

PAPER • OPEN ACCESS

## Oil well compressive strength analysis from sonic log; a case study

To cite this article: Z Hamdi *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **495** 012077

View the [article online](#) for updates and enhancements.



**IOP | ebooks™**

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the [collection](#) - download the first chapter of every title for free.

## Oil well compressive strength analysis from sonic log; a case study

Z Hamdi<sup>1</sup>, M S Momeni<sup>2\*</sup>, B Meyghani<sup>3</sup>, D Zivar<sup>4</sup>, B Y Chung<sup>5</sup>, M Bataee<sup>6</sup> and M A Asadian<sup>7</sup>

<sup>1</sup>School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University

<sup>2</sup>Department of Petroleum Engineering, Curtin University, Malaysia

<sup>3</sup>Department of Mechanical Engineering, Faculty of Engineering Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia

<sup>4</sup>Center of Research In Enhanced Oil Recovery, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia

<sup>5</sup>Department of Chemical Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia

<sup>6</sup>School of Engineering, Asia Pacific University of Technology & Innovation, Technology Park, Bukit Jalil, Kuala Lumpur, Malaysia

<sup>7</sup>Iranian Offshore Oil Company (IOOC), Khakzad St. Turaj St. Modares Cross, Valiasr St. Tehran, Iran

\*Email: ms.momeni@curtin.edu.my

**Abstract.** Appropriate selection of bits for different bore-hole sections is the key to achieve superior drilling performance. This is done with the intention to maximize the rate of penetration while maintaining bit integrity and drilling safety, which plays an important role in maintaining well economies. An accurate selection of drilling bit is dependent on the physical characteristics of formation and the compressive strength of rocks. The acquisition of rock strength along the wellbore can be obtained from various sources such as logs, cutting and rock mechanical test or drilling data. This paper posed a trial to obtain compressive strength profile of oilfield's formation from a sonic log. According to the results, the formations have been divided into several groups from very soft to very hard formation to optimize bit selection. The acquisition of rock strength information in different conditions is made possible by the generation of similar rock strength logs by different sources. Nevertheless, the best prediction will be given by meter-by-meter based logs from different references. Hence, log based or drilling based methods remains the most preferred methods used to obtain rock strength logs. In this paper, it is desired to predict the compressive strength of wellbore by using empirical correlation based on well logging data and then investigate the confidence of results by data obtained from drilling data. Later, this method is used to predict uniaxial compressive strength in the entire of oilfield.

**Key words:** Rock mechanics, Well logging, Compressibility strength, Sonic log, Unconfined compressive strength



## 1. Introduction

The unconfined compressive strength (UCS) of sedimentary rocks is a key parameter needed to address a range of geomechanical problems ranging from limiting wellbore instabilities during drilling [1], to assessing sanding potential [2] and quantitatively constraining stress magnitudes using observations of wellbore failure [3].

Various applications can be used for the development of rock strength profiles along the wellbore. With testing on core samples, rock strength can be found using rock mechanical laboratory test. Laboratory test to find UCS can be done through uniaxial or Tri-axial tests. Tri-axial tests have to be carried out under different confining stresses to determine the failure criterion of a specific core depth [4]. An array of geomechanical problems in reservoirs acquainted to the unavailability of core sample for laboratory testing must be addressed in practice. In fact, core samples of overburden formations (where many wellbore instability problems are encountered) are almost never available for testing.

To tackle the problems on hand, a number of empirical correlations have been proposed as a practical solution. These correlations relate rock strength to parameters measurable with geophysical well logs [5]. Almost all proposed formulae to find rock strength from geophysical logs use one of the below variables:

- P-wave velocity ( $V_p$ ), or equivalently, interval transit time ( $\Delta T = V_p - 1$ ), which is directly measured,
- Young's modulus ( $E$ ), which is derived from velocity and density measurements, or
- Porosity ( $\phi$ ), which is usually derived from density measurements assuming rock matrix and fluid densities.

Besides, an alternative approach developed to overcome the time-consuming process of Tri-axial testing is to conduct rock mechanical tests on small cutting samples [6]. The critical transition force (CTF) is identified as deformation occurs on the sample without any increment in vertical load. The prediction of compressive strength of drilled formations is then done by the correlation done between CTF and UCS. To predict rock compressive strength drilling data also can be used as a tool.

Prediction of rock strength can also be done using drilling data that is developed based on rate of penetration (ROP) models [7-9]. Each bit types such as roller cone, polycrystalline compact bits (PDC) and natural diamond bits (NDB) are accompanied by their individual ROP models [10-12]. The variables that effect ROP like drilling data (e.g. WOB, RPM, flow rate, mud weight and type), bit types and wear and the rock formation properties are all taken into account in the ROP models [13-15]. The rock formation properties included are lithology, abrasiveness, pore pressure and rock strength. For a previously drilled well, all the above-mentioned information is recorded except the rock strength [16-18]. The generation of rock strength is done by the inversion of a bit specific rate of penetration models using data collected from previously drilled well. The effects of operating parameters, bit design and wear, drilling hydraulics, mud rheology and pore pressure are normalized model [19, 20].

Table 1 listed a range of P- and S-wave velocities for a number of rocks. They are meant primarily for illustrative purposes: one of the main ideas is to show that the sound velocities depend strongly on the conditions under which the measurements are performed. Consider for example dry, loose sand near the surface. In the upper 1 meter, the P-wave velocity is saying  $300^m/s$ , and the S wave velocity below  $100^m/s$ . With increased burial (increased stress on the sand grains), both velocities increase substantially, so that at 100 m depth, the same sediment will have P- and S-wave velocities which are at least twice as high as on the top.

**Table 1.** Sound velocities for some common rock types [14].

Material	Density $\times 10^3$ [ $kg/m^3$ ]	$V_p$ [ $m/s$ ]	$V_s$ [ $m/s$ ]	Conditions
Sand, dry, loose	1.5 - 1.7	300-1000	50-400	dry, from surface to $\approx 50m$ depth
Sand, dry	1.6 - 1.7	1000-1700	400-900	dry, loaded from $\approx 1$ to $\approx 35$ Mpa
Sand, wet, loose	1.8 - 2.2	1500-2000	50-400	saturated, from surface to $\approx 50m$ depth
Sandstone, competent	2.0 - 2.65	1800-4500	1000-3000	dry, various porosities
Berea sandstone	2.2	3800-4000	2300-2400	brine saturated, confined
Sandstone, weak	1.7 - 2.0	1000-2000	600-1200	dry, various porosities
Red Wildmoor sst.	2.0	1700-2000	1100-1300	dry, confined
Clay	1.9 - 2.1	1500-1600	100-300	saturated, from surface to $\approx 50m$ depth
London Clay, deep	2.0	1700-1800	800-1100	saturated
Shale	2.3 - 2.8	1600-4500	700-3000	saturated, various porosities
Weak Shale, North Sea	2.35	2400-2600	1200-1300	saturated, unconfined
Limestone	2.4 - 2.7	3500-6000	2000-3500	various

### 1.1. Empirical correlation to quantify uniaxial compressive strength

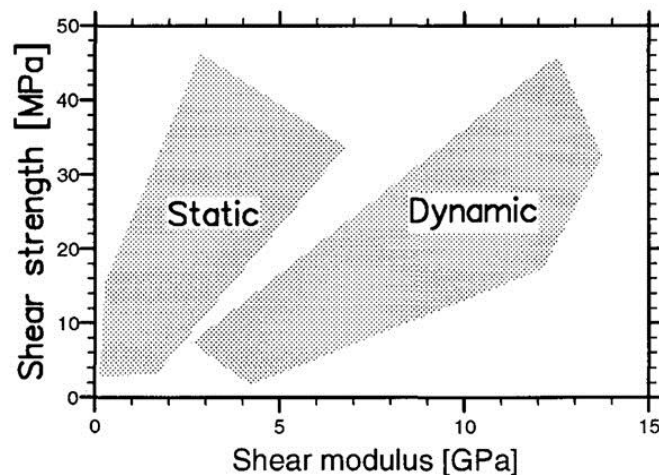
The provision of indirect measurement of fluid and rock characteristics for the evaluation of subsurface formation is the ultimate objective of well logging. Although, well logging is known to provide information on rock strength, the utilization of electric logs for the determination of drill ability is uncommon. Laboratory uniaxial tests can provide the correlations of rock strength with logs where the stress at shear fracture in a core specimen is correlated to the value of the log properties at the core sample depth. However, the lab data is available only for the intervals where the well was cored and does not account for in-situ strength. Thus, making an inadequate representation of the entire well [13].

Equations in Tables 2 presented a number of relationships in common practice for estimating the unconfined compressive strength of sedimentary rock from geophysical logging data.

### 1.2. Estimation of strength parameters

Figure 1 showed the relation between the shear strength and the static and dynamic shear moduli for a few weak sandstones. Less scatter of data is shown than indicated in the shaded areas. The dataset is, however, so limited that we have chosen not to focus on that point, since a correlation developed from a too small dataset might be misleading. The dataset emphasizes one important point: there is a

significant difference between static and dynamic moduli. It is important to be aware of this when considering correlations between strength and dynamic elastic moduli. In particular, one should not use a static correlation directly when sonic velocities are used to derive the elastic moduli.



**Figure 1.** Empirical correlations between shear strength and static and dynamic shear moduli [21].

**Table 2.** Empirical relationships between unconfined compressive strength (UCS) and other physical properties of rocks

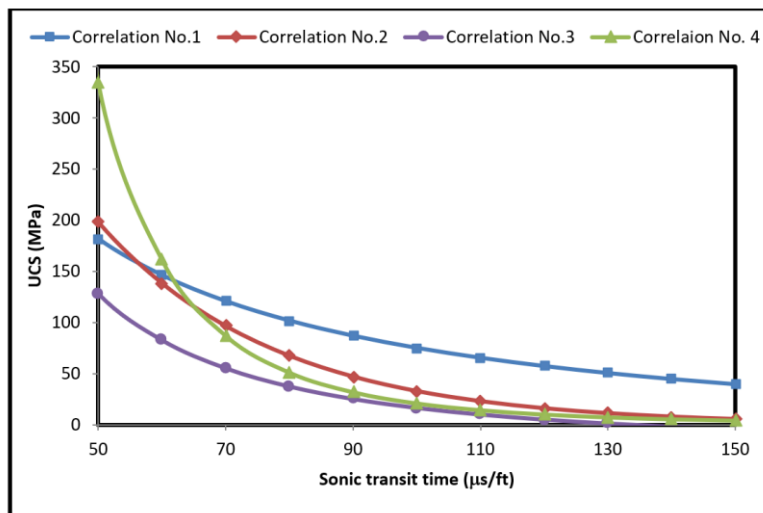
Correlation No.	UCS (MPa)	Region where developed	General comments
(1) <sup>[22]</sup>	$0.035V_p - 31.5$	Thuringia, Germany	-----
(2) <sup>[23]</sup>	$1200\exp(-0.036\Delta t)$	Bowen Basin, Australia	Fine grained, both consolidated and unconsolidated sandstones
(3) <sup>[24]</sup>	$1.745 \times 10^{-9}\rho V_p^2 - 21$	Cook Inlet, Alaska	Coarse grained sandstones and conglomerates
(4) <sup>[14]</sup>	$3.3 \times 10^{-20}\rho^2 V_p^4 [(1 + \nu)/(1 - \nu)]^2 (1 - 2\nu)[1 + 0.78V_{clay}]$	Gulf Coast	Derived from sandstones with UCS > 30 MPa
(5) <sup>[25]</sup>	$2.28 + 4.1089E$	Worldwide	-----
(6) <sup>[26]</sup>	$0.77(304.8/\Delta t)^{2.93}$	North Sea	Mostly high porosity Tertiary shales
(7) <sup>[27]</sup>	$10(304.8)/(\Delta t - 1)$	North Sea	Mostly high porosity Tertiary shales
(8) <sup>[26]</sup>	$7.97E^{0.91}$	North Sea	Mostly high porosity Tertiary shales
(9) <sup>[28]</sup>	$(7682/\Delta t)^{1.82}/145$	-----	Lime stone
(10) <sup>[29]</sup>	$10^{(2.44+109.14/\Delta t)}/145$	-----	Lime stone

