Calculating unconfined rock strength from drilling data

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ABSTRACT: It is critical to obtain the rock strength parameters along the wellbore. Rock strength logs are used to conduct different types of analysis such as preventing wellbore failure, deciding on completion design methods and controlling sand production. One source of data which is often overlooked in calculating rock strength is drilling data. To utilize the drilling data in calculating strength, correlations are developed from inverted rate of penetration models. From these models unconfined compressive rock strength can be calculated from drilling data. The rate of penetration models takes into account operational drilling parameters, bit types/designs and geological formation information. Results from various onshore and offshore fields verify that drilling based rock strength compares to other methods of estimating rock strength. The big advantage using drilling data is that rock strength can be calculated for all hole sections, less expensive onshore wells and from old wells, where electrical logs or preserved core samples do not exist.

1 INTRODUCTION

It is critical to obtain the rock strength information along the wellbore. For instance, it is critical in obtaining the safe mud weight window to avoid wellbore instabilities and when planning the casing program. Sand produced during oil extraction is also to a great extent controlled by the compressive strength of the reservoir sandstone. Rock strength also controls the drilling rate of penetration (ROP) and bit wear, and is therefore important information to the drilling engineer during drilling operations.

Information about the rock strength can be directly measured from rock mechanical tests, performed either at rig site or in the laboratory, or obtained indirectly from electrical log correlations. Well preserved core samples for conducting laboratory measurements are rare and logs are usually only available in the reservoir sections of the wells which will limit the availability of continuous rock strengths along the wellbore. Especially, the cap rock or the shale above the reservoir where wellbore stability is a concern does in many cases require detailed analysis. In this case using drilling data to get these rock mechanical properties, which are available for every meter of the well and for all hole sizes becomes an invaluable asset. However, drilling data are overlooked as a method for calculating rock strength. The objective of this paper is to show that unconfined rock strength based on drilling data compares to rock strength obtained from sonic correlations.

2 UCS CALCULATED FROM INVERTED ROP MODELS

2.1 *ROP models*

To reduce the well costs, one important task for the drilling engineer is to conduct drilling optimization analyses. One way to optimize the drilling operation is to increase the rate of penetration (ROP). Drilling optimization by utilizing ROP models has reduced drilling cost substantially (e.g. Nygaard et al. 2002). The ROP models are mathematical models which describe how the penetration rate is affected due to; changes in operational drilling parameters, changes in the rock properties, and changes in bit types and design.

There are several operational drilling parameters that affect the ROP and therefore need to be included in the model. Increasing weight on the bit will push the bit teeth or cutters further down into the formation, crush more rock, and thereby increase ROP. Increasing the rotational speed, measured as revolution per minute (RPM), will also remove more rock per minute and will therefore improve the ROP. Drilling mud, flowing through the bit nozzles, removes the loose rock chips away from the bit face. Mud and flow related drilling properties like; mud-density, flow rate, and viscosity will also influence the ROP. An ROP model needs to include the effect of all the parameters above such as, WOB, RPM, flow rate, mud density and viscosity.

The rock properties of the formations penetrated during the drilling of the well will also greatly affect the ROP. Increase in rock strength, which is an indirect drilling resistance, will also limit the teeth or cutters depth of cut for a given set of bit design and applied operating parameters. Pore pressure will to a large extent control the effective stresses in the formations. Over-pressured formations will reduce effective stresses and increase ROP compared to normally pressured zones. Actually, one of the methods to detect overpressure zones is to use a sudden increase in ROP over a short interval (drilling break) (Rehm & McLendon 1971). High abrasiveness of the rock will contribute to accelerated bit wear which indirectly reduces ROP.

The two main bit designs are roller cone and drag bits. Rollercone bits have three cones which rotate around their axis. On the cones, teeth are milled out of the matrix or inserted. The teeth combine crushing and shearing to fracture the rock. Drag bits, on the other hand, consist of a fixed cutter mechanism which can be cutting blades, diamond stones, or cutters. Today, the most common type of the drag bits are PDC bits which use Polycrystalline Diamond Compact (PDC) cutters mounted on the bit blades/body. The drag bits fracture the rock by shearing. Due to the difference in the design of rollercone and drag bits and how they fracture the rock, the different bit types are treated separately in the ROP models.

