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A Novel Rate of Penetration Prediction Model for Hybrid Bit in Highly Unconfined Compressive Strength Formation

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Abstract

Predicting the rate of penetration before drilling is important to enhance the drilling potency and thereby scale back the invisible lost time and cost. For this, a sensible prediction model is essential. In Sinai Oil fields, Sidri concession, 8 1/2" section consists of conglomerates with overall Unconfined Compressive Strength varies from 20,000 to 40,000 psi. Which primarily drilled with polycrystalline Diamond Compact bits and tungsten carbide insert drill bits. Drilling 1000 meters in the 8-1/2" section required a minimum of 6 to 8 drill bits with an average rate of penetration of 2.8 meter per hour and also the average drilled interval of 135 meters per one bit. On the other hand, the hybrid bit achieved the best record and therefore the longest drilled interval in Sidri concession achieving 200 % improvement from offsets average performance. The new Hybrid bits weren't tested for the best prediction model to estimate the drilling performance. In this paper, 5 techniques are used to model field data. These methods are multiple regression, MSE, D-exponent, Bingham, and the Warren model. Four wells are used for the analysis within in Sidri concession in Sinai oil fields. The models testing using plot and time comparisons showed that the Warren model gives the best match with actual ROP profile data then the MSE model becomes second in class for matching actual ROP data.

Keywords*: Bazhenov Formation; Abnormally high reservoir pressure; Blowout equipment; Preventer; Shale oil; Drilling; Coiled tubing installation; Well.*

1. Introduction

Normally drilling process is the highest costing phase in petroleum industry. During the planning phase, drilling optimization studies were implemented. That can be characterized by the higher rate of penetration, which reduces drilling time, bit wear, tripping time, and therefore overall drilling costs. So that, it is important to have a good ROP predictive model. The basic idea of drilling optimization relies on using old data of existing wells. Data of similar wells, in similar geological characteristics, are collected to operate a process of Well drilling at minimum costs, operational risks. ROP is one of the parameters that can be analyzed to achieve this goal [1].

There are different ROP models available that use different drilling mechanical and operational parameters. Depending on the simplicity and complex nature of the models, their prediction also varies. So that every model has its shortcomings and its strong sides. For instance, Galle and Woods [2] have developed a model for drilling soft-formations. However, Hareland and Rampersad [3] developed their model only for drag bits. Bingham's [4] model is applicable for low WOB and rotational speed [5].

In Sinai Oil fields, Sidri concession, the 8 1/2" hole section is considered the most challenging section to the success of the entire wells. The challenges in this section are a lot; the high unconfined compressive strength of conglomeratic formation along the whole section, torque fluctuation, high vibrations that were introduced with PDC bits that led to high bit wear in a short time. As a result of the previous challenges, the operator was suffering from the high cost per every drilled meter and the time consumed in drilling that section. TCI drill bits had drawbacks during drilling of this formation such as low ROP, bit bearing failures due to high torque generated in drilling high unconfined compressive strength formation. Each drill bit type has its strengths and weaknesses; therefore, each is suitable for specific applications. Sometimes, specific technology matches well with the application, and it is the ideal solution [6]. Hybrid drill bit technologies produced a new generation of drill bits. The Hybrid bit combines both roller cone bit and PDC bit in one. it combines the best of the two drill bits, using the high drilling performance of the Diamond PDC bit and the stability of the Roller cone bit. It also combines the formation crushing action of the Roller cone bit and the shear cutting action of the PDC bit. The rolling cones are positioned partially towards the back of the blades to open up a bigger junk slot for cutting evacuation [7].

Figure 1. KYMERA Hybrid Bit (KM524)

8 1/2" KYMERA Hybrid drill bit (Type: KM524, 4 Blades, cutter size: 0.529 in and 4 nozzles) had been used in several wells, and via comparing the drilled intervals, ROP, and the cost per meter with offset wells and over monitoring the optimum drilling parameters, it had been observed that hybrid bit achieved all the operator targets with highest ROP and longest drilled interval [8].