**2. Methodology**

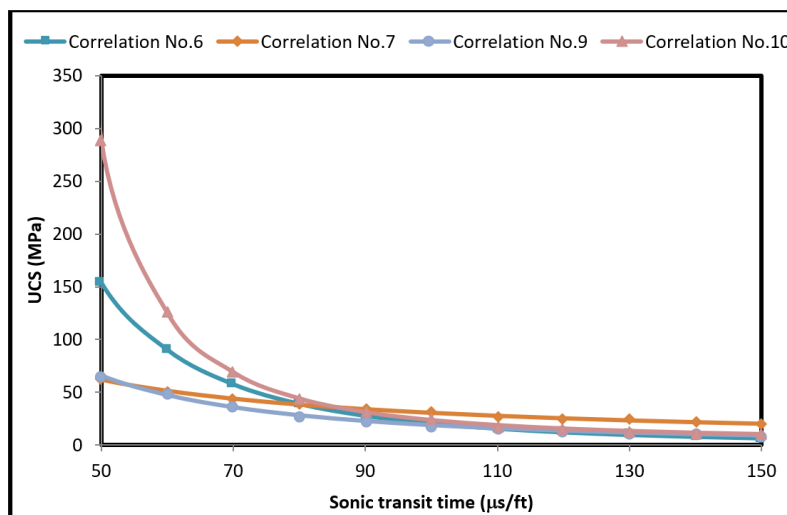
From the above discussion, it is concluded that correlations are the most suitable way to calculate the uniaxial strength of the rocks rather than other methods. The selection of the appropriate correlation is an important factor that affects in final results.

All the correlations presented in table 2 are shown in Figures 2 and 3. These figures showed that in high values of transient times indicating a low compressive strength rocks, the prediction of most of the correlations are in a same range but in low values of transient times the prediction of compressive strength is different for each correlation. It seemed that a suitable correlation is one that can predict the compressive strength values in both cases. It is clear from the figures that some of the correlations cannot predict the high values of compressive strength, so, the correlations with capability of prediction of high values of compressive strength can be more favorable.

In the next section, the compressive strength is predicted by modified Warren method which include bit wear function using drilling data. Next, the results from drilling data method and empirical correlations are compared to find the most appropriate correlation that can be used in this oilfield.



**Figure 2.** Empirical correlation graph for number one to four.



**Figure 3.** Empirical correlation graph number six to ten.

### 2.1. Procedure And Field Data

In this paper an oil field was selected to be analyzed. To do so, following data were collected to determine compressive strength of underground formations. Data include: sonic, neutron, density, gamma ray logs and drilling data.

Drilling data consists of bit data, formation parameters, drilling parameters, bit dull condition and finally mud logging report of the well. Bit data consists of size, type, IADC code, jet sizes and dull bit grade for each bit. Formation parameter consists of formation lithology and logging data records; drilling parameters include: depth in, depth out, time of drilling and operating conditions.

Due to the high cost of well logging operations, logging interval of a well is usually limited to reservoir intervals; so logging data is less available to interval other than reservoir. Since, in this study determination of compressive strength profile of underground formations from surface is desired, existing data is limited to old drilled wells in this oilfield. So, the gathered data were raw and in the form of scanned documents of well logs. Therefore, first step was converting raw data to digitized ones. For this purpose, LOGCARD software was used.

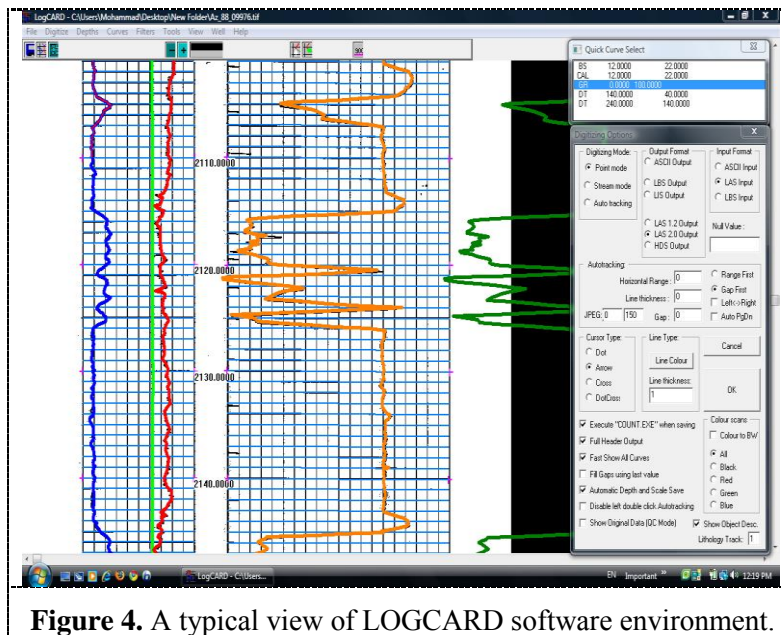
**Table 3.** Typically mud logging data format.

MD (m)	TVD (m)	ROP (ft/min)	N (RPM)	WOB (klbs)	MW (pcf)	Q (gpm)	PV (cp)	
1307	1307	0.328	172	33	66.8	888.4	3	Bit diameter = 17.5-inch Nozzle size = 16 Tooth dull grade = 4 Bit life = 76 hrs. IADC Code = 115 Number of nozzles = 3
1308	1308	0.371	174	33	66.8	888.9	3	
1309	1309	0.345	175	33	64.0	889.5	3	
1310	1310	0.355	176	30.8	64.0	889.7	3	
1311	1311	0.393	176	35.2	66.8	888.4	3	
1312	1312	0.453	172	35.2	66.8	886.3	3	
1313	1313	0.483	134	28.6	66.2	918.8	3	
1314	1314	0.307	178	33	66.2	918.0	3	
1315	1315	0.383	173	35.2	66.2	917.2	3	
1316	1316	0.383	178	37.4	66.8	916.9	3	
1317	1317	0.372	178	28.6	66.2	917.7	3	
1318	1318	0.355	178	30.8	66.8	917.5	3	
1319	1319	0.257	178	33	66.8	917.5	3	
1320	1320	0.268	178	35.2	66.8	916.4	3	
1321	1321	0.312	178	35.2	66.8	916.7	3	
1322	1322	0.285	178	35.2	66.8	915.6	3	
1323	1323	0.24	178	30.8	66.8	914.6	3	
1324	1324	0.328	178	37.4	66.8	912.5	3	
1325	1325	0.427	178	35.2	66.8	912.2	3	
1326	1326	0.492	178	37.4	66.8	911.7	3	
1327	1327	0.362	178	39.6	66.8	911.9	3	
1328	1328	0.362	178	37.4	66.8	911.9	3	
1329	1329	0.328	178	39.6	66.8	909.5	3	
1330	1330	0.345	178	39.6	66.8	910.3	3	

### 2.2. Digitizing Data

In application of this software to digitize data, we should define logging parameters, units and their range of variations. Then by gridding the document and following the tracks of log and determining step size and output format, digitized results will be obtained.

In this study all of output format was LAS (Log ASCII Standard) and the step size was equal to 0.5 if depth unit was in term of foot and equal to 0.1524 if depth unit was in term of meter.



**Figure 4.** A typical view of LOGCARD software environment.

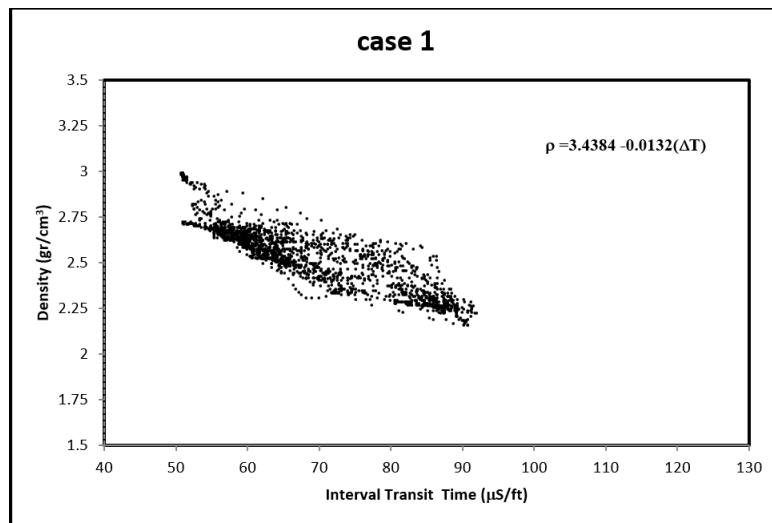
### 2.3. Density prediction

Usually, density log is used for determination of rock density. When we used this log, it is observed that the recorded values were underestimated. These arose from low quality of wellbore and it's washed out area. The inaccuracy seen in the values for density of rock was mainly affected by drilling mud density.

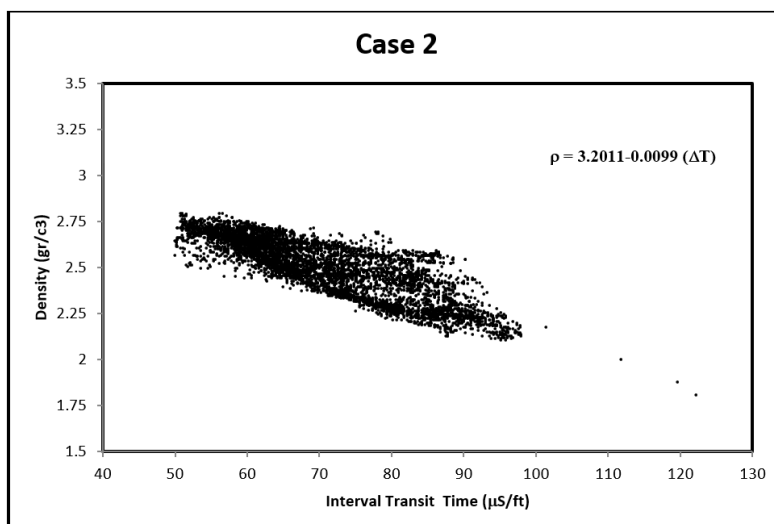
Another approach that can be used to predict density was the use of sonic logs. For this purpose, sonic and density data of two new good quality drilled wells in the reservoir were used to predict a correlation between sonic travel time and bulk density in this oilfield.

