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Prediction of rock mechanical properties from Wireline Data and their use in Drilling Simulation

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Abstract

We have used wireline log data to derive rock strength and abrasivity as a function of depth for a well. This information was fed to a computer-based drilling simulator that was then used to drill the well in simulation using the same operating parameters as had been used in the field.

Comparison of the field and simulated rates of penetration and states of wear of the bit for different bit runs showed close agreement. This demonstrated not only that our technique for deriving the rock-mechanical strength and abrasivity values from the geophysical data was correct, but also that the drilling mechanics algorithm in the simulator was able to match the drilling performance in the field.

We believe that when the simulator is tuned in this way to reproduce field drilling behavior, it may be used to investigate different drilling scenarios with the objective of finding the most desirable conditions for drilling a future well in a similar geological environment.

Introduction

Computer-based simulation of the drilling of hydrocarbon wells is of value in planning field operations, in optimizing the drilling parameters while drilling and in training drilling engineers. A good simulation of the drilling process requires a model that relates the operational drilling inputs (weight on bit (wob) rotary speed, mud properties and flow rate etc.) to the outputs (rate of penetration, (rop) and rate of wear of the drill bit). It also requires knowledge of the properties of the rocks

to be drilled. The most important of these are the rock type, its strength and abrasivity. Direct measurements of these properties are not easily obtained for typical hydrocarbon wells, so it is of interest to develop means of obtaining them indirectly from more easily available measurements. One such possible source is from wireline logging data, principally the natural gamma ray, density, neutron porosity and sonic logs. In this paper, we present results obtained by deriving the required rock properties from wireline log data and comparing the predictions of a drilling simulator based on them with field results.

Drilling Simulation

The Payzone drilling simulator is a computer program that predicts the rate of penetration and rate of wear of a drill bit from a set of operational and lithological inputs. The output is principally in the form of a prediction of the bit rate of penetration and wear and thence of depth as a function of time. Some other aspects of the simulator have been described elsewhere (1 - 4). In the present case, the objective was to compare the predictions of the simulator with field results using a lithology derived from wireline data as described above.

Our method of using the simulator has been to adopt as simple an approach as possible. Previous experience with drilling simulators (5, 6) has demonstrated that it is difficult to make an accurate simulation of the drilling process even if the relevant lithological, bit and operating parameters are known. This is in part because of the problem of knowing how to combine the large number of variables that affect the drilling response. The question is made more difficult in many field situations as some important parameters may not be well known. Issues may range from having an inadequate description of the geometry of the bit that was or will be used to an uncertainty in the nature of the rock being penetrated and/or its state of pressurization.

We have tried to avoid these problems by adopting an approach in which the simulator is “tuned” to reproduce the drilling behavior under a known set of conditions that are as similar as possible to those of the well that is to be

investigated. Thus, if the rate of penetration of a particular type and style of drill bit is known at a depth and in rock types that are similar to those for which we wish to know some future behavior, tuning the simulator to match the known historical record allows us to avoid having to predict the drilling behavior from first principles. This is not to say that we should not strive to have as accurate a drilling model as possible. Rather it is a means of avoiding having to specify and make detailed measurements of the bit geometry, rock properties, pressure regime, operating conditions and many other parameters. Once the simulator is tuned, when we run simulations to investigate drilling behavior under some new conditions, our assumption can now be that the new drilling response will be different from the tuned situation only insofar as **changes** in the applicable parameters are concerned (and are well modeled), not their **absolute** values. Simply put, this means that, say, if the new operating conditions call for investigating the effect of an increase in rotary speed of 10%, we only need to predict how a 10% change in rotary speed will increase the rop beyond the recorded field value, rather than calculating the new rop from first principles.

