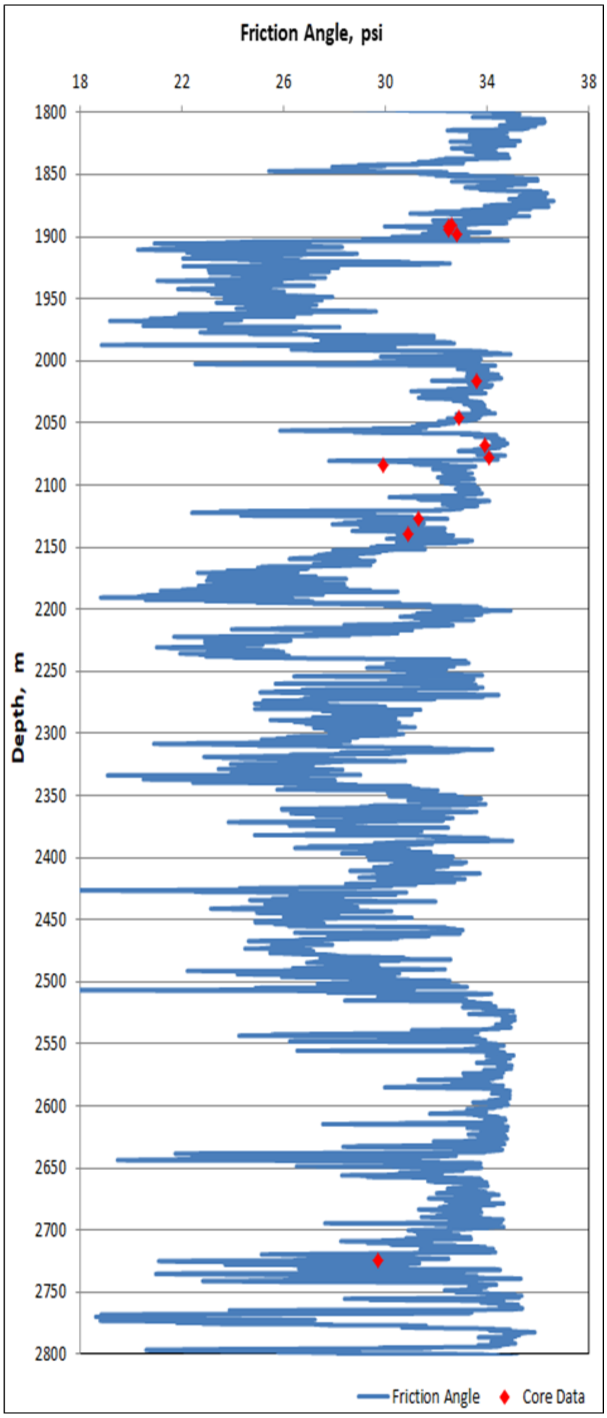


Fig. (9): Internal Friction Angle for well S2. **Fig. (10): Internal Friction Angle for well S3.**

4.3 Determination of UCS

The un-confined compressive strength significantly affects wellbore stability because it is a vigorous player to determine the failure criterion [22]. Therefore, compressive strength estimation should be accurate because it is the final word on the eventual calculations [23]. To get better results and avoid obstacles, several models have been investigated. Table (2) shows these correlations with the results of statistical analysis (RMSE), where the results showed a significant difference between Young Modulus correlation and other correlations, the reason is due to the dependence of the Young Modulus correlation on E_S and it is non- limitation by shally formations. After that the laboratory test data is compared with the results, as presented in Figures (11) to (14).

Table (2) Various published correlations to calculate the UCS.

Equation for UCS	Names of Published Correlations	Root Mean Square Error (RMSE, psi)	Remarks
$UCS = 0.0866 * \frac{E_{dyn}}{C_{dyn}}[0.008V_{sh} + 0.0045(1 - V_{sh})]$	Coates Denoo, 1963	1767.545201	
$UCS = 1200e^{(-0.036\Delta t_c)}$	McNally, 1987	6021.376747	Australia
$UCS = 1.4138 * 10^7 \Delta {t_c}^{-3}$	McNally, 1987	765.875069	Gulf Coast
$UCS = 254(1 - 2.8\emptyset)^2$	Vernik et al., 1993	5847.594145	
$UCS = (2.28 + 4.1089E_s) * 145.037$	Bradford, et al., 1998	229.3667259	
$UCS = (4.242 + E_s) * 145.037$	YME, 2002	53.23181247	
$UCS = (46.2e^{0.0247E_s}) * 145.037$	Moos, et al., 2003	4757.76922	
$UCS = 0.9616\Delta {t_c}^2 - 136.5\Delta t_c + 5002$	Novel, et al., 2021	164965.9605	Shale Gas, Lithology neglecting
$UCS = 0.2686\Delta {t_c}^2 - 50\Delta t_c + 2339$	Novel, et al., 2021	14967.9491	Shale Gas, Lithology considering
Where: $C_{dyn} = \frac{1}{K_{dyn}}$; $UCS = psi$; $E_s = GPa$; $\Delta t_c = us/ft$; $E_{dyn} = psi$; $K_{dyn} = psi$			