After a well is drilled, the drilling and bit parameters (such as WOB, RPM, flow rate, nozzles, bit design and well diameter) in combination with drilling conditions (mud properties and pore pressure) and the resulting ROP are known. These data are then used in a ROP model to generate a drillability resistance. The drillability resistance is the resistance the bit has to overcome to shear the rock. It can be compared to rock strength, but the challenge is to develop similar results for the drillability resistance for different drilling parameters, bit designs and geologies. The goal is to create one unique rock strength log based on ROP models regardless if it was used rollercone or drag bits.

2.2 *ROP model for Roller cone bit*

Warren (1987) proposed the following ROP model for Rollercone bits:

$$ROP = \left(\frac{aS^2 d_b^3}{RPM^b WOB^2} + \frac{b}{RPM d_b} + \frac{c d_b^3 \mu MW}{0.000516 \rho q v_n} \right)^{-1} \quad (1)$$

In the equation above, S is the rock strength, RPM is rate of penetration, WOB is weight on bit, d_b is bit diameter, q flow rate, ρ is mud density, μ plastic viscosity, MW is mud weight, v_n bit nozzle velocity, and a, b, c are model constants.

After the well has been drilled all the information's are known and the equation above can be solved with respect to rock strength S. The first term $(aS^2 d_b^3)/(RPM^b WOB^2)$, defines the maximum rate at which the rock is broken into small chips by the bit. It is based on the assumptions that the WOB is supported by a fixed number of teeth, independent of the tooth penetration depth. The second term $b/(RPM d_b)$ modifies the predictions to account for the distribution of the applied WOB to more teeth as the WOB is increased and the teeth penetrate deeper into the rock. The first two parts of the equation is called the perfect cleaning model since its does not include the reduction of ROP due to cuttings removal. When ROP is high, it may be slowed down if the rock cuttings are not removed fast enough away from the bottom of the hole. The teeth are then hindered by cuttings to penetrate new rock. To encounter for this effect the third term in the model $(c d_b^3 \gamma_f \mu)/(0.000516 \rho q v_n)$ models the rate cuttings are removed from the bottom, based on the hydraulic impact force and the properties of the mud for one set of nozzles (Warren 1987).

The Warren model excludes two important parameters which also alter the ROP. One effect is the effect of overbalance created by the pressure difference between mud weight MW and pore pressure PP given as:

$$pe = MW - PP \quad (2)$$

The higher mud weight, compared to the pressure in the pores below the bit, will push the already drilled rock chips to the bottom and reduce the effectiveness of the cleaning. This effect is called the chip-hold effect (Hareland & Hoberock 1993). Hareland & Hoberock (1993) included the following term in the Warren ROP model to encounter for the chip hold down function:

$$fc(pe) = cc + ac(pe - 120)^{bc} \quad (3)$$

Where cc, ac, bc are lithology dependant model constants and pe is defined in equation 2.

Second effect missing in the Warren model is bit wear. When the section is drilled the teeth of the rollercone bits start to wear and become dull. The stress on each cutter are reduced when the dullness increase the teeth area. Hence the ROP will reduce. This effect will increase the rock strength to unrealistically values for the ROP model given above. To obtain more realistic wear values Hareland et al. (1996) introduced the effect of bit wear in the ROP model as:

$$Wf = 1.0 - \frac{Wc \sum_{i=1} WOB_i RPM_i Abr_i S_i}{8.0} \quad (4)$$

The effect of bit wear is denoted wear factor (*Wf*) and is a value between 0 and 1. *W*c is a wear coefficient which is bit design specific, and has to mach the field reported bit wear. To calculate the effect of bit wear, the lithology dependant relative abrasiveness (Abr_i) of the rock needs to be known.