Figures 5 and 6 showed the result of the correlation between interval transit time and bulk density and their accuracy. It is seen that correlation in case two has less accuracy in comparison with case one, because it involved a longer interval with respect to the first case and include more type of lithology changes.





**Figure 5.** Correlation between Density and Interval Transit Time, case 1.

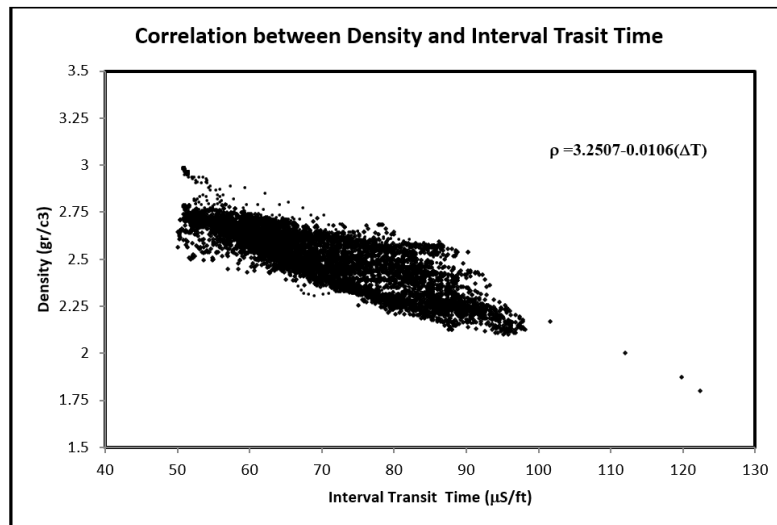


**Figure 6.** Correlation between Density and Interval Transit Time, case 2.

So, the final correlation between bulk density and interval transit time (Figure 7) was obtained from two wells data as follow:

$$\rho = 3.2507 - 0.0106(\Delta T) \quad (1)$$

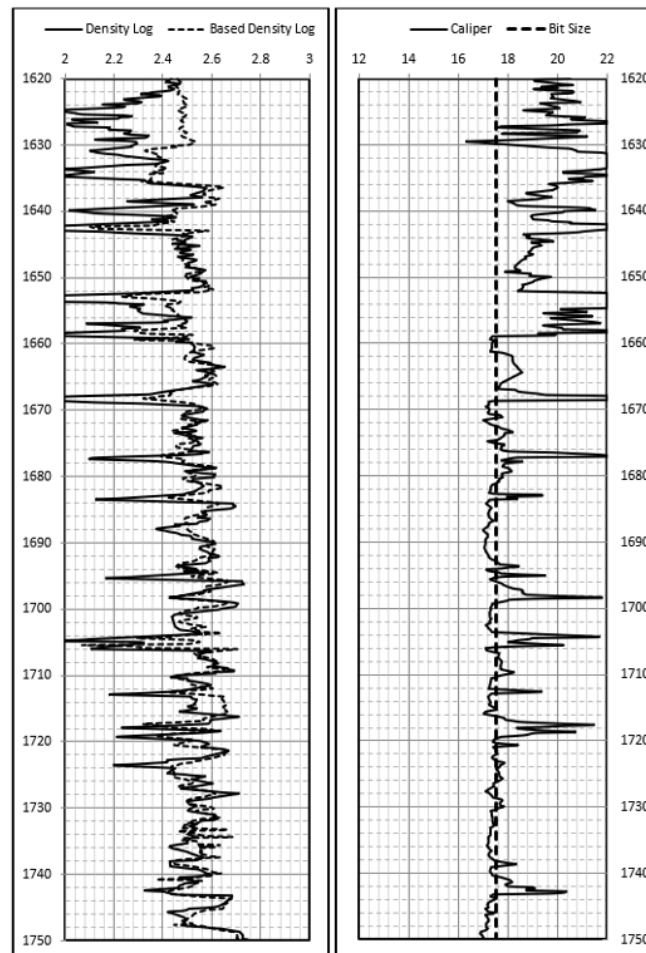
where  $\Delta T$  is in  $\mu S / ft$  and  $\rho$  is in  $gr / cm^3$ .



**Figure 7.** Final Correlation between Density and Interval Transit Time.

Equation 1 was used for all wells to predict density along the wellbore. To evaluate rectitude of our correlation, we compare our prediction with recorded density log in another wells for intervals that hole size was near bit size. It was observed that this prediction has good accuracy for our work.

Figure 8 shows recorded log density and predicted density for an interval of 120m, also indicates the hole size and bit size for that interval. It can be seen that wherever, the wellbore has good quality, the predicted and recorded density is coinciding with each other.



**Figure 8.** Predicted and recorded density log and Caliper log showing the bit size and hole size.

#### 2.4. Prediction of UCS using drilling data

Modified Warren [7] model was selected for calculating compressive strength of rock from drilling data. Wear function was calculated based on Bourgoyne model (equation 2). In this model the rate at which bit wear occurs depends on formation abrasiveness, weight on bit, rotary speed, tooth metallurgy, and cross-sectional area that teeth present to the formation.

$$\frac{dh}{dt} = \frac{1}{\tau_H} \left( \frac{N}{100} \right)^{H_1} \left( \frac{\left( \frac{W}{D} \right)_{max} - 4}{\left( \frac{W}{D} \right)_{max} - \frac{W}{D}} \right) \times \left( \frac{1 + \frac{H_2}{2}}{1 + H_2 h} \right) \quad (2)$$

From a dull bit,  $\tau_H$ , formation abrasiveness, hours, can be calculated by integrating above equation,

$$\tau_H = \left( \frac{N}{100} \right)^{H_1} \left( \frac{\left( \frac{W}{D} \right)_{max} - 4}{\left( \frac{W}{D} \right)_{max} - \frac{W}{D}} \right) \times \left( 1 + \frac{H_2}{2} \right) \left( \frac{t_b}{\frac{h + H_2 h^2}{2}} \right) \quad (3)$$

And  $H_1$ ,  $H_2$ ,  $H_3$  and  $(W/D)_{\max}$  are constants which depend on the bit design parameter (Tables 4 and 5).

**Table 4.** Recommended tooth wear parameter.

Bit Class	$H_1$	$H_2$	$H_3$	$(W/D)_{\max}$
1-1 to 1-2	1.90	7	1.00	7.0
1-3 to 1-4	1.84	6	0.80	8.0
2-1 to 2-2	1.80	5	0.60	8.5
2-3	1.76	4	0.48	9.0
3-1	1.70	3	0.36	10.0
3-2	1.65	2	0.26	10.0
3-3	1.60	2	0.20	10.0
3-4	1.50	2	0.18	10.0
Insert	1.50	1	0.02	Next Table

**Table 5.** Maximum design weight on bit 1000 lb/in.

Bit Size (in)	Milled Tooth Bits						Insert Tooth Bits						
	1-1	1-2	1-3	1-4	2-1,2-2	2-3	3	4	5	6	7	8	9
6 <sup>1</sup> / <sub>8</sub>	---	5.6	6.0	6.6	6.9	---	7.9	---	---	---	---	---	---
6 <sup>3</sup> / <sub>4</sub>	---	5.7	6.1	6.6	7.1	7.2	8.5	---	3.1	4.4	4.5	5.2	4.0
7 <sup>7</sup> / <sub>8</sub>	6.0	6.2	6.6	7.0	7.5	7.6	8.7	9.4	3.5	4.5	5.0	5.7	4.5
8 <sup>3</sup> / <sub>4</sub>	6.2	6.5	6.8	7.2	7.8	8.0	9.5	10.0	3.7	5.1	5.2	5.9	4.6
9 <sup>7</sup> / <sub>8</sub>	6.5	6.7	7.1	7.0	7.6	7.7	8.9	---	3.6	5.1	5.1	5.9	4.6
10 <sup>5</sup> / <sub>8</sub>	---	6.4	---	7.0	---	---	8.8	---	3.5	5.0	5.0	5.8	4.5
12 <sup>1</sup> / <sub>4</sub>	5.9	6.1	6.4	6.7	7.3	7.4	8.5	---	3.5	4.9	4.9	5.6	4.4
14 <sup>3</sup> / <sub>4</sub> -15	---	5.3	---	5.8	---	6.3	7.4	---	3.4	4.7	4.8	5.4	4.3
17 <sup>1</sup> / <sub>2</sub>	---	5.0	---	5.7	---	---	7.0	---	3.0	4.2	4.2	4.8	3.8

Most of used insert-teeth-bit usually fail by fracturing of the brittle tungsten carbide. For this tooth type, fractional tooth wear,  $h$ , represents the fraction of the total number of bit teeth that has been broken. Because the modified Warren model is a combination of theoretical and empirical equations, a series of coefficients were developed. The coefficients  $a$ ,  $b$  and  $c$  are characteristic of the bit design. Table 6 shows bit specifications that used for calculating compressive strength in modified Warren model.

**Table 6.** Bits data.

Bit Number	1	2	3	4	5
Size	17 1/2	17 1/2	17 1/2	12 1/4	12 1/4
Type	GTX-G1	GTX-G3	GTX-G3	SV	G547-XL
Nozzles	3×16	3×16	2×16+1×18	3×16	4×16+2×14
Depth In	1224	1557	1760	1869	1889
Depth Out	1557	1760	1869	1889	2554
Hours Run	76	79	60	23	176
Tooth dull grade	4	2	3	3	2
a	0.021	0.015	0.015	0.02	0.0019
b	2.7	3	3	3	3
c	0.0019	0.0019	0.0019	0.02	0.0001

Figures 9 to 16 shows input parameters to equation 2 for calculating rock compressive strength for interval 1307-2555 m. Then result inserted in the equation 4 for computing uniaxial compressive strength.

$$S = C_0(1 + a_s P_e^{b_s}) \quad (4)$$

Where,  $S$  and  $C_0$  are the confined rock strength and unconfined rock strength, respectively. The coefficients  $a_s$  and  $b_s$  depend on the formation permeability and are shown in Table 7. Figure 17 shows a resulted profile for uniaxial compressive strength along this interval based on drilling data.

The UCS profile from drilling data presented in figure 17. To find a better correlation, different empirical correlations were used and compared with final results. Table 8 shows different empirical correlations results. Base on the results, it is concluded that the Fjaer correlation (Correlation No.4) nearly match the UCS profile from drilling data.