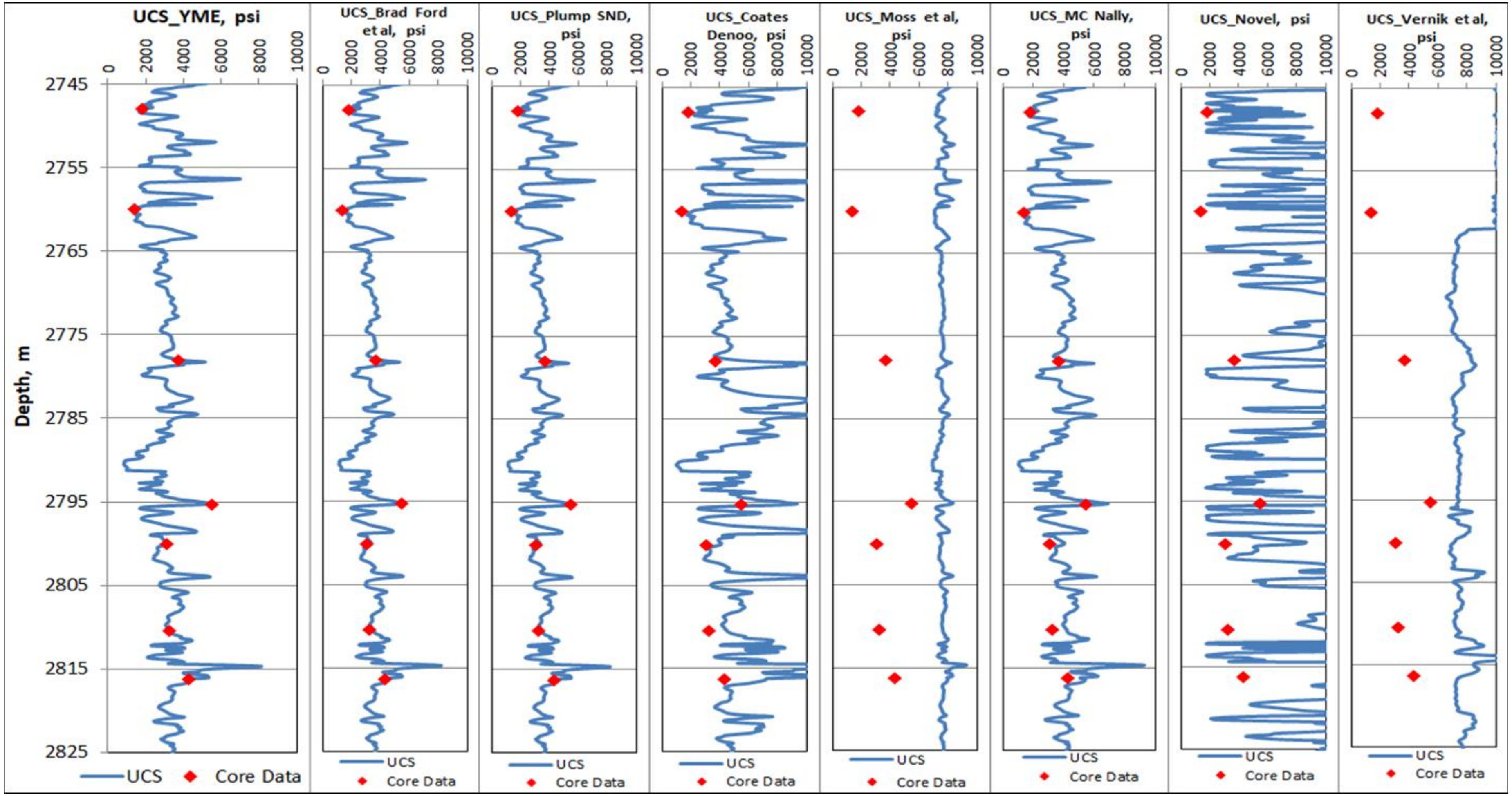


Fig. (11): Unconfined compressive strength measured by several methods for well S1