When the wear is included in the ROP model it gives a new ROP equations that include the main effects on ROP given as:

$$ROP = Wf \left(fc(pe) \left(\frac{aS^2 d_b^3}{RPM^b WOB^2} + \frac{b}{RPM d_b} \right) + \frac{c d_b^3 \gamma_f \mu}{0.000516 \rho q v_n} \right)^{-1} \quad (5)$$

The ROP model in Equation 5 from Hareland & Hoberock (1993) models the effects different operating conditions and rock strength has on ROP. However, in practical use the strength calculated from this model has not given a uniform rock strength which was universally transferable from well to well when bit design was changed.

To overcome this lack of transferability of the rock strength, a large number of field and laboratory observations has been analyzed to observe the effect various operational parameters has on ROP for rollercone bits. The results from this analysis are shown in Figure 1. Figure 1 plots the different operational conditions effects on ROP for a rollercone bit. From Figure 1 we can see that increase in WOB and RPM will increase the ROP. That is in alignment with the effects described above and also to the behavior in the Warren (1987) perfect cleaning model. Increase in flow rate and reduction in nozzle size gives an increase in ROP (Fig. 1). The hydraulic horsepower is a function of the flow rate, mud weight and nozzle size and follows the same ROP increasing trend. Increase in hydraulic horsepower (HHP) across the bit, increase in flow rate and reduction in nozzle sizes do also increase the ROP. It’s due to the improved cutting removal efficiency. Increase in mudweight (MW) and viscosity (PV) does both reduce ROP caused by the chip hold down effect. Increase in bit size reduces ROP since the weight is distributed over a larger area. To include the results from Figure 1 we have modified the ROP model in equation 5 to better simulate the operational effects on ROP as seen in Figure 1 to the form:

$$ROP = Wf \left(f(hyd) \left(\frac{aS^{(2-bs)} d_b^2}{RPM \cdot WOB^{(2-bs)}} \right) \right)^{-1} \quad (6)$$

For our perfect cleaning model we have introduced a new experimental constant b_e to fit the data in Figure 1. *a* is a bit dependant constant. The chip hold function and cutter cleaning of the ROP model in equation 5 is replaced by an effect based hydraulic formula (*f(hyd)*) that treats the effect of flow rate, mud weight and plastic viscosity, hydraulic horse power and nozzle sizes according to Figure 1. The rock strength S can then be calculated by inverting the rollercone bit ROP model in equation 6.

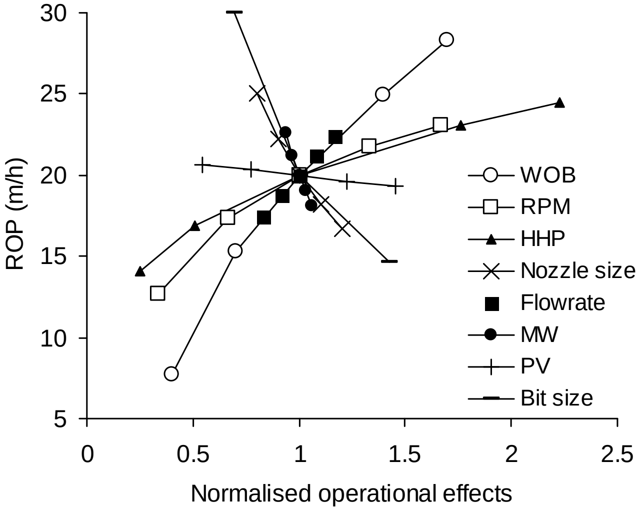

Figure 1. Normalized effects of operational parameters on ROP for rollercone bits. *HHP* is hydraulic horsepower. *PV* is plastic viscosity.

2.3 *ROP model for PDC bit*

The operational effects on ROP for new PDC bits are analyzed and are shown in Figure 2. Figure 2 gives the same information for a PDC bit as Figure 1 gives for rollercone bits. Figures 2 and 3 shows that increase in WOB, RPM, flow rate, HHP, and bit size increases the ROP. For Nozzle size, mudweight, plastic viscosity the effect is the opposite. The various operational parameters have similar ROP trends for both PDC and rollercone bits. Therefore, it may be expected that the ROP model for PDC bits can be of a similar form as the ROP model for rollercone bits.