The target of this paper is to use the collected drilling data to test different ROP models for the new Hybrid drill bit in the same hole section with the actual ROP in three nearby wells. And therefore introduce the best ROP model matches with new KYMERA Hybrid bit technology.

2. Methodology

The target in Sidri area is the conglomerate formation. The thickness of Conglomerate ranges from 900 m to 1500 m and with the same lithology. The conglomerate formation has high unconfined compressive strength (UCS) that varies between 25,000 – 40,000 psi which is composed mainly of 95 % granitic fragment which had been formed from basement erosion. Four drilled wells have been selected for this study (X, Y, Z & S). One well (Well-X) has been selected to be a reference well to develop the ROP model. three wells (Y, Z & S) have been used to check the reliability of the developed ROP model. The location map and well-to-well correlation of the four studied wells are shown in Fig. (2 & 3).

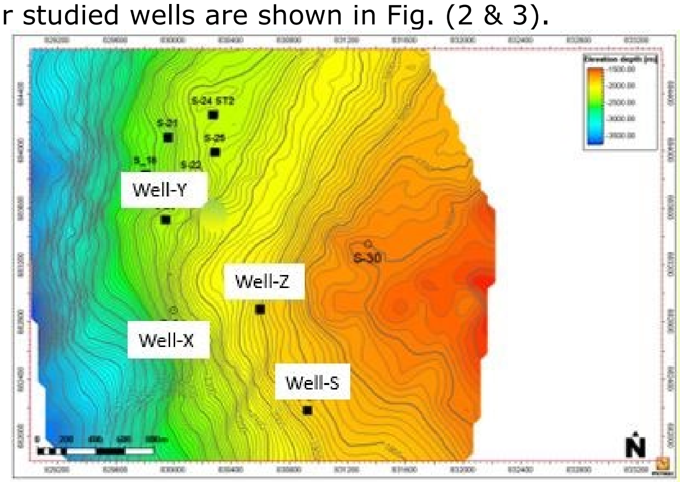

Figure 2. Geological map of the four selected wells

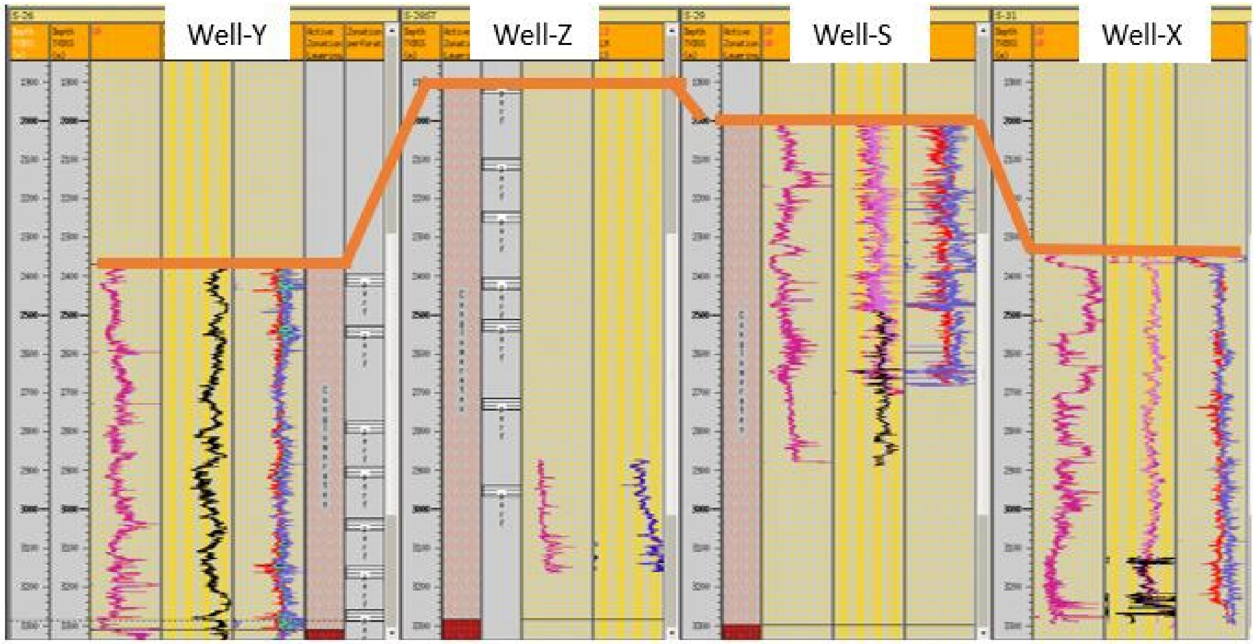

Figure 3. Four wells cross-section

3. ROP models

The process of optimization depends on many factors and parameters. These parameters stand as obstacles to increase the ROP and reduce the non-productive time and costs of the drilling operations. Some of the parameters are controllable such as the weight on bit (WOB), rotary speed of drill string (RPM), bit type, flow rate, and mud properties. On other hand, other parameters are uncontrollable like formation pressure and mechanical properties. several mathematical models are suggested to analyze the parameters, describe their relationship with the rate of penetration, and find solutions to have control over them as described below [9].

3.1. MSE - mechanical specific energy concept

In 1965, Teale [10] has proposed the concept of mechanical specific energy (MSE). By definition, it's defined as input energy to the output ROP [11].

$$\mathrm{MSE} \approx \frac{\text{Input Energy}}{\text{Output ROP}} \qquad (1)$$

MSE is a quantitative technique that estimates the power required to drill a specific formation type and given bit type [12].

$$MSE = \frac{480*T*N}{Db^2*ROP} + \frac{4WOB}{\pi*Db^2} \qquad (2)$$