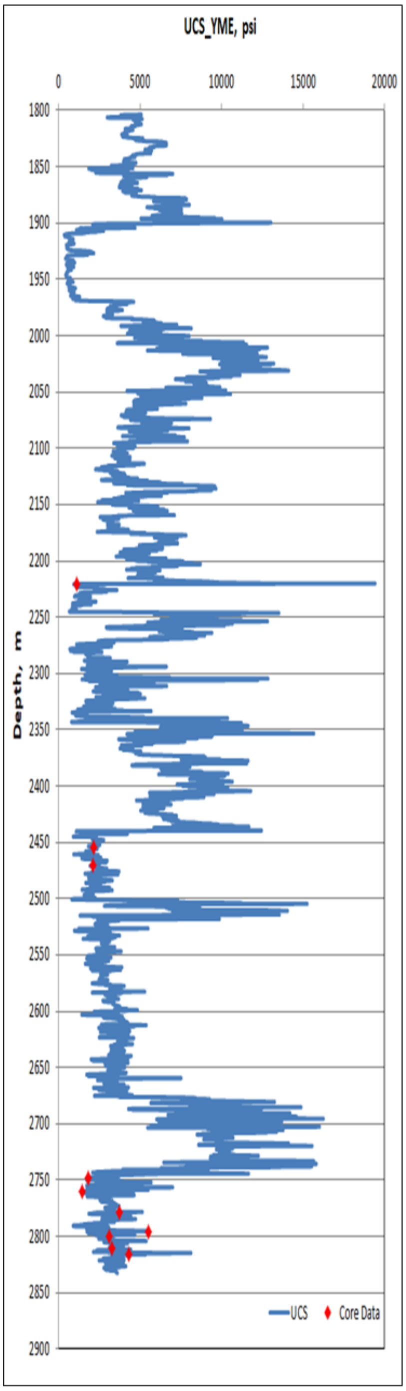


Fig. (12): UCS for well S1

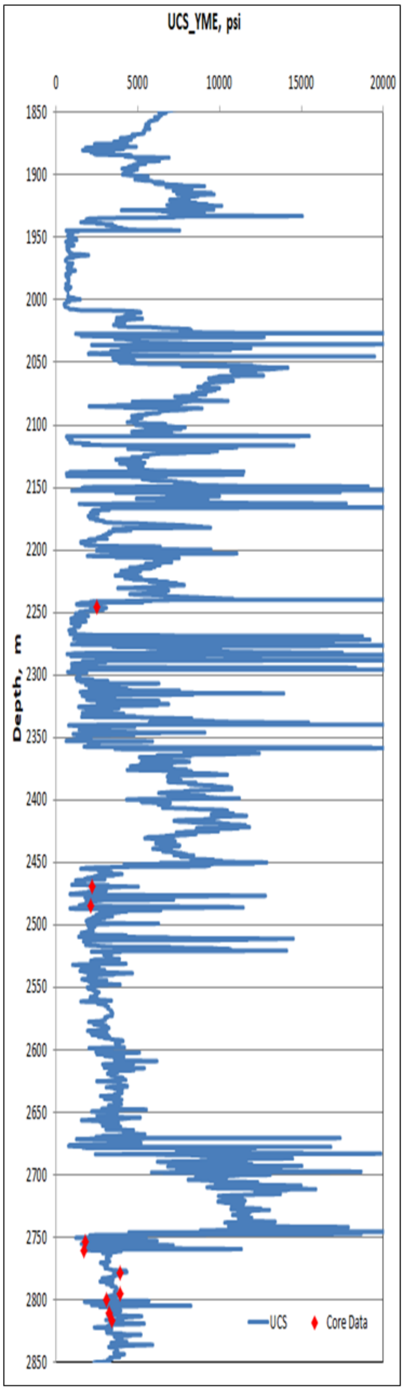


Fig. (13): UCS for well S2.

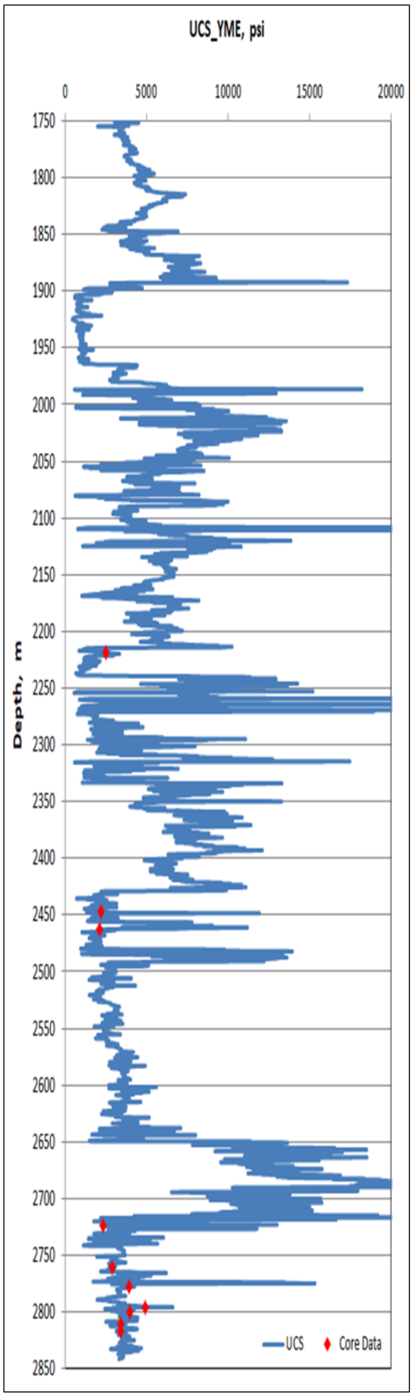


Fig. (14): UCS for well S3.