However, PDC bits have different design parameters than rollercone bits and fail the rock only by shear. ROP models for PDC bits must therefore treat bit designs differently than the rollercone ROP models. PDC bits contain several small circular cutters of PDC material. Each individual cutter is in contact with the formation and creates a shear failure in front of the cutter and small chips of the rock named cuttings are removed from the bottom of the hole. The shear failure created by the cutter the depth is controlled by the weight on cutters. Therefore will an increase in number of cutter reduce the ROP (Figure 3). PDC cutters are oriented to formation at an angle from vertical, named back rake angle. In Figure 3 an increase in back rake (less aggressive) reduces ROP. The effect of the cutters oriented with at an angle sideways (side rake) can also be investigated. Bit with no side rake angles has a value of 0°. Change in this angle will also affect ROP as seen on Figure 3.

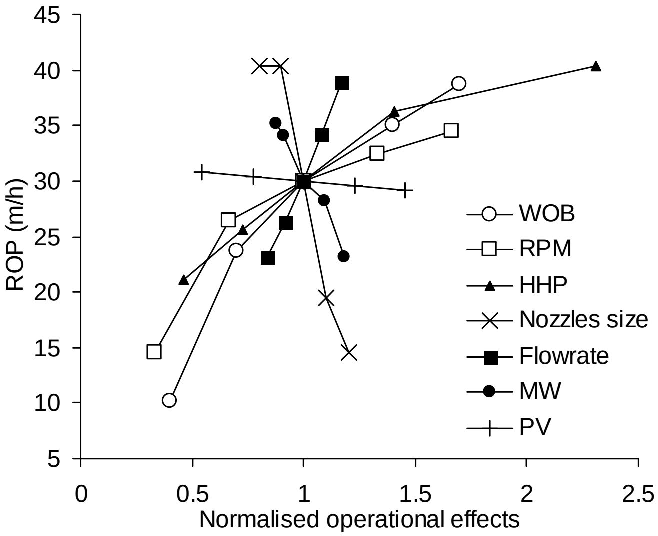

Figure 2. Normalized effects of operational parameters on ROP for a PDC bit.

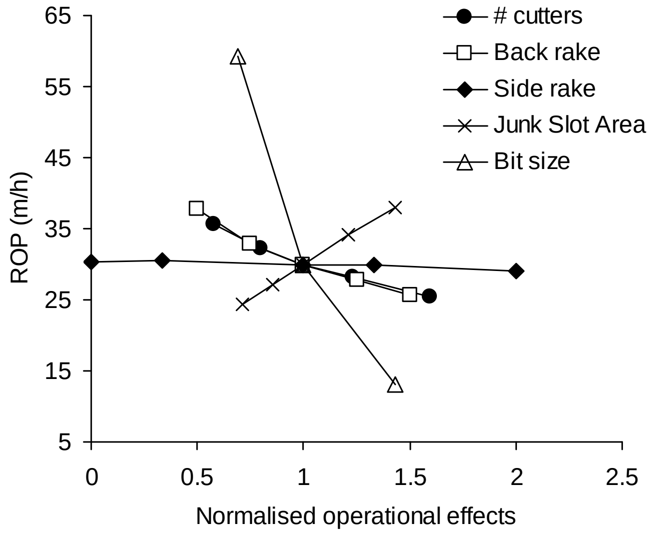

Figure 3. Normalized effects of PDC bit design parameters on ROP.

When the cutter starts to wear the wear of the cutters creates a wear area under the cutter which reduce the stress distributed under each cutter since the weight on each cutter is constant. The effect of increased wear flats is less depth of cut and results in a ROP reduction. To calculate the correct cutter wear the thickness of the cutter also needs to be considered. The specific bit information mentioned above has to be included in the PDC ROP model. The ROP model for PDC bits will then take a similar form as the ROP model for rollercone but with the bit specific details *f(bit)* for PDC bit:

$$ROP = Wf\left(f(hyd)\left(\frac{f(bit)\cdot aS^{(2-be)}\cdot d_b^2}{RPM\cdot WOB^{(2-be)}} \right) \right)^{-1} \qquad (7)$$

Equation 7 will reproduce the effects of operational and bit specific parameters on ROP for PDC bits (Figure 2 and 3). The *f(hyd)* reproduces the ROP effect of variation of nozzle sizes, hydraulic horsepower, flow rate, mudweight and the plastic viscosity of the mud. The bit specific function *f(bit)* normalize the effect of number and size of cutters and cutter back rake and side rake as shown in Figure 3.