**Table 7.** Permeability coefficient.

Formation	Permeable	Impermeable
$P_e$	$P_h - P_p$	$P_h$
$a_s$	0.0133	0.00432
$b_s$	0.577	0.782

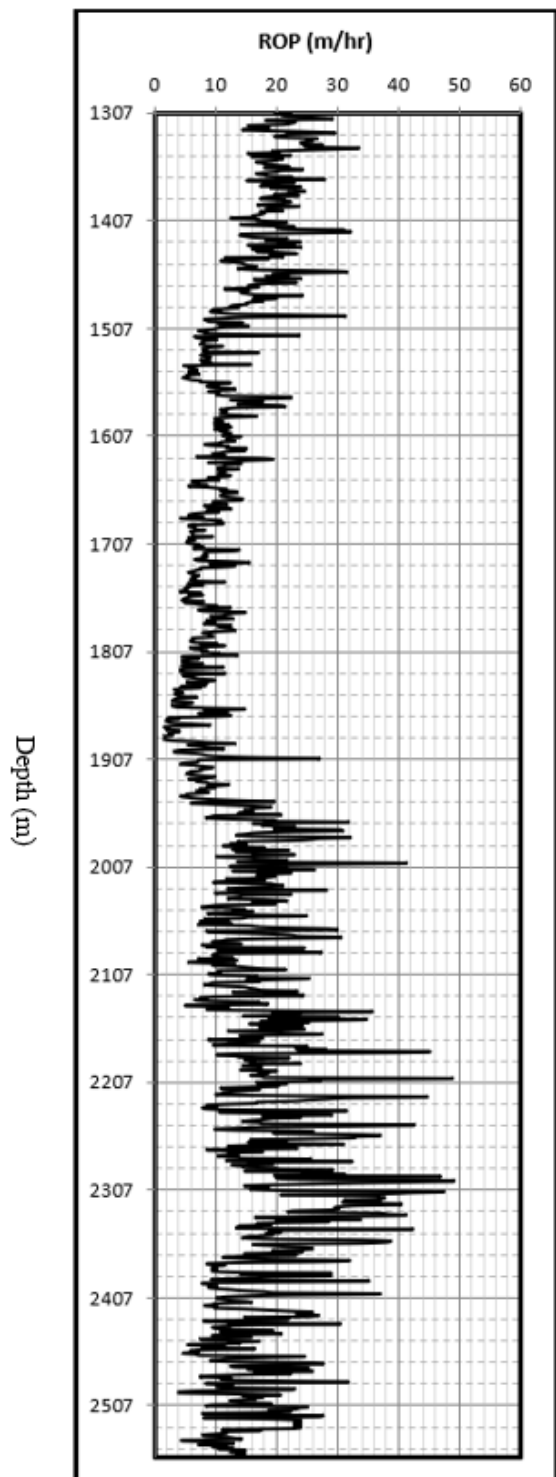


Figure 9. Rate of penetration profile.

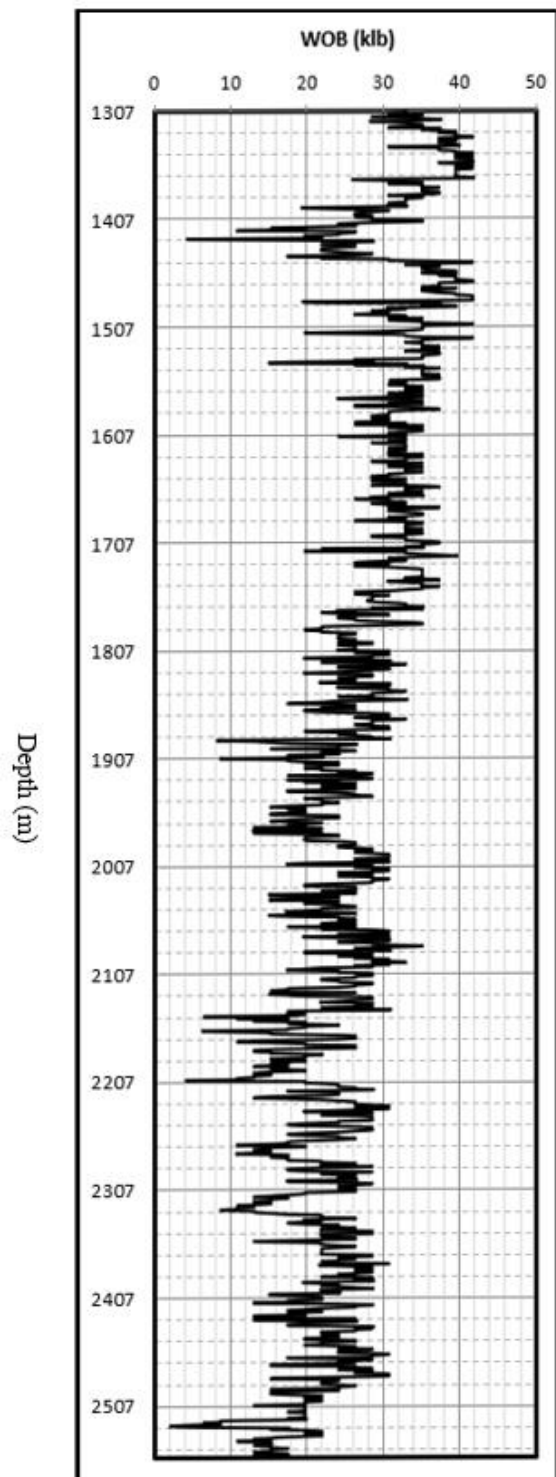


Figure 10. Weight on bit profile.

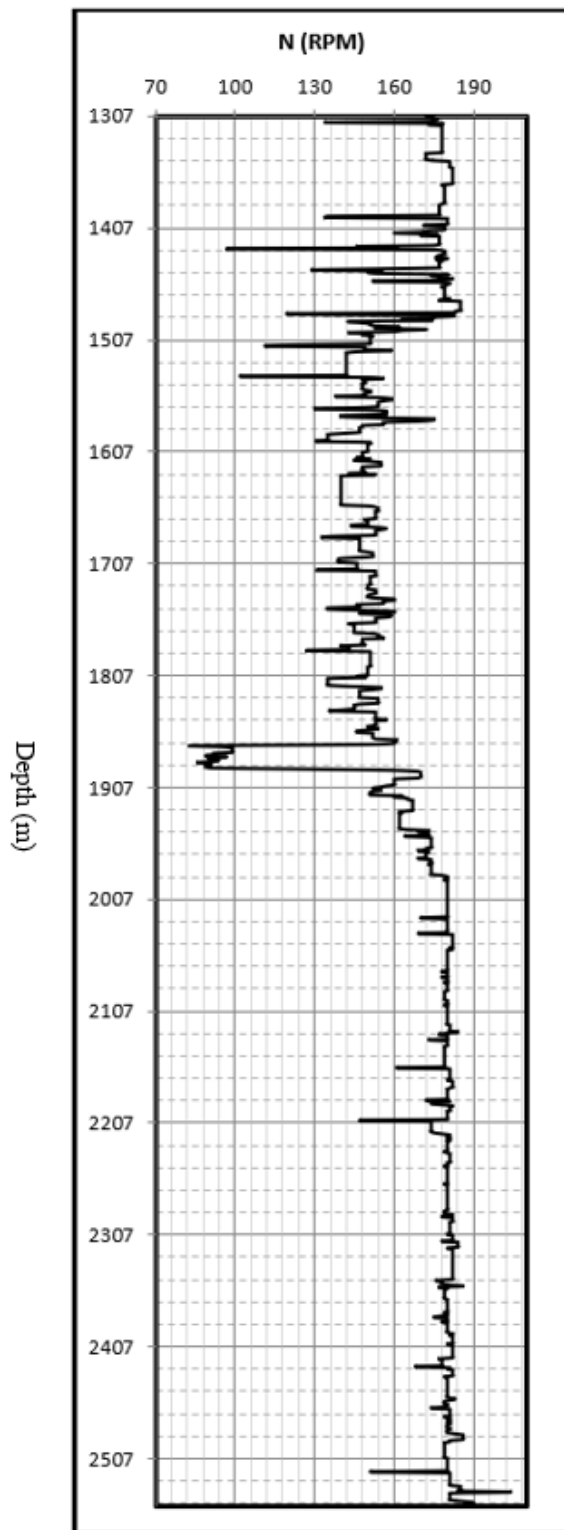


Figure 11. Rotary speed profile.

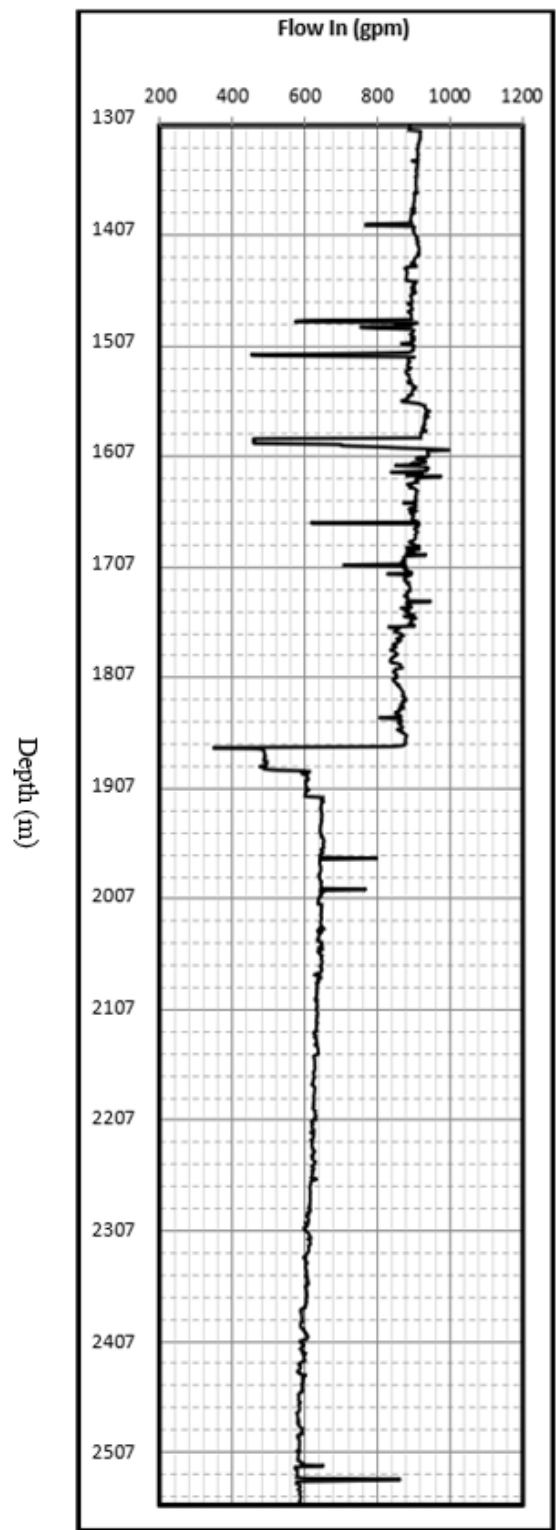


Figure 12. Flow in profile.