4.4 Determination of Cohesion

The ability of the rock parts to stay united with each other is called cohesive or cohesive strength. Moreover, the shear strength of the rock is cohesion when no applied normal stress [24], cohesion is predicted as:

$$C_o = \frac{UCS}{2\left[\sqrt{1+(tan\varphi)^2}+tan\varphi\right]} \quad (6)$$

The cohesion was calculated based on the unconfined compressive strength and the angle of friction using Equation (6). **Fig. 15 to 17** shows reasonable agreement between the obtained cohesion by this correlation and the laboratory point data measured along the interval of interest.

4.5 Determination of Tensile Strength

The tensile strength of rocks is one of the important parameters in evaluating the rock strength and estimating the horizontal stresses magnitudes. Rocks have relatively low tensile strength, hence failure in rocks typically shows brittle failure (breaks quickly), no plastic strains after reaching tensile strength [25]. Brazilian tests are implemented to get a tensile strength amount. For intervals with no laboratory tests, the tensile strength is considered as 10-12% of the uniaxial compressive strength [26].

$$T_o = k \times UCS \quad (7)$$

Where:

T_o: tensile strength, psi.

Equation (7) is used to estimate the tensile strength, which gave a good match with core data as shown in Figures (18) to (20).

5. Statistical Analysis

Statistical analysis was utilized to evaluate the accuracy of the predicted rock mechanical features based on the aforementioned empirical correlations (Table 3). In Figure 21, we see the RMSE (root mean square error) between the estimated values and the experimental ones.

The RMSE were calculated using Eq. 8.

$$RMSE = \sqrt{\frac{\sum(x_i - y_i)^2}{n}} \quad (8)$$

Where:

The number n denotes the total number of core-measured values, xi is the actual value, and yi is an estimate.

Figure (21) explains that (YME, 2002) gives the least error percentage, and then (Bradford, 1998, SND_RPC) comes, and then (McNally, 1987, Coates Denoo, 1963). While the error percentage increases when the (Moos, 2003, Vernik, 1993) correlations were used.

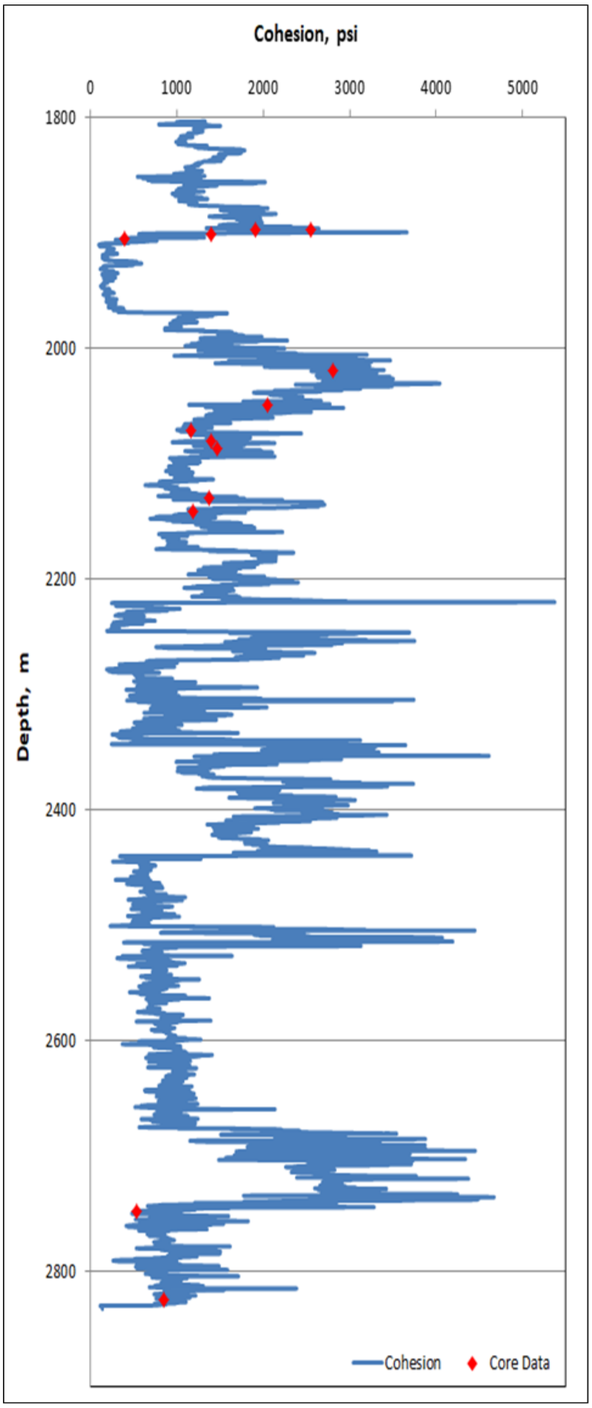


Fig. (15): Cohesion for well S1.