2.4 *Calculating UCS from ROP models*

The rock strength calculated in the ROP models above is the rock strength, at the bit operating conditions, at the bottom of the hole. In ordinary drilling operations the mud weight are higher than the pore pressure and the bit operate under confined conditions. Therefore, the rock strength calculated in the ROP models is the confined rock strength. To calculate the unconfined rock strength a failure criteria is used of the form.

$$S = S_0\left(1 + a_s \cdot pe^{b_s}\right) \qquad (8)$$

S is the confined compressive rock strength. S_0 is unconfined compressive strength *pe* is overbalance given as difference between the mud weight and pore pressure. a_s,b_s are fitting constants for the failure criteria. Figure 4 shows sample values for the a_s,b_s constants which are calculated based on triaxial tests. For this triaxial rock tests the a_s and b_s constants were determined to be 0.24 and 0.68 for the shale and 0.30 and 0.70 for the sandstone.

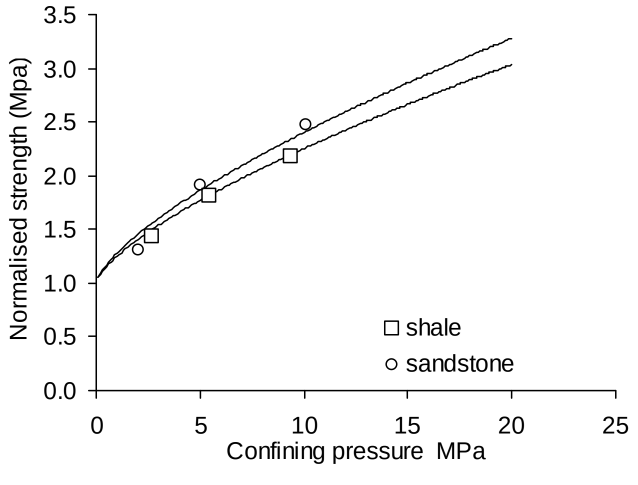

Figure 4. Determination of a_s and b_s values for shale and sandstones.

3 CALCULATING UCS FROM SONIC LOGS

The use of sonic velocity logs to determine elastic properties of rock is well established. There exist several correlations between rock strength and sonic travel time or a combination of different logs (e.g. Kasi et al. 1983, Tokle 1986, Onyia 1988). Onyia (1988) did 23 triaxial compressive laboratory tests from different lithologies. He developed a continuous rock strength log where he used the triaxial tests to calibrate the sonic travel times measured on a continuous well core. The continuous log based rock strength was correlated with the wireline sonic travel time and gave the relationship in Equation 9:

$$S_{0S} = \left(\frac{1.00}{k_1(\Delta t_c - k_2)} \right) + k_3 \tag{9}$$

Where Δt_c is travel time, S_{0S} is sonic based unconfined compressive and k_1, k_2, k_3 are constants. Our approach was to correlate sonic travel time measured on cores with unconfined compressive strength from triaxial tests. The failure criteria are derived from consolidated triaxial compressive rock mechanical tests on sandstone and shales cores. For each core depth consolidated compressive triaxial test was conducted. The triaxial tests were loaded to 2 MPa confining pressures before shearing. Details about the testing procedures and laboratory set up for the different materials are given in Nygaard et al. (2007). For each line a failure curve on the form given in equation 9 was derived to find the unconfined compressive strength for each depth. When the sample was consolidated sonic velocities were measured in the triaxial cell across the sample. In Figure 5 the shale and sandstone data are plotted with a best curve fit for the sandstones, shales and the combined curve fit for both samples. The experimental derived constants for equation 9 are given in Table 1. The data are partly scattered which shows that sonic velocity alone can not fully predict the rock strength. When comparing the rock strength from ROP models with the sonic correlations the combined correlation was used.