In order to achieve the highest possible ROP, the MSE should be kept as low as possible. Which should close as possible to the formation's compressive. Teale's assumed the MSE value would equal the rock compressive strength at perfect efficiency. However, the efficiency of drill bits at peak performance (before reaching founder point) always in the range of 30-40%.

3.2. Warren model

In 1981, Warren [5] presented a model to predict ROP for soft-formation tri-cone bits. The model was derived with experimental data that were obtained from laboratory tests. That performed using large-scale rig under conditions similar to that experienced in the field. The model relates ROP to the rock strength, WOB, rotary speed, bit type, and bit size in the given formula [13].

$$ROP = \left(\frac{\mathrm{a}s^2 Db^3}{N\,WOB^2} + \frac{\mathrm{b}}{\mathrm{N\,Db}} + \frac{c\,Db\,\gamma\,\mu}{Fm}\right)^{-1} \qquad (3)$$

Here the constants (a, b, and c) are the bit constants in penetration model

3.3. Bingham model

Bingham's (1964) ROP model constructed an empirical relation that is applicable for all bit types. he suggested the following laboratory-derived equation which is applicable for low WOB and rotational speed (N) [9, 14]:

$$ROP = K\left(\frac{WOB}{Db}\right)^{a5} N \qquad (4)$$

Where, (K) is the constant of proportionality that includes the effect of rock strength and (a_5) is the bit weight exponent. There are the minimum and maximum coefficient bounds for proper computation of these two model coefficients to fit the model to field data.

3.4. Drillability D-exponent

This technique assumes that the drillability of a well is correlative within nearby wells provided that the lateral geology features are quite similar. The D-exponent depends on both the strength and the pressure of rocks, which can differ significantly between wells. The D-exponent is proportional to rock strength and increases linearly with depth for normally pressured formations. While it decreases with depth for abnormally pressurized formations (shales). Here is below the formula clarifying the relation between ROP and D-exponent dimensionless variable [15-16].

$$ROP = 10^{\left(Dexp*\log\left(\frac{12WOB}{10^6 Db}\right)+log60\ N\right)} \qquad (5)$$

This method is also affected by other factors that can narrow its functions, just like the lithology, bit type, bit wear, motor or turbine runs, and unconformities in the formation [17].