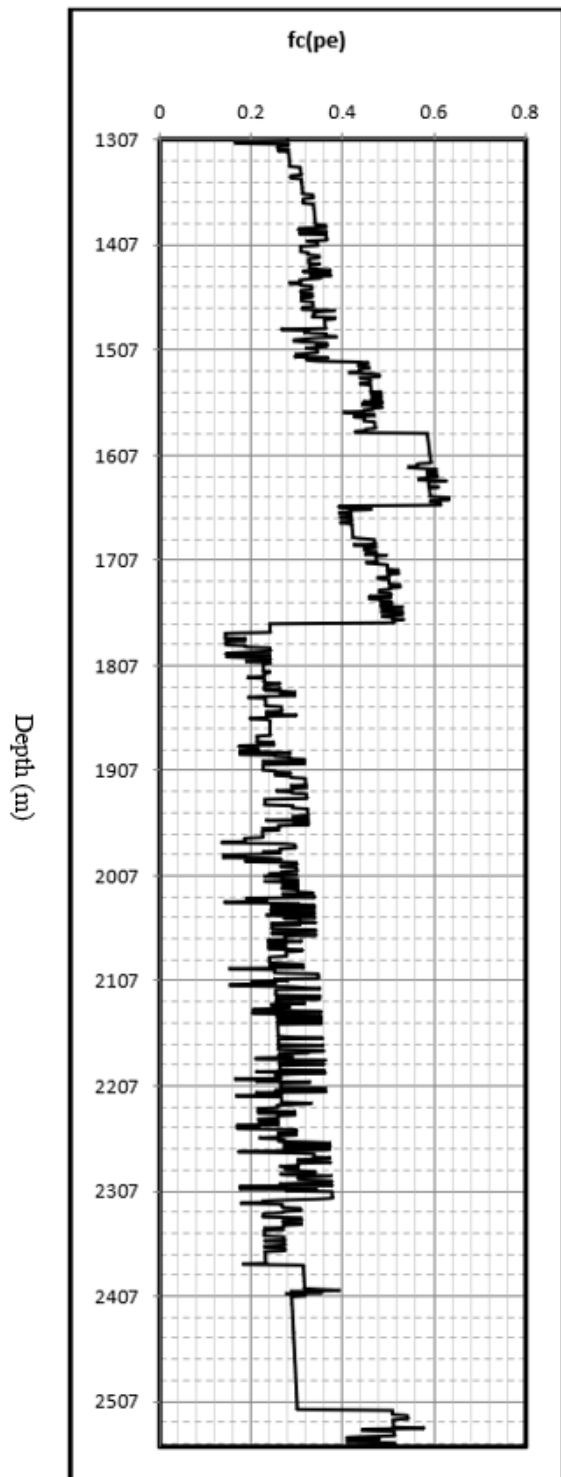


Figure 13. Chip hold-down function profile.

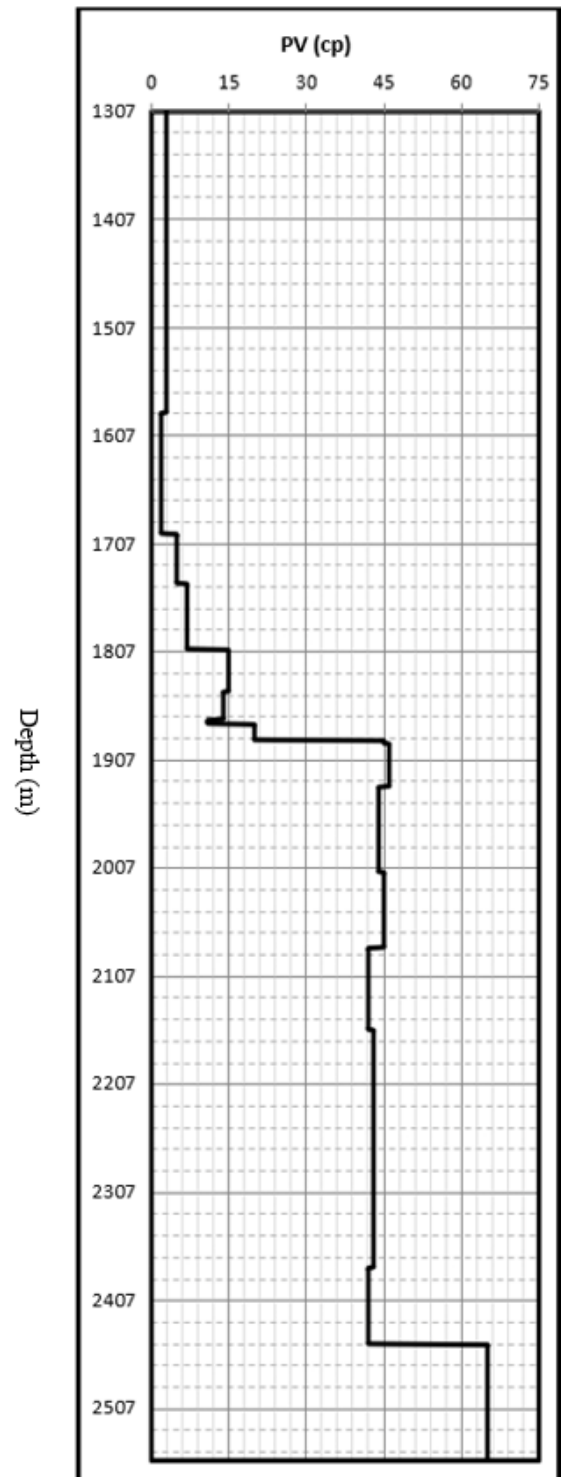


Figure 14. Viscosity profile.



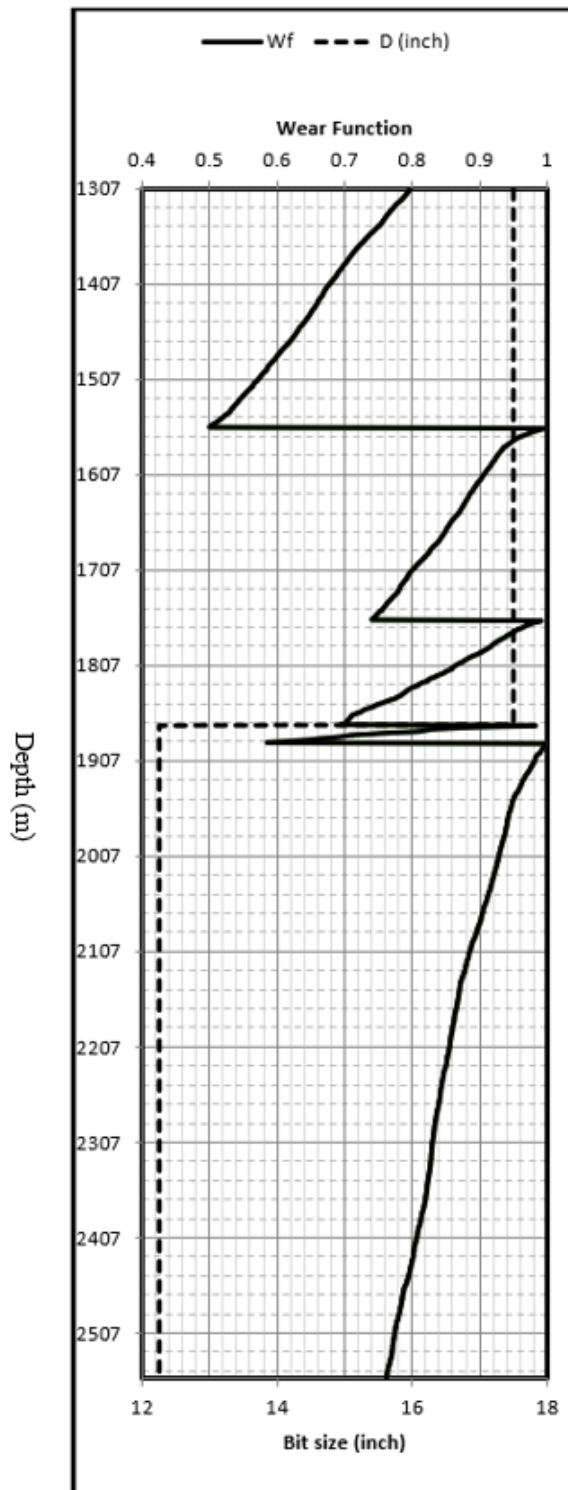


Figure 15. Wear function and Bit size.

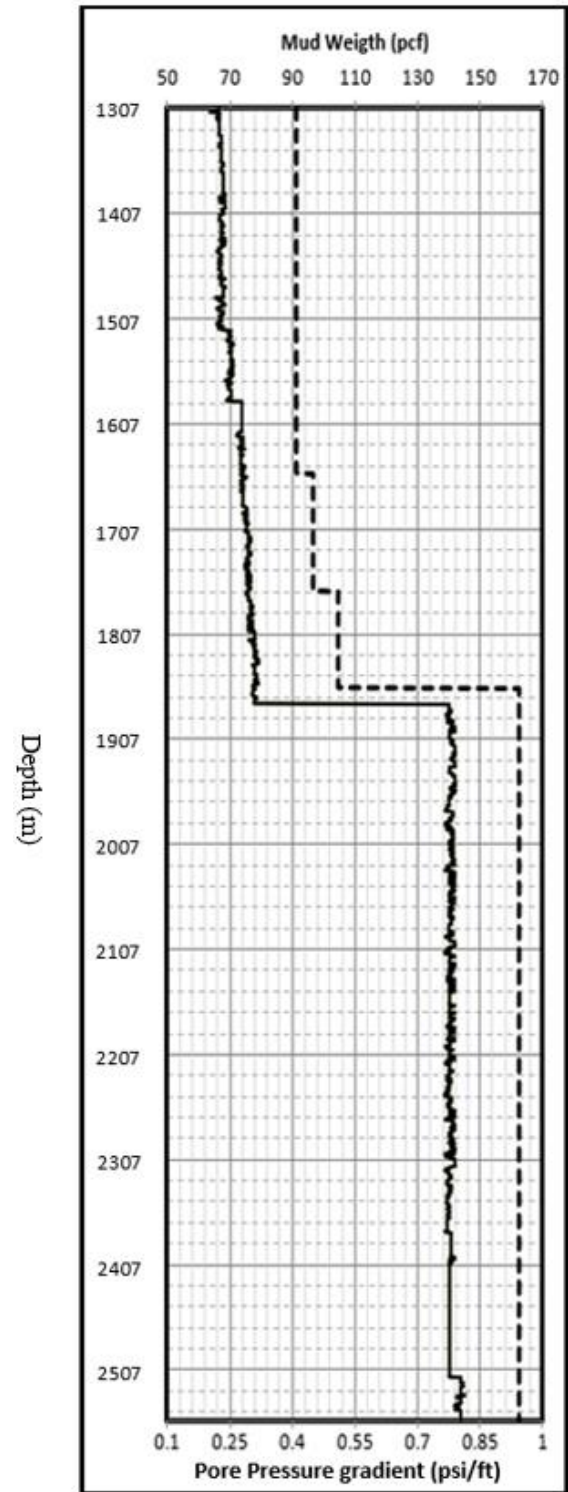


Figure 16. Mud weight and pore pressure gradient.