Table 1. Experimental constants for rock strength correlation based on sonic logs.

	k_1	k_2	k_3	r^2
Sandstone	0.0011	50	3.42	0.9
Shale	0.0013	50	-2.66	0.9
Combined	0.0012	50	0.22	0.9

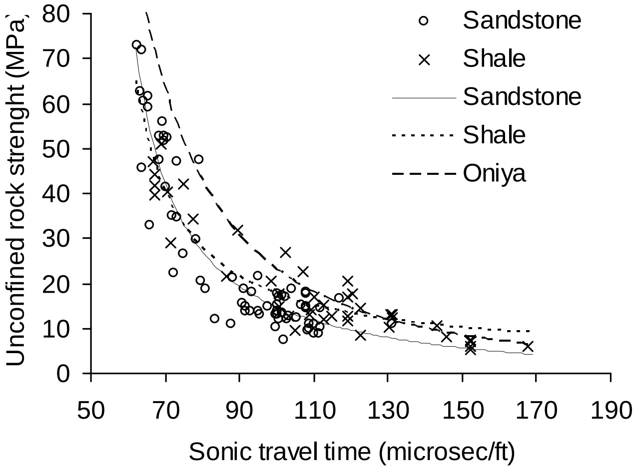

Figure 5. Unconfined compressive strength and sonic travel time correlations for shale and sandstone.

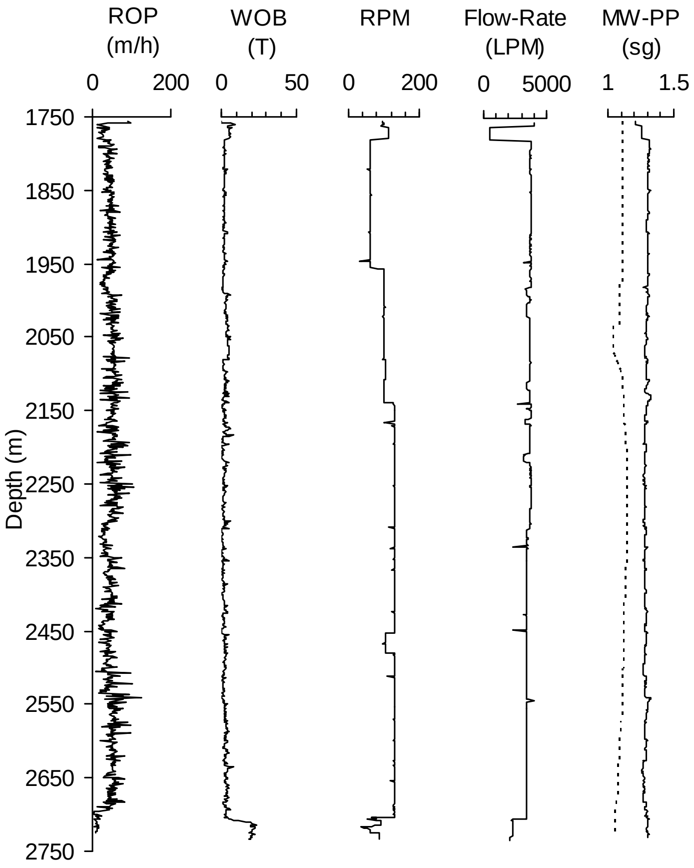

Figure 6. Operational data for a 12 ¼" section (Well A) in the North Sea.