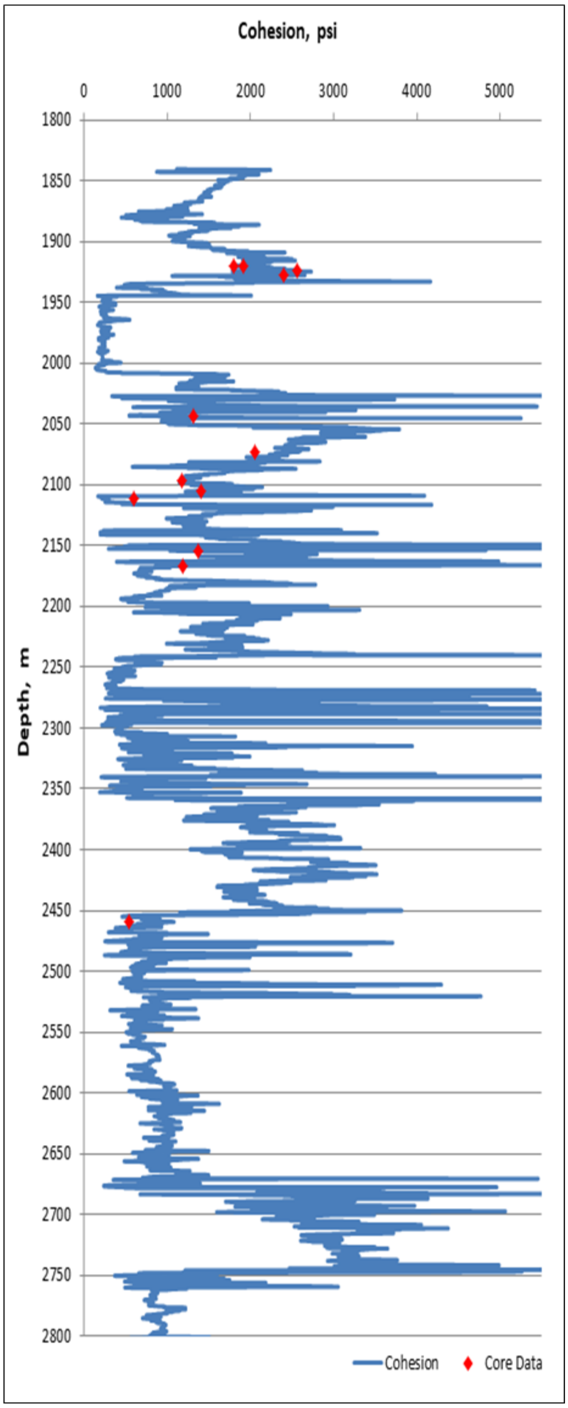


Fig. (16): Cohesion for well S2.