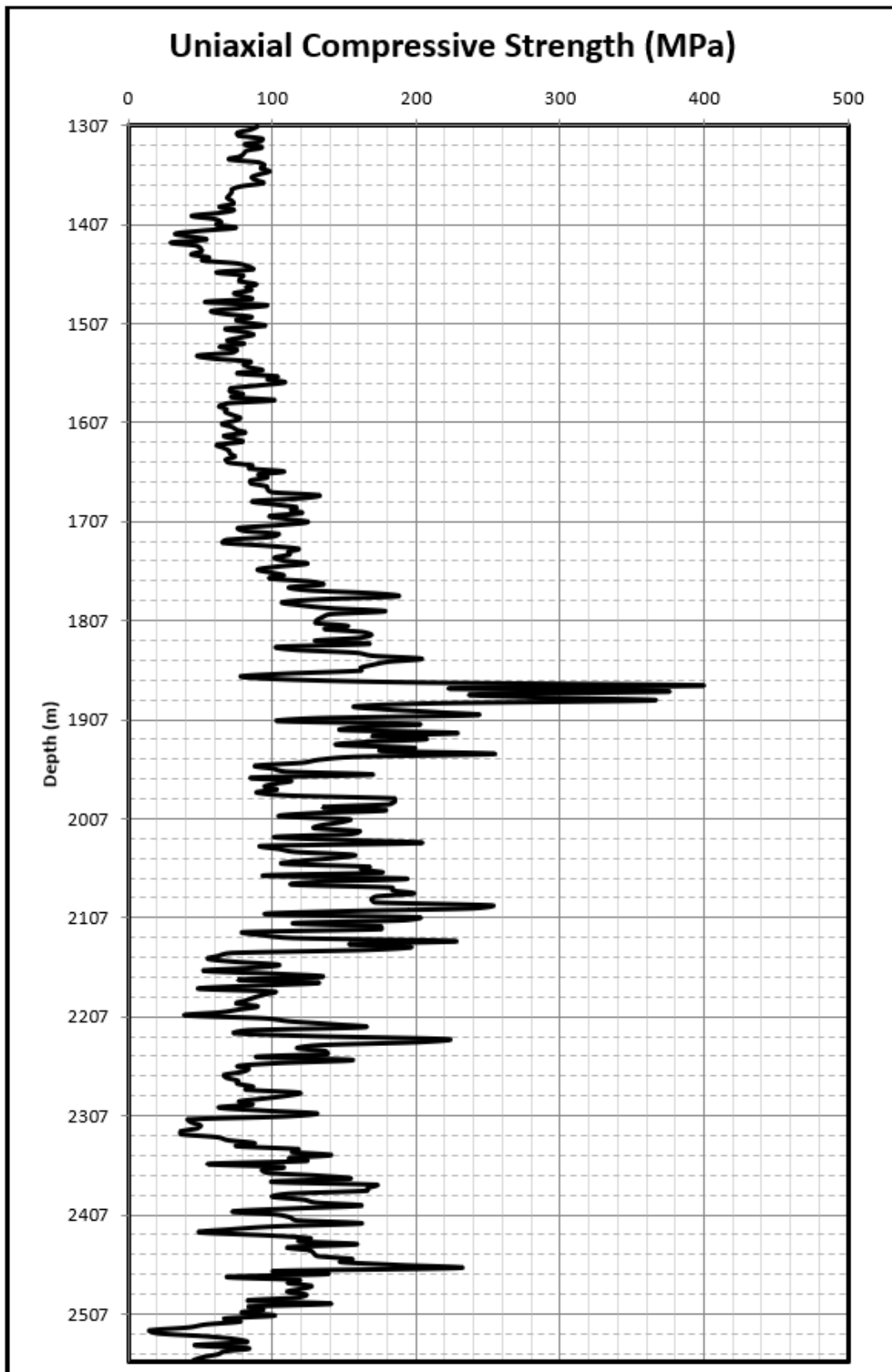


Figure 17. Predicted uniaxial compressive strength based on modified Warren model.

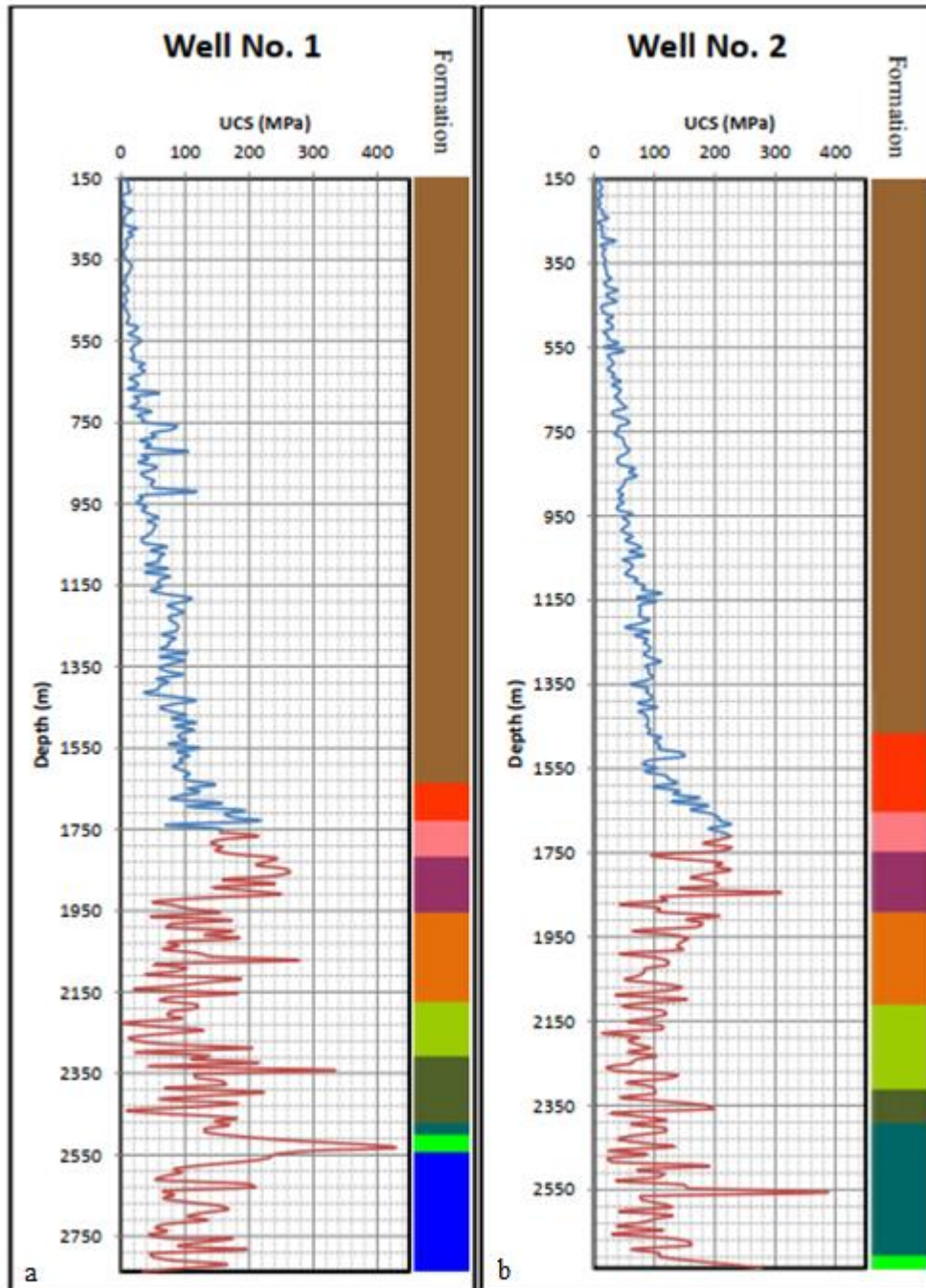
**Table 8.** Predicted uniaxial compressive strength, MPa, based on all correlation for a typical interval.

Depth (m)	$\Delta T$ (us/ft)	Density (gr/cm <sup>3</sup> )	Clay	$\nu$	Correlations							
					No.1	No.2	No.3	No.4	No.6	No.7	No.9	No.10
1801	73.9188	2.47	0.44	0.304	112.8	83.8	52.2	107.5	48.9	41.8	32.3	56.9
1802	72.3526	2.48	0.44	0.304	115.9	88.7	55.9	118.4	52.1	42.7	33.6	61.2
1803	72.1275	2.49	0.42	0.303	116.4	89.4	56.5	118.8	52.5	42.9	33.8	61.9
1804	67.7942	2.53	0.41	0.303	125.9	104.5	68.3	157.1	63.0	45.6	37.8	77.4
1805	66.9727	2.54	0.49	0.301	127.8	107.7	70.8	174.7	65.3	46.2	38.6	81.0
1806	75.2787	2.45	0.44	0.301	110.2	79.8	49.2	98.9	46.3	41.0	31.2	53.5
1807	64.8695	2.56	0.25	0.299	132.9	116.1	77.7	174.1	71.7	47.7	41.0	91.4
1808	64.5461	2.57	0.37	0.299	133.8	117.5	78.9	192.6	72.7	48.0	41.3	93.2
1809	73.4297	2.47	0.40	0.299	113.8	85.3	53.3	108.4	49.8	42.1	32.7	58.2
1810	81.3807	2.39	0.37	0.299	99.6	64.1	37.5	65.9	36.9	37.9	27.1	41.7
1811	65.7849	2.55	0.16	0.301	130.7	112.4	74.6	153.9	68.8	47.0	39.9	86.6
1812	54.9913	2.67	0.10	0.301	162.5	165.7	122.0	330.5	116.3	56.5	55.3	183.4
1813	61.6785	2.60	0.31	0.299	141.5	130.3	89.7	227.4	83.1	50.2	44.9	111.7
1814	67.3743	2.54	0.37	0.299	126.8	106.1	69.6	158.5	64.1	45.9	38.2	79.2
1815	69.754	2.51	0.45	0.295	121.4	97.4	62.7	142.1	57.9	44.3	35.9	69.7
1816	65.5451	2.56	0.23	0.295	131.3	113.3	75.4	164.6	69.5	47.2	40.2	87.9
1817	53.6668	2.68	0.13	0.295	167.3	173.8	129.9	375.8	124.9	57.9	57.8	205.3
1818	62.6858	2.59	0.39	0.291	138.7	125.6	85.7	223.3	79.2	49.4	43.6	104.6
1819	66.0093	2.55	0.33	0.291	130.1	111.5	73.9	170.4	68.1	46.9	39.7	85.5
1820	57.6392	2.64	0.11	0.299	153.6	150.7	107.8	269.3	101.3	53.8	50.8	148.6
1821	54.1052	2.68	0.11	0.299	165.7	171.1	127.2	358.1	122.0	57.4	57.0	197.6
1822	63.6146	2.58	0.31	0.295	136.2	121.5	82.2	198.2	75.9	48.7	42.4	98.7
1823	83.4939	2.37	0.30	0.295	96.3	59.4	34.0	55.8	34.2	36.9	25.9	38.5
1824	66.7132	2.54	0.18	0.303	128.4	108.7	71.6	145.9	66.0	46.4	38.9	82.1
1825	54.8867	2.67	0.11	0.303	162.9	166.4	122.6	333.8	117.0	56.6	55.5	185.0