4 FIELD VERIFICATION AND APPLICATION

To calculate the rock strength with the ROP models as described above drilling data, lithology information and bit data needs to be known. After a well is drilled all the information needed is available. In Figure 6 the drilling data for a 12 ¼ inch section (Well A) in the Norwegian Sea is given. Confined rock strength is then calculated based on the ROP model. Then the unconfined compressive strength is calculated according to Equation 8. The section was drilled with two different bits. The first 939 meter of section, down to 2696 m was drilled with a PDC bit. The last 28 meter was drilled with a rollercone bit. Each bit run had to be treated individually with the respective ROP model for PDC bit and rollercone bits. Based on the data in Figure 6 the rock strength is calculated and reported in Figure 7. A large portion of the section the formations are soft. The calculated rock strengths are less than 10 MPa for the interval down to 2670m. After 2670 harder formation was encountered and strengths peaks up to 70 MPa. To verify this strength log the strength for a close by 12 ¼ inch section in the field was calculated (Well B). The 12 ¼ inch section for well B was drilled with four rollercone bits. In Figure 7 the ROP based rock strength logs are overlaid for these two sections. The rock strengths logs show a very good match and verify the repeatability of developing rock strength with the use of drilling data regardless of bit types used.

Figure 8 show the results for ROP model based rock strength curves fro two different fields in the North Sea. Figure 8a gives the results for two 24 inch sections. Figure 8b shows the results from two 12 1/4” sections. The rock strength curves have a good repeatability for both examples. It further verifies that ROP based rock strength works for different areas, bit types and hole sizes.

The sonic based rock strength in Figure 7 is calculated based on the combo correlation developed above. The sonic based rock strength correlates with the ROP based strength for the section above 2670 where the strength is low. For the harder parts in the bottom of the section the sonic logs picks up the trend of the ROP models. However, the ROP models calculate higher values for the unconfined strength than the sonic log derived strength in the hardest part. To further investigate harder formations, ROP based rock strength was correlated with rock strength derived from rock mechanical tests from an Italian onshore field (Zausa et al. 1997). The rock mechanical tests are conducted on small cutting samples (Zausa et al. 1997). Possible fractures and weak zones that the ROP model based rock strength will experience as weaker zones will be left unnoticed by the rock mechanical based rock strength log. And they may not be completely comparable. But the rock strength derived from rock mechanical tests and the ROP model based rock strength match in trends and for actual values. This result strengthens the hypothesis that ROP rock strength correctly represents also the higher strengths values.

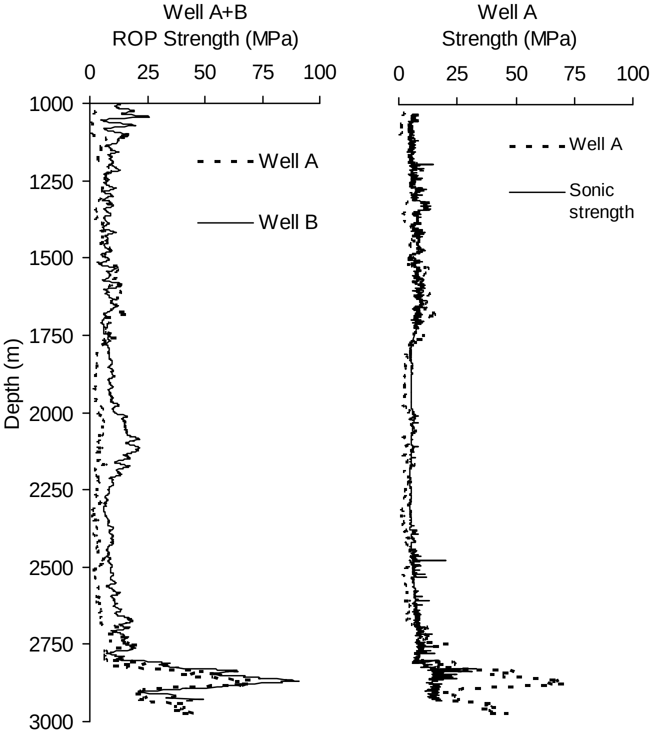

Figure 7. Rock strength calculated for two 12 ¼ inch section in the Norwegian Sea using ROP models and compared with sonic transit time derived rock strength.