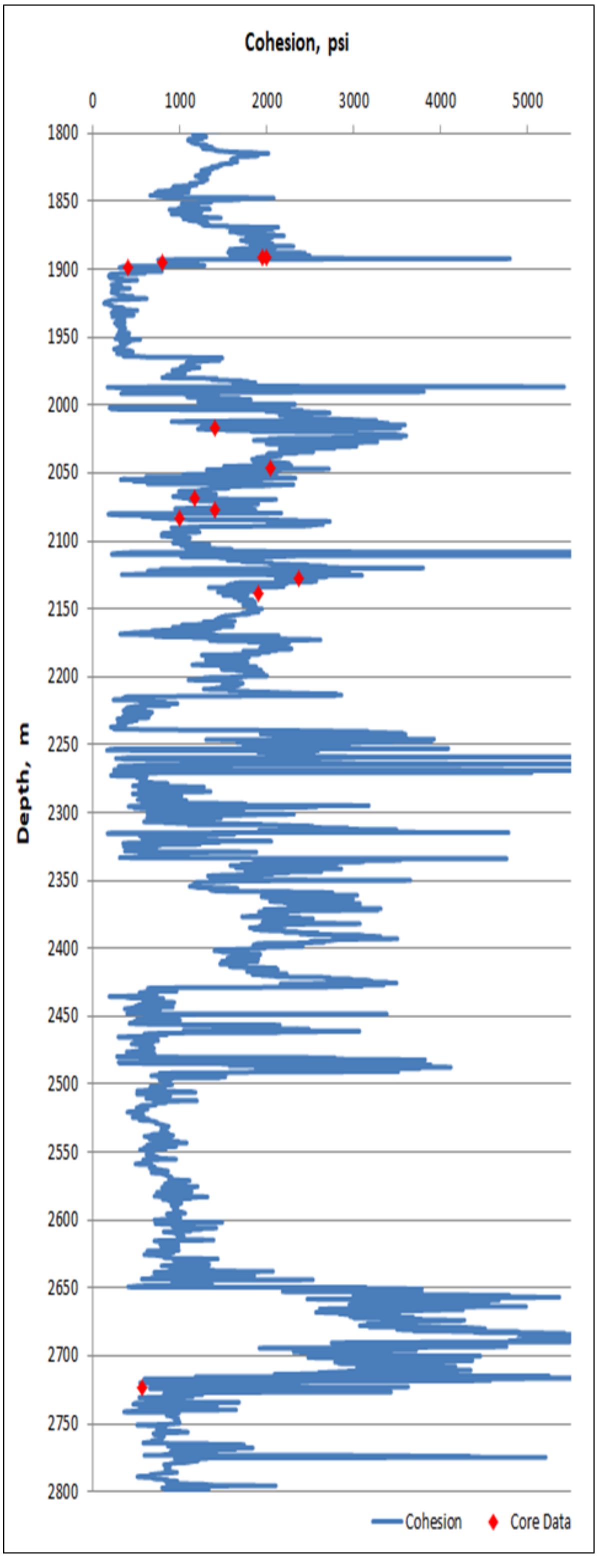


Fig. (17): Cohesion for well S3.

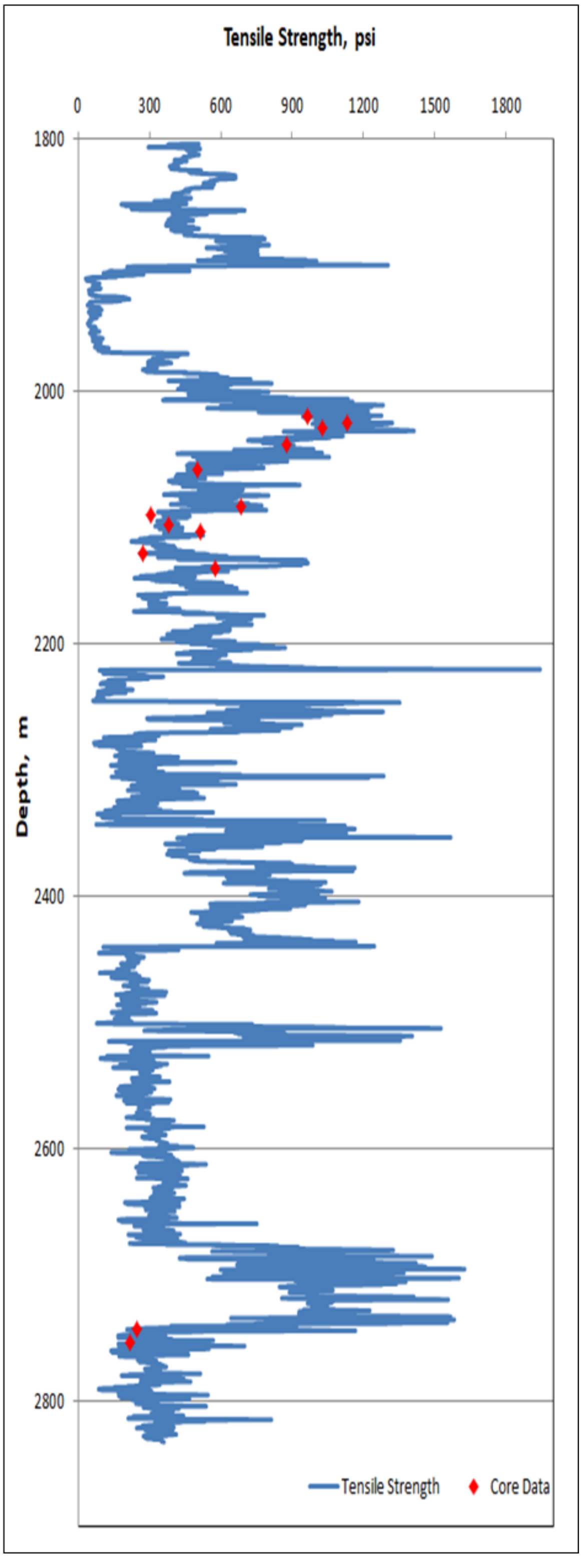


Fig. (18): Tensile Strength for well S1.