3.5. Multiple regression analysis

Regression analysis is used to give the relationships among one dependent and two or more independent variables. This method takes into account changes of several properties simultaneously. The multiple regression. Equation of Y on X1, X2… is commonly given by Y = b0 + b1 X1 + b2 X2 + … [18]. Where b0 is the intercept and b1, b2… are analogs to the slope in a linear regression equation, also called regression coefficients [18]. This flexible method of data analysis can be applicable when a quantitative variable is to be examined concerning other factors [19]. The ROP would be referred to it as the factor of observation (Y) and Relevant drilling parameters make up the regression variables ($X1-5$). By having these values in a Microsoft Excel sheet and by processing the regression data analysis, we will end up with the values of the coefficients ($b0-5$). Now, by having the values of the coefficients, we will be able to estimate the ROP values from the below equation.

$$ROP = 0.582396 + -0.0027\ Depth + 0.014381\ Flowrate + -0.0842\ WOB + 0.02776\ RPM + 0.657027\ Torque + -5.2E\text{-}05\ UCS \qquad (6)$$

4. ROP modelling and testing result

The Drilling data of four wells in Sidri concession of the Sinai oil field is used to verify the accuracy of the models presented in this paper. The drilling data was collected from mud log reports for each well. Except S & JIF from the below equations:

$$Fm = \frac{Q*(\gamma*\Delta P)^{0.5}}{57.8}; \qquad S = 277EXP\,(-10\emptyset)$$ [20]

The method of implementing the techniques and models to predict ROP in this study is largely based on the well-to-well correlation procedure. Together with drilling data, coefficients are used to obtain the ROP for a well. These coefficients are then used together with drilling data for a close-by well to predict the ROP of this well. It is supposed that neighbor Well will have comparable effects from drilling parameters on the ROP. Different techniques were tested in this study to determine these coefficients.

Multiple regression techniques are used to obtain coefficients (3.5). Four models have been altered to similarly be used to correlate well-to-well. Instead of using a selection of coefficients, a specific value is calculated based on well data and ROP. This value is then used in the same model for a close-by well to calculate the ROP. This procedure is done with a drillability D-exponent model (3.4), Bingham model (3.3), warren model (3.2), and the MSE model (3.1).

In "Well-Z" used another bit type (PDC bit) within the interval between (2491 to 2819 meters), so the ROP values deviate from the normal trend due to that effect. This effect was removed from plot and time comparison techniques. Also, all wells were planned with oil base mud system "1.05 KG/L" but in "Well-S" used Dyna-Drill Water-base mud "1.12 KG/L" due to logistic problem. That affects the ROP profile in certain models.

4.1. MSE model

The MSE profile of the reference well was initially constructed then calculated the ROP model profile for the other three wells.

Figure 4, shows the comparison between actual and MSE predicted ROP model profiles. For the reference Well The calculated profile is identical to the actual one with no gaps. the other three Wells show a fairly good match (except the mentioned interval 2491 to 2819 in well-Z) as the model assumes that the amount of energy that is required to drill a certain volume of rock is correlative within nearby wells.