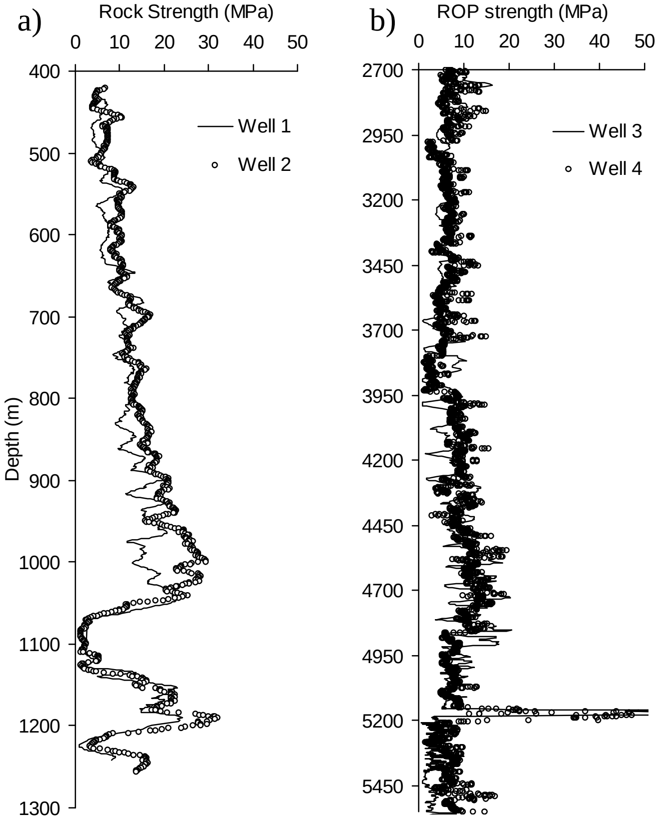

Figure 8. a) is ROP model based rock strength calculated for two different 24” sections. b) is ROP model bsed rock strength for two 12 ½” sections.

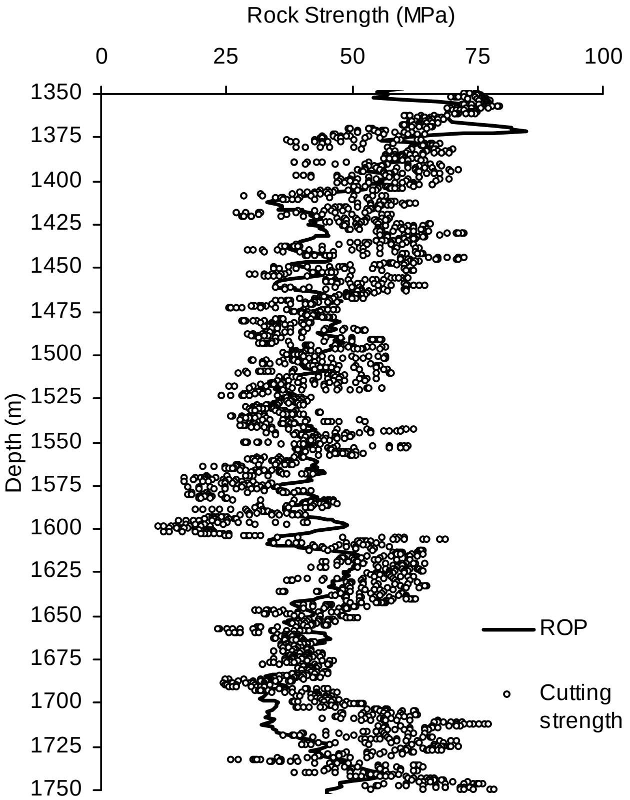

Figure 9. ROP model rock strength compared with rock strength from rock mechanical tests done on drilled cuttings.

5 CONCLUSIONS

Rate of penetration models for PDC and rollercone bit have been normalized to calculate the unconfined compressive strength regardless of what bit designs, formations or operating parameters are used.

Unconfined compressive strength developed from ROP models gives similar results compared with other comparable methods like sonic log correlated unconfined compressive strength and strength from rock mechanical tests done on small cutting samples.

Rock strength from drilling data can be calculated for all sections and all wells since only data related to drilling is required. This method is therefore a versatile method for obtaining rock strength.

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