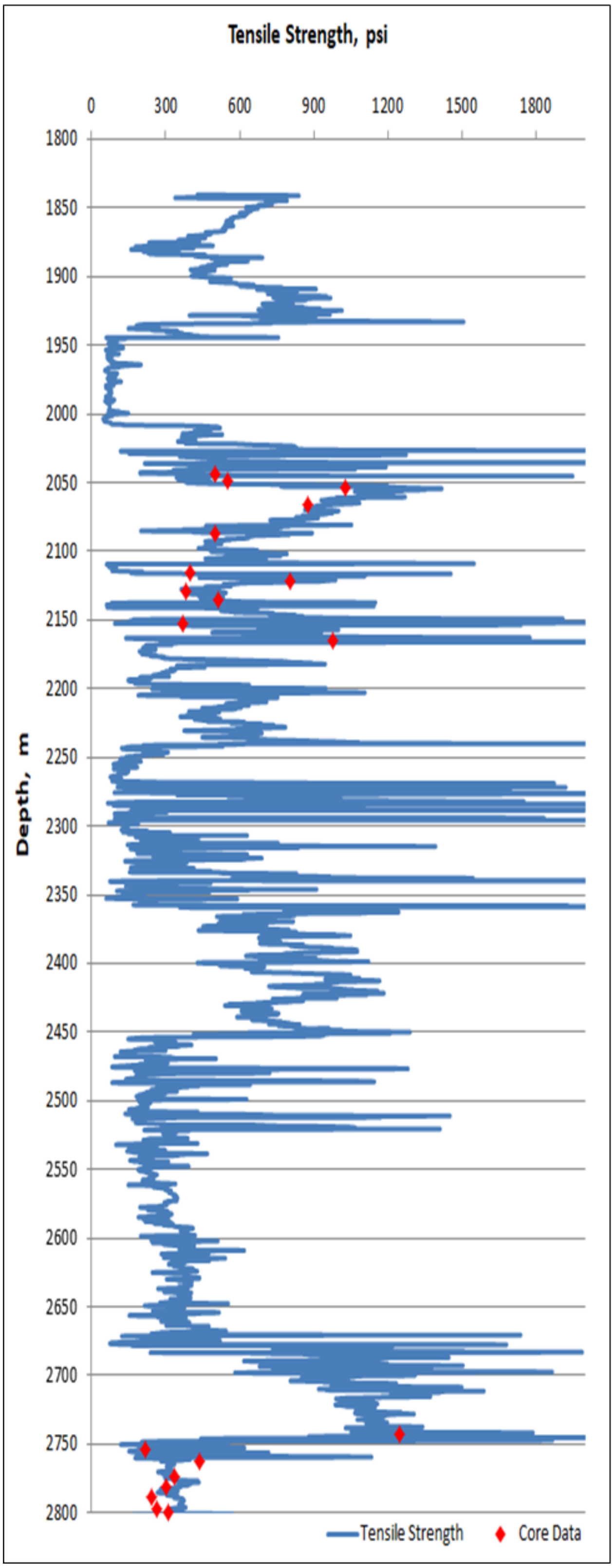


Fig. (19): Tensile Strength for well S2.

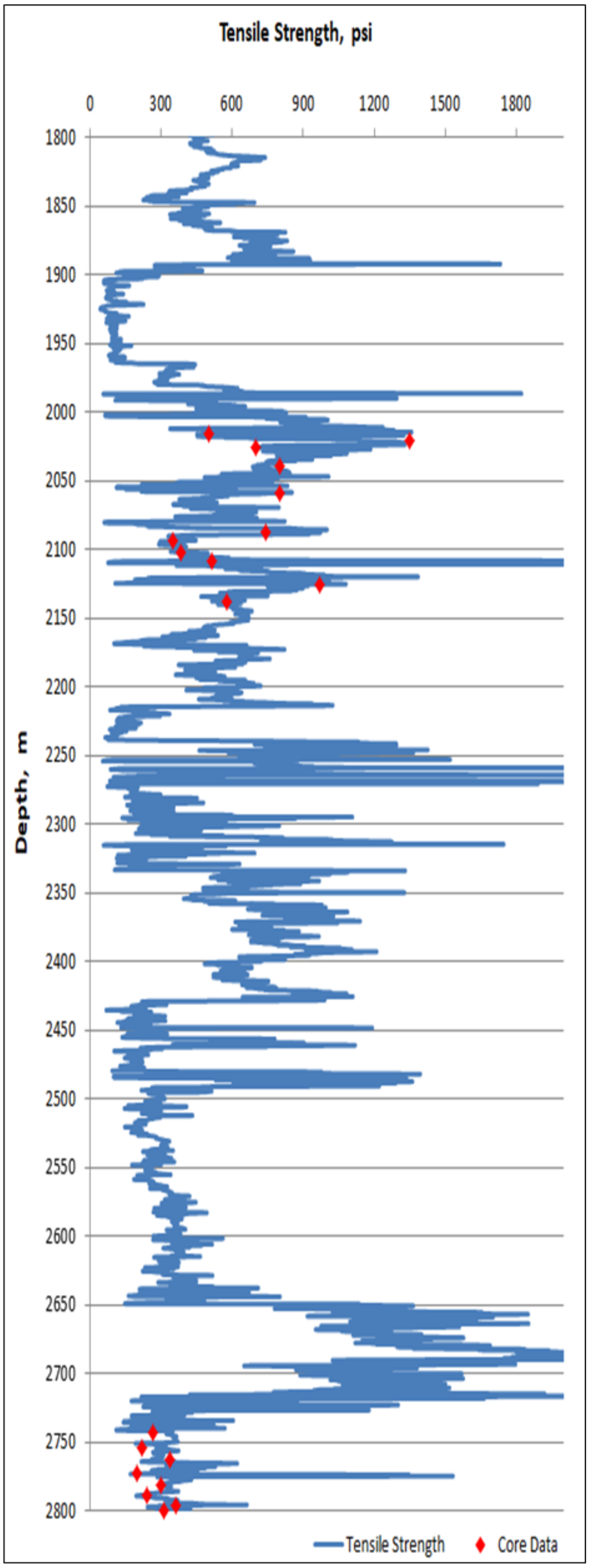


Fig. (20): Tensile Strength for well S3.