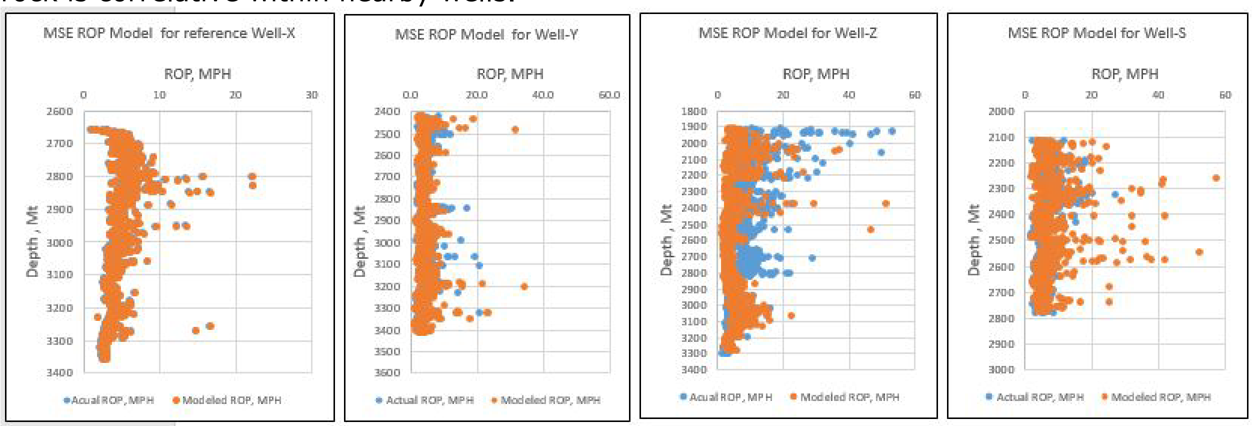

Figure 1. MSE model vs actual ROP

4.2. Warren model

The model is applied on reference well to get warren constants and applied those constants to get the below Warren Equation then those constants used accompanied with the drilling data to build the model profile. As seen in Figure 5, the predicted ROP of the reference well appears to fit well with the actual ROP profile. Similarly, the predicted ROP values appear to close to the actual values in the whole section of Well-Y and Well-Z (except the said interval) but tend to deviate only in "Well-S" due to the effect of increasing mud weight on that well.

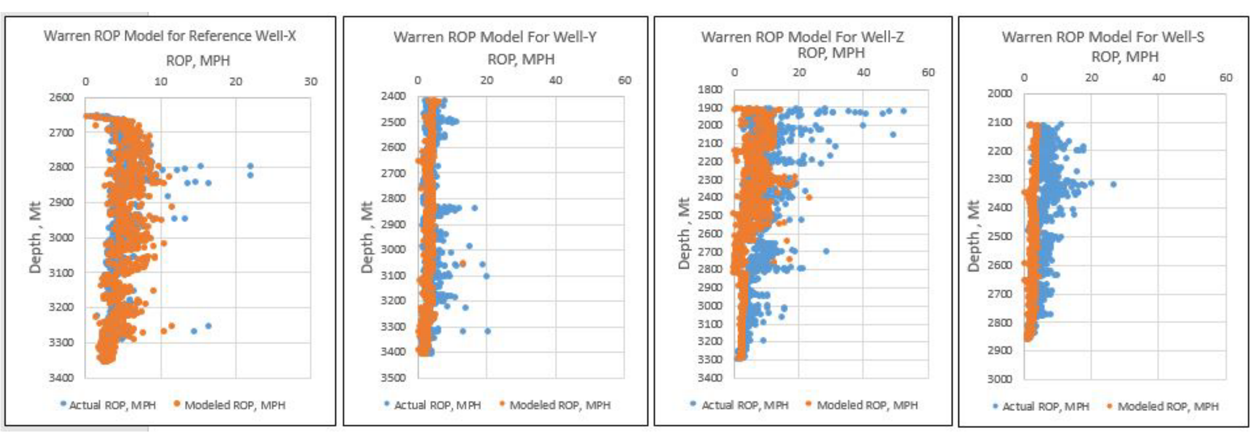

Figure 2. Warren model VS Actual ROP

4.3. Bingham model

The model is applied on reference well to get Bingham constants to get the Bingham equation as below, then used that constants associated with the drilling data to construct the model profile. As illustrated in Figure 6, the predicted ROP appears to not fairly match with the actual ROP profile of reference Well. Similarly, the predicted ROP values seem not fairly matched with the actual profile in all wells. As Bingham model neglect the drilling depth and effectively applicable for low WOB and RPM.