### 3. Results and discussion

It is shown that Fjaer correlation is the most suitable correlation that can be used for calculating uniaxial compressive strength of this oilfield. It almost confirmed the calculated compressive strength from drilling data. Because of the complexity of formula and required to many parameters to find the compressive strength from the drilling data, it is more practical to use an empirical correlation such as Fjaer to predict uniaxial compressive strength. In this section, the correlation is used to predict the compressive strength of different formations at this oilfield. The Fjaer correlation is derived from extensive laboratory test results on a wide range of sedimentary rocks and used more compressive strength rather than parameters to calculating other correlations. Fjaer correlation is based on four important parameters that included sonic transit time, bulk density, Poisson's ratio and clay content. These parameters can be obtained from sonic, density, gamma ray and graphic well logs. In order to predict the UCS's profile of this oilfield, we selected eight wells with reasonable distance to cover the oilfield completely. Also, it is worthwhile to mention that well No.3, well No.5, well No.6 and well No.8 have incomplete well logging data along some intervals. The UCS's profiles for different wells are shown from figure 18 to 21. The profiles showed that the uniaxial compressive strength is increased by

depth. The increase in UCS of rocks in shallower depth is related linearly to compaction of layers to weight of overburden beds and compaction of layers.



**Figure 18.** UCS profile: a) Well No.1 and b) Well No.2.

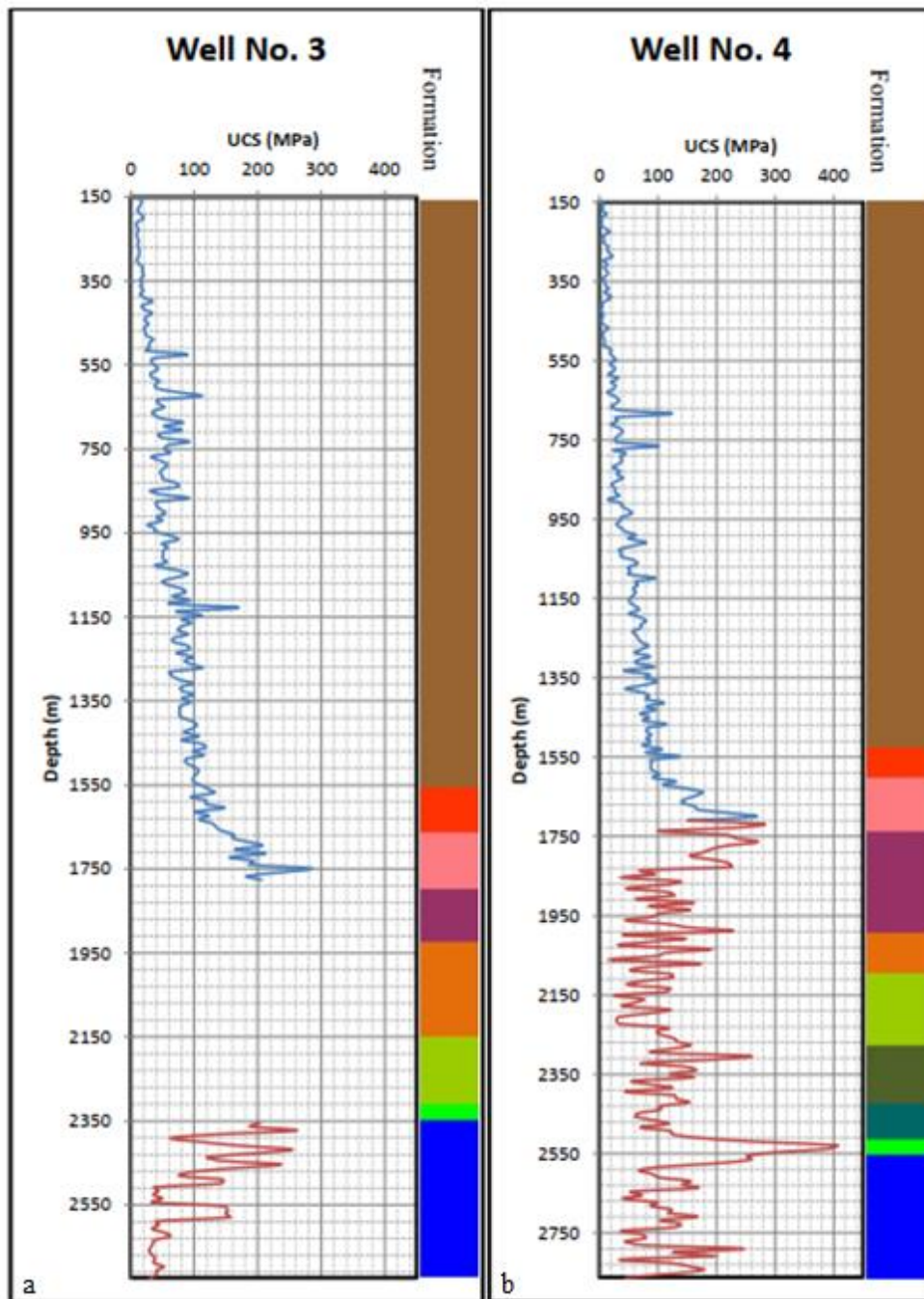


Figure 19. UCS profile: a) Well No.3 and b) Well No.4.

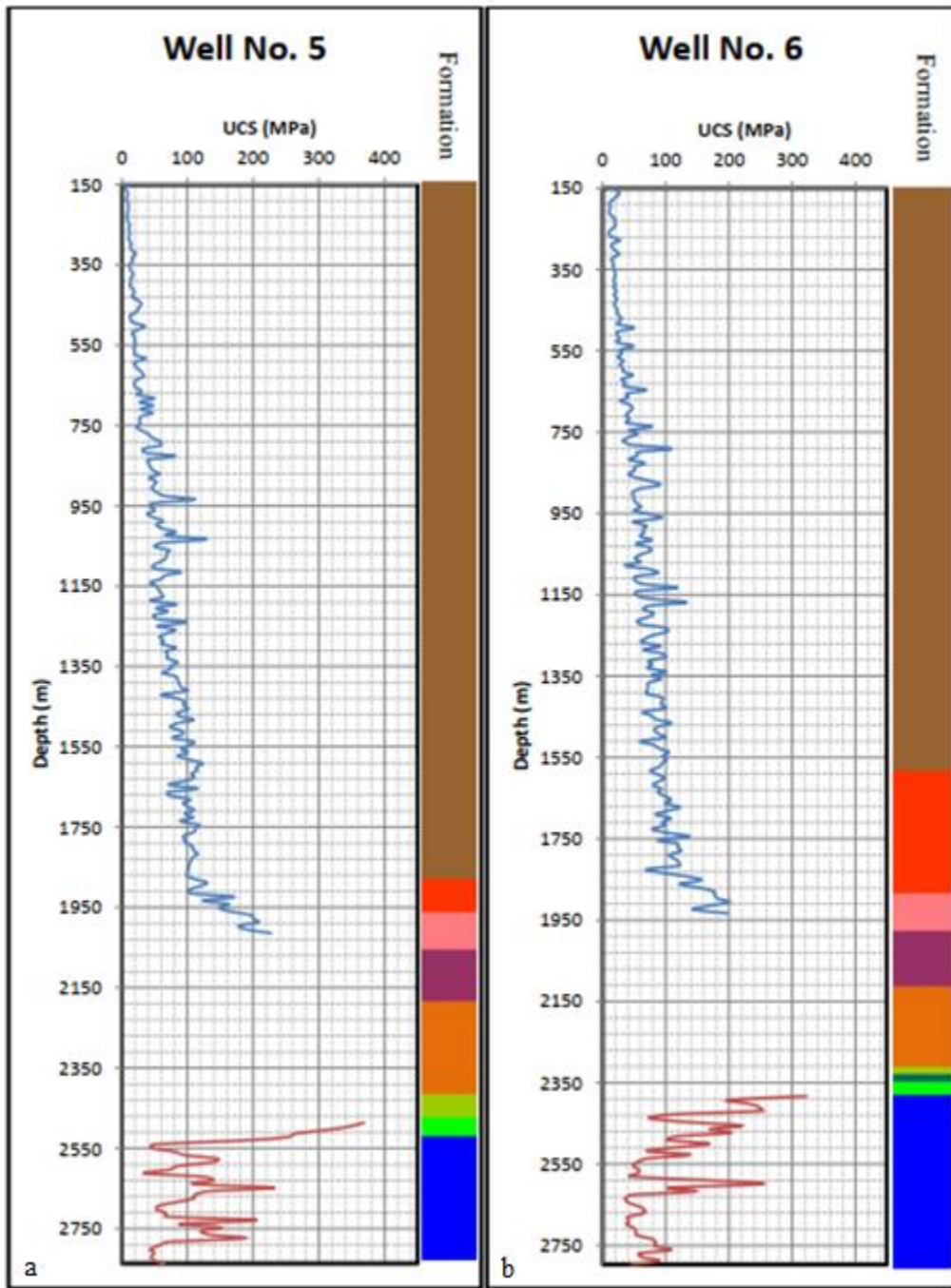
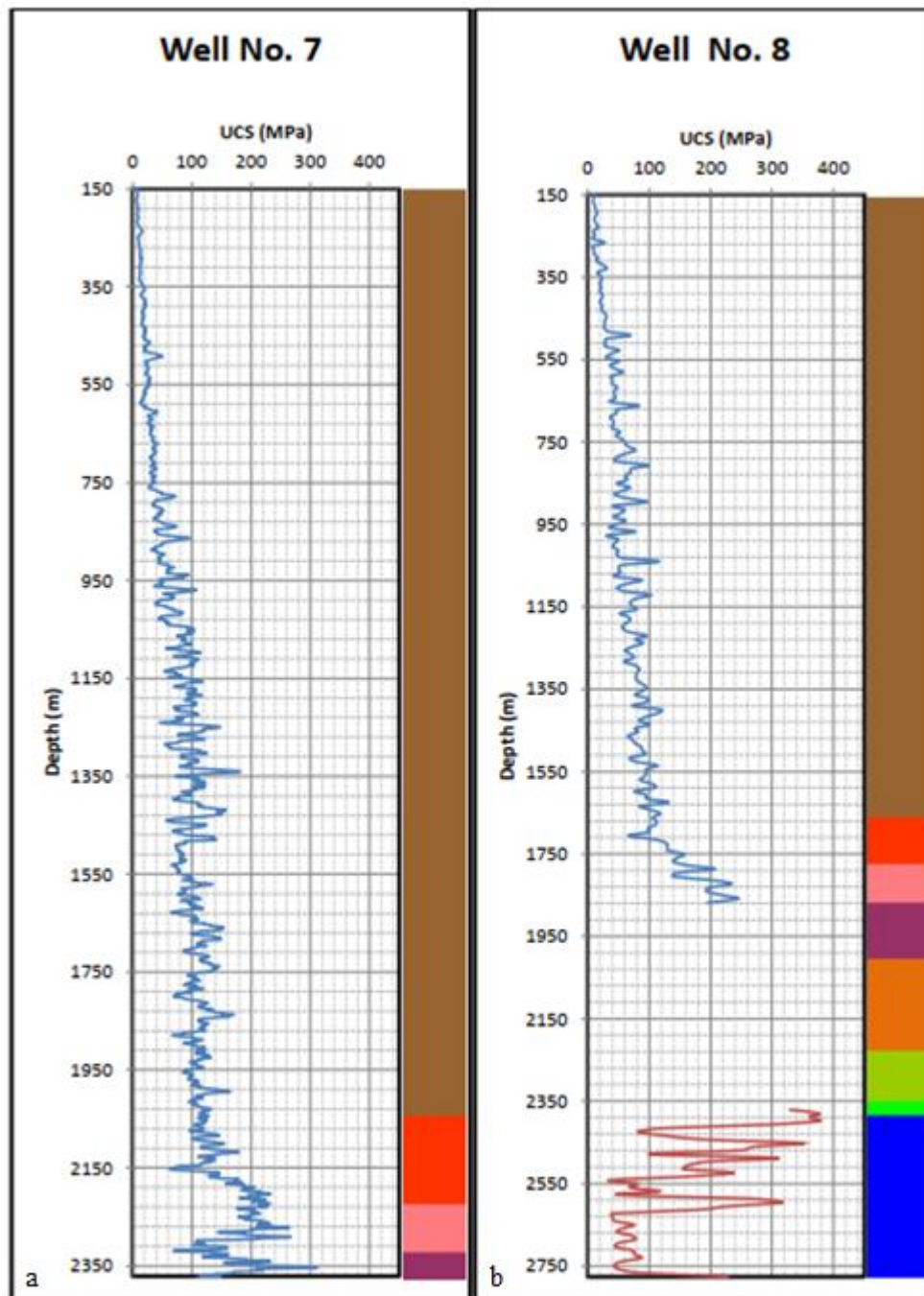