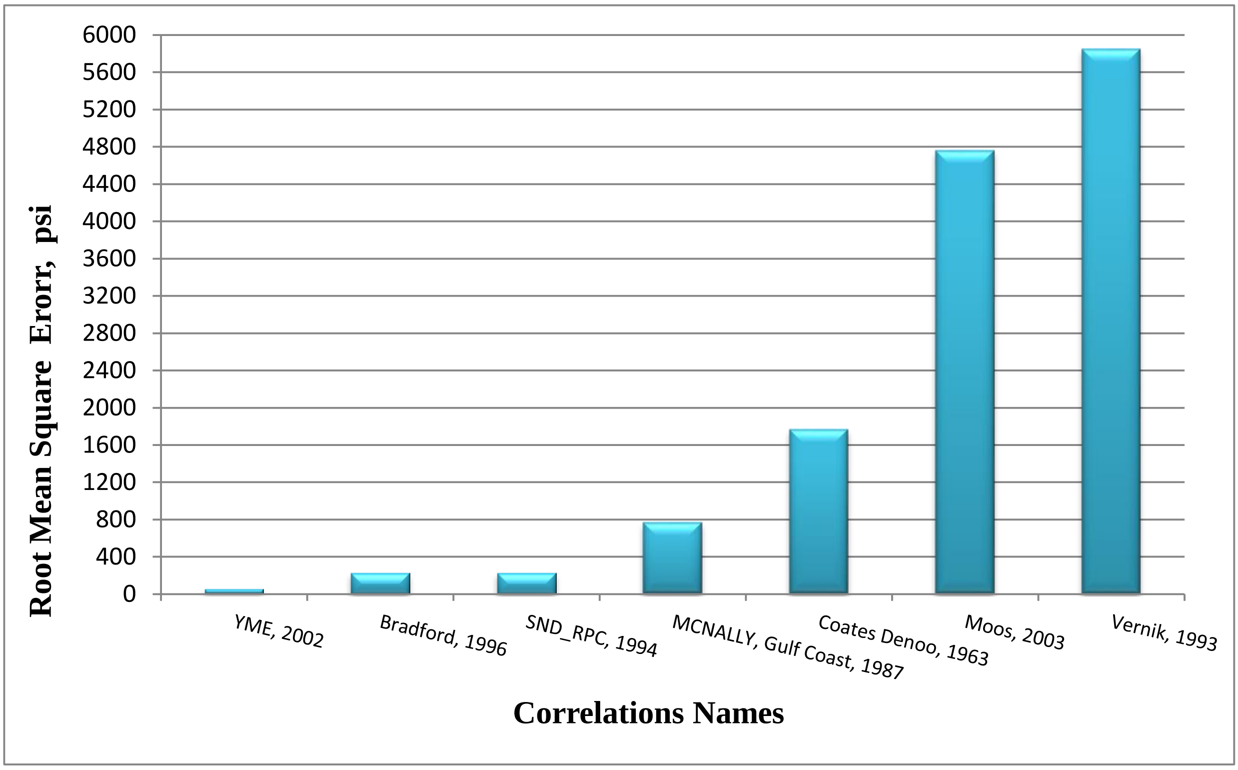


Fig. (21): Comparison between results of unconfined compressive strength by different correlations.

6. Conclusions

In this work, we have investigated whether we can application correlations between petrophysical and mechanical properties using wireline log data. The empirical relationships between UCS and ES with Ed and VP that were reported by previous authors were compared to the authors' data, below are the main results obtained from this work.

- The John Fuller equation (Eq. 2) used to estimate the Young's Modulus showed a good match with core tests, so it is recommended to use it in the fields of southern Iraq.
- Estimate the UCS depend on the E_S gives a closer prediction from the actual, contrary to the use of E_d,Δt_c,$\emptyset$, which give incorrect results.
- The Novel, 2021 correlation must be excluded in estimation the UCS because of very large different between the predicted UCS and core data, because this correlation was formulated for shale gas.
- It is recommended to calculate the UCS based on Young Modulus, 2002 correlation in Southern Iraqi fields, the reason is because this correlation give a close value to laboratory

data (RMSE=53.23psi) regardless of the diversity of the lithology of section studied from Sadi to Zubair.

Acknowledgments

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NOMENCLATURE

Δt_c = compressional slowness, us/ft.

Δt_s = shear slowness, us/ft.

C_o = cohesion, psi.

T_o = tensile strength, psi.

$\emptyset$ = porosity, fraction.

E_d = dynamic Young Modulus, psi.

E_S = static Young Modulus, psi.

G_{dyn} = shear modulus, psi.

GR = Gamma Ray.

INOC = Iraqi National Oil Company.

K_{dyn} = bulk modulus, psi.

RMSE = root mean square error.

UCS = unconfined compressive strength, psi.

k = constant.

ρ = bulk density, gm/cc.

φ = internal friction angle, degree.

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