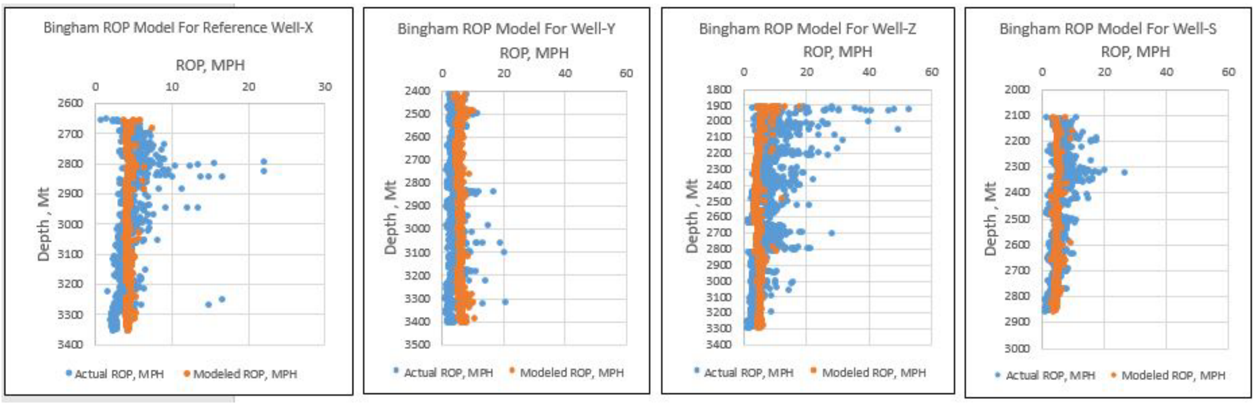

Figure 3. Bingham model vs actual ROP

4.4. Drillability D-exponent

The D-exponents profile of the reference well has been first calculated. Then both actual and calculated D-exponents are compared as shown in Figure 7 the calculated profiles of the reference Well is identical with the actual one with no gaps.

Similarly, the D-exponent model was tested by comparing the actual ROP profile with the predicted profiles for the other three wells. The predicted ROP values appear to close to the actual values in the whole section and tend to deviate little bit in the most upper 300 meters (especially in Well-Z), this is due to the depth change between those wells and the reference well. this model is highly affected by rock strength.