Figure 20. UCS profile: a) Well No.5 and b) Well No.6.



**Figure 21.** UCS profile: a) Well No.7 and b) Well No.8.

#### 4. Conclusions

The development of rock strength profiles along the wellbore can be done via the application of multiple methods. The most accurate method on preserved core samples is rock mechanical laboratory testing. The drawback of using laboratory results for drilling applications are the consumption of time and unavailability of core samples. Furthermore, core samples of overburden formations are not available for testing.

As an alternative tool for the prediction of rock compressive strength, drilling data can be used. The ROP models needs to include all the parameters that influence ROP, such as operational drilling parameters (e.g. WOB, RPM, flow rate, mud weight and type), bit types and wear and the rock formation properties. It is clear that gathering of all needed parameters using drilling data to compute compressive strength is difficult and time consuming but it can prepare a profile for compressive strength along the wellbore.

A number of empirical correlations have been proposed as a practical method to these problems which relate rock strength to parameters measurable with geophysical well logs. Approximately all proposed formulae for determination of rock strength from geophysical logs utilize porosity, sonic travel time or elastic modulus to predict uniaxial compressive strength of rocks.

The goal of this paper was to calculate the compressive strength of an oilfield formation from sonic log parameters. Since the number of empirical correlations that can be selected is too much, it was necessary to find the best correlation to match the UCS profile resulting from drilling data method. So, we tried to find a UCS profile from drilling data and then compared it with the UCS results from different empirical correlations. We found that Fjaer correlation almost matched UCS results of drilling data, Fajer correlation was used in our study.

To find the UCS profile of this oilfield, eight wells were chosen with reasonable distance to cover the entire of oilfield. By using Fjaer correlation and well logging data, the UCS profile were calculated for different wellbores. The results for different wells were same for each well.

Based on the results of this study, the following conclusions can be drawn:

1. Predicted UCS relate a healthy relation with UCS derived from different lithology types.
2. For different wellbores, the trend of UCS is nearly the same in entire of the field.

Based on Fjaer correlation and Deer and Miller classification, the studied oilfield can be classified based on the strength of the rocks.

## References

- [1] Moos D, Peska P, Finkbeiner T and Zoback M 2003 Comprehensive wellbore stability analysis utilizing Quantitative Risk Assessment *J Petrol Sci Eng* **38** 97-109
- [2] Santarelli F, Detienne J and Zundel J 1989 Determination of the Mechanical Properties of Deep Reservoir Sandstones to Assess the Likelihood of Sand Production. In: *ISRM International Symposium*, (Pau, France: International Society for Rock Mechanics and Rock Engineering)
- [3] Zoback M D, Barton C A, Brudy M, Castillo D A, Finkbeiner T, Grollmund B R, Moos D B, Peska P, Ward C D and Wiprut D J 2003 Determination of stress orientation and magnitude in deep wells *International Journal of Rock Mechanics and Mining Sciences* **40** 1049-76
- [4] Nygaard R and Hareland G 2007 Application of Rock Strength in Drilling Evaluation. In: *Latin American & Caribbean Petroleum Engineering Conference*, (Buenos Aires, Argentina: Society of Petroleum Engineers)
- [5] Chang C D, Zoback M D and Khaksar A 2006 Empirical relations between rock strength and physical properties in sedimentary rocks *J Petrol Sci Eng* **51** 223-37
- [6] Zausa F, Civolani L, Brignoli M and Santarelli F 1997 Real-Time Wellbore Stability Analysis at the Rig-Site. In: *SPE/IADC Drilling Conference*, (Amsterdam, Netherlands: Society of Petroleum Engineers)
- [7] Hareland G and Hoberock L 1993 Use of Drilling Parameters To Predict In-Situ Stress Bounds. In: *SPE/IADC Drilling Conference*, (Amsterdam, Netherlands: Society of Petroleum Engineers)
- [8] Rampersad P, Hareland G and Boonyapaluk P 1994 Drilling Optimization Using Drilling Data and Available Technology. In: *SPE Latin America/Caribbean Petroleum Engineering Conference*, (Buenos Aires, Argentina: Society of Petroleum Engineers)
- [9] Warren T M 1987 Penetration Rate Performance of Roller Cone Bits *SPE Drilling Engineering* **2** 9-18



- [10] Hareland G and Nygaard R 2007 Calculating Unconfined Rock Strength From Drilling Data. In: *1st Canada - U.S. Rock Mechanics Symposium*, (Vancouver, Canada: American Rock Mechanics Association)
- [11] Hareland G and Rampersad P 1994 Drag - Bit Model Including Wear. In: *SPE Latin America/Caribbean Petroleum Engineering Conference*, (Buenos Aires, Argentina: Society of Petroleum Engineers)
- [12] Hudson J A and Harrison J P 2000 *Engineering Rock Mechanics: An Introduction to the Principles*: Elsevier)
- [13] Andrews R J, Hareland G, Nygaard R, Engler T W and Virginillo B K 2007 Methods of Using Logs to Quantify Drillability. In: *Rocky Mountain Oil & Gas Technology Symposium*, (Denver, Colorado, U.S.A: Society of Petroleum Engineers)
- [14] Fjar E, Holt R M, Raaen A, Risnes R and Horsrud P 2008 *Petroleum related rock mechanics* vol 53: Elsevier)
- [15] Goodman R E 1989 *Introduction to Rock Mechanics* vol 2: Wiley New York)
- [16] Bataee M and Irawan S 2014 Review of Geomechanical Application in Reservoir Modeling *Journal of Applied Sciences* **14** 981-90
- [17] Bataee M and Mohseni S 2011 Application of Artificial Intelligent Systems in ROP Optimization: a Case Study. In: *SPE Middle East Unconventional Gas Conference and Exhibition*, (Muscat, Oman: Society of Petroleum Engineers)
- [18] Rashidi B, Hareland G and Nygaard R 2008 Real-Time Drill Bit Wear Prediction by Combining Rock Energy and Drilling Strength Concepts. In: *Abu Dhabi International Petroleum Exhibition and Conference*, (Abu Dhabi, UAE: Society of Petroleum Engineers)
- [19] Bataee M, Edalatkhah S and Ashena R 2010 Comparison between Bit Optimization Using Artificial Neural Network and Other Methods Base on Log Analysis Applied in Shadegan Oil Field. In: *International Oil and Gas Conference and Exhibition in China*, (Beijing, China: Society of Petroleum Engineers)
- [20] Bataee M, Irawan S and Kamyab M 2014 Artificial Neural Network Model for Prediction of Drilling Rate of Penetration and Optimization of Parameters *Journal of the Japan Petroleum Institute* **57** 65-70
- [21] Knowledgebase A 2017 Determining rock dynamics properties , Static test methodology. iRing INC)
- [22] Freyburg E 1972 Der Untere und mittlere Buntsandstein SW-Thuringen in seinen gesteintechnischen Eigenschaften *Deutsche Gesellschaft Geologische Wissenschaften. A; Berlin* **176** 911-9
- [23] McNally G H 1987 Estimation of coal measures rock strength using sonic and neutron logs *Geoexploration* **24** 381-95
- [24] Moos D, Zoback M D and Bailey L 2001 Feasibility Study of the Stability of Openhole Multilaterals, Cook Inlet, Alaska *SPE Drilling & Completion* **16** 140-5
- [25] Bradford I, Fuller J, Thompson P and Walsgrove T 1998 Benefits of Assessing the Solids Production Risk in a North Sea Reservoir using Elastoplastic Modelling. In: *SPE/ISRM Rock Mechanics in Petroleum Engineering*, (Trondheim, Norway: Society of Petroleum Engineers)
- [26] Horsrud P 2001 Estimating Mechanical Properties of Shale From Empirical Correlations *SPE Drilling & Completion* **16** 68-73
- [27] Lal M 1999 Shale Stability: Drilling Fluid Interaction and Shale Strength. In: *SPE Asia Pacific Oil and Gas Conference and Exhibition*, (Jakarta, Indonesia: Society of Petroleum Engineers)
- [28] Militzer M and Stoll R 1973 Einige Beitrageder geophysics zur primadatenerfassung im Bergbau *Neue Bergbautechnik, Lipzig* **3** 21-5
- [29] Golubev A and Rabinovich G 1976 Resultaty primeneia appartury akusticeskogo karotasa dlja predeleina proconstykh svoistv gornych porod na mestorosdeniaach tverdykh isjopaemykh *Prikl. Geofiz. Moskva* **73** 109-16