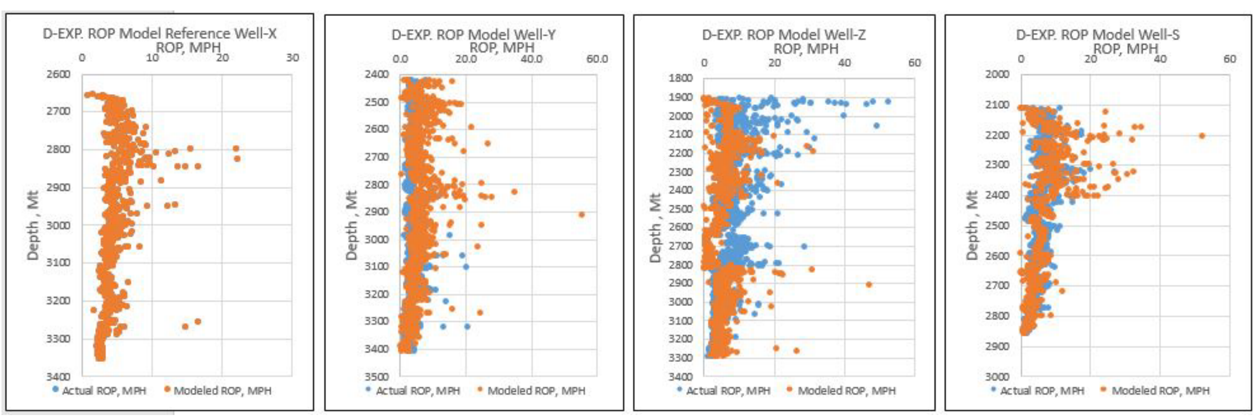

Figure 4. D-Exponent model vs actual ROP

4.5. Multiple regression

Relevant drilling data for each well is uploaded in Microsoft Excel file. The data used for the multiple regression analysis is depth, RPM, flow rate, UCS, WOB, and torque, together with the observation factor ROP. The analysis then provides output data it has computed, where the coefficients are of interest. The first value of coefficients is the intercept (b0). The following coefficients (b_{1-7}) are to be multiplied with the regression variables according to their order. ROP is modeled from the below equation.

The computed curve fitting correlation coefficients are provided in the above equation. Mud weight and ECD effects were not used as in all wells "1.05 KG/L OBM" were used while in "well-S" used "1.12 KG/L WBM" which affects ROP prediction.

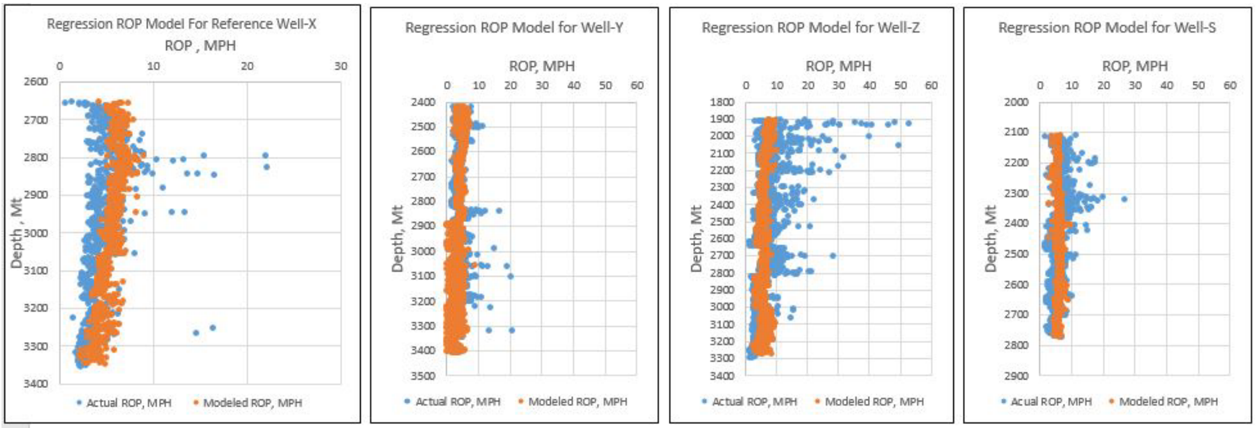

Figure 5. Multiple regression model vs actual ROP

The model is applied on reference well to get multi-regression constants then used those constants with the drilling data to establish the model profile. Figure 8 shows the modeled ROP profile appears to be not fairly matched with reference Well ROP actual profile. Similarly, the multi-regression ROP model was tested by comparing the actual ROP profile with the predicted profiles for the other three wells. The predicted ROP values appear to close to the actual values in the whole section in Well-Y and tend to have poor data resolution on the other two wells. A Large deviation from actual profile especially at top and middle section depth and match on the bottom section.

4.6. Plot comparison

Producing identical plots is highly unlikely, however within a specific margin is achievable. A method is therefore implemented to identify how much of the predicted ROP plot remains within certain margins of the observed plot. +/- 10 % margins are selected and used to give a practical analysis.

In order to identify the amount of a plot that is within a margin, a method is introduced. This method gives the percentages of the plot within the margin. An increase in the percent of a plot within the margins increases the validity of the method used to generate that plot. To attain the percentages of the plot within the margins (see the below equation). The equation is applied to all ROP modeled data plots. The equation generates "1" values if the ROP predicted plot is within the given boundaries, and "0" values if not. Finding the average of the resulting values will generate the percentage of the plot within the margins.

$((ROPpredicted) = MEDIAN\ ((ROP{-}10\%) : (ROP{+}10\%));\ 1;\ 0$

This process is applied for all generated plots of the predicted ROP model for each well to obtain the ROP model coefficient on each well. Then got the average value of each model in four wells to obtain the one coefficient for each model as shown in tables 1. But Well-S average value was not considered in table 1 the total average value due to mud weight difference effect.

Table 1.Model plot comparison using average coefficient of three wells for +/-10% margin

	D-EXP	MSE	Bingham	Warren	Regression
Well Y	0.3403	0.5299	0.2475	0.5538	0.4484
Well Z	0.3342	0.3336	0.2795	0.5184	0.3849

4.7. Time comparison

The objective of time comparison analysis is to compare the total drilling time of the estimated ROP with the actual drilling time derived from the observed ROP. This analysis boosts methods that might not estimate ROP plots well, but can still determine a good overall drilling time estimate. Results of this analysis simply state the amount and the absolute percentages of time deviation of the predicted ROP time depending on the below equation. But Well-S average value was not considered in the total average value in Table 2 due to mud weight difference effect. Drilling time = drilled interval/ROP.

Table 2. Model time comparison using average deviation coefficient

	D-EXP	MSE	Bingham	Warren	Regression
Well Y	0.3496	0.0823	0.3613	0.0909	0.0493
Well Z	0.2239	0.0922	0.1149	0.0779	0.2257
Well S	0.2293	0.9178	0.3761	1.2747	0.1388
Average %	26.76	12.41	28.41	8.44	13.79

5. Conclusion

Warren model resulted in the best match with the actual ROP profile in both Well-Y and Well-Z together in both plot (53.61%) and time deviation comparison (8.44%) techniques but Well-S has poor match and appear to be under prediction in the whole profile due to the increasing of mud weight effect. MSE model resulted in a good match with actual ROP profile for the three Wells average value in both plot (42.15%) and time deviation comparison (12.41%) techniques. Also the model affected with depth difference in relative to the reference Well which shown in top section of Well-Z

Multiple regression techniques give a good match with actual ROP profile for the three Wells average value in both plot (43.65%) and time deviation comparison (13.79%) techniques. On the other hand, the curve resolution is very poor in Well-Z and Well-S comparing with the actual profile due to depth difference relative to reference Well. As the curve resolution enhanced with increasing depth.

D-Exponent and Bingham models resulted in poor match with actual ROP profile in the two comparison techniques. As D-Exponent model was greatly affected with depth difference with regard to the reference Well that is appeared in the top section of Well-Z. Also Bingham model has very low data resolution over the whole profiles due to the small number of parameters in its ROP prediction model (WOB, RPM & Bit size). In addition, the D-Exponent model appears to have better match than Bingham despite of having the same variables, because of the D-exponent includes the rock strength effect.

In Well-Z, there is an interval (2491 to 2819 meter) that drilled with other PDC bit that shows an increase in ROP on the actual profile, this increase is tricky in ROP model testing. The multi regression technique and Bingham model curves deflected towards increasing unlike others kept at low ROP for the modeled bit type. It was concluded that, Warren and then MSE ROP models introduce the best ROP model prediction the new KYMERA Hybrid bits which was the objective from this paper.

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Nomenclature

N	*surface revolution per minute (RPM)*
D_b	*bit size (in),*
WOB	*Weight on bit (klbs),*
T	*drilling torque (lb. ft),*
ROP	*rate of penetration (ft/hr)*
MSE	*mechanical specific energy (kpsi)*

S	*formation unconfined compressive strength (psi),*
F_m	*jet impact force (lbf),*
γ	*mud weight (ppg),*
μ	*apparent viscosity (cp).*
K	*Bingham model constant of proportionality*
a_5	*Bingham model bit weight exponent*
Q	*flow rate (gpm),*
ΔP	*pressure drop across the bit (psi).*
ø	*formation porosity (fraction)*

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