There are many possible methods of tuning the simulator. Again, we have adopted a simple approach. Our primary concern has been to match the total drilling time and the final state of wear of the bit for each bit run since these parameters will be of the greatest interest to an engineer planning a new well. The bit run time is related to the sharpness or aggressivity of the bit, and the wear state to its wear resistance. However, the two measures also depend on rock strength and abrasivity, respectively, and these vary foot by foot as the rock properties change. Thus the tuning process consists both of matching the foot-by-foot performance of the bit and also assuring that the overall parameters of the bit run (total drilling time and final bit wear state) are duplicated.

Since the drilling time depends on both rock strength and bit aggressivity, and the rate of wear depends on rock abrasivity and bit wear resistance, there are in principle many combinations of each pair of parameters that could generate the same result, so if neither is known with certainty, their choice becomes arbitrary. Our decision has been to start with the rock properties. The choice of rock unconfined compressive strength (UCS) is natural since that parameter is used directly in the simulator algorithm that determines rate of penetration and there is also much experience in deriving its value from geophysical logs. Rock abrasivity is much less clearly understood, so we have chosen to define it as being proportional to UCS multiplied by the rock quartz content. This seems to work well at least for sedimentary rocks.

The tuning procedure now becomes one of deriving the rock strength and abrasivity from the geophysical (wireline) data and then tuning the bit aggressivity and wear resistance to match the overall bit run performance. We can obtain some measure of the quality of the simulation by noting that if the foot-by-foot changes in bit rate of penetration are well matched, that probably indicates that our chain of derivation from geophysical data to rock properties to drilling response is reasonably accurate, while a good modeling of the overall bit

run parameters is an indication that our understanding of bit behavior, and in particular its rate of wear, is adequate. We now examine these two aspects in more detail.

Derivation of drilling inputs from wireline log data

The essential rock properties needed as inputs for a drilling simulator are the rock strength, governing the rate of penetration of the drill bit, the abrasivity, which determines the rate of wear, and the rock type or mineralogy, which has an important secondary effect on both the rate of penetration and wear. We have attempted to derive these properties from wireline log data.

The field data were from a well drilled at a location west of the Shetland Islands (Scotland). The data had wireline records from the well that were matched in depth to records of the drilling input and output parameters every 0.99ft. approximately. In addition, we obtained notes concerning the bit types used and their wear states at the end of each bit run.

The wireline data consisted of gamma, density, porosity (neutron) and sonic logs. In addition, logs of interpreted UCS and lithology were provided to us. While we could have used the latter directly in our drilling simulation, we chose instead to use our own methods for determining the lithology and UCS so that our simulation could be tested and demonstrated using data derived directly from the uninterpreted wireline logs.

To determine the lithology, we used the method for analyzing wireline data to determine the proportions of quartz and clay plus the porosity described in (7). Sandstones were those materials with the highest values of quartz (greater than about 55%). Siltstones were interpreted when the quartz gave way to porosity (porosity greater than about 15%) and shales were those materials with the highest clay contents (greater than about 25% clay). For detailed drilling simulations, the quartz values were also used to provide an abrasivity parameter by multiplying the quartz content by the rock compressive strength.

Comparison of actual sonic velocities from the wireline log to those velocities calculated using the formulae relating sonic velocity and constituents in (8) provided a satisfactory check on the overall performance of this approach to determining the constituents. We also found that our interpreted units closely matched the geological logs supplied to us. The main difference was that in the supplied logs, there was no distinction between our siltstones and the shale, with these both being labeled as mudstones in the case of the supplied logs. The sandstones were, however, separated into hard and soft sandstones in the supplied data – a distinction that had little significance for our purposes. Limestones and tuffs that were also present in minor amounts could not be identified using our approach, which is designed just for clastic sediments. For these, we used the supplied lithology whenever these rocks were said to be present.

To estimate the UCS we simply cubed the Pwave velocity obtained from the sonic logs. The variations in strength

obtained this way showed the same variability as the UCS log provided by BP. While the absolute values can be controlled by application of appropriate constants and by compensating for the effect of the in-situ stress conditions on the seismic velocity, there was not the need to obtain these in this case because of the tuning procedure that we have applied which ties the total time for the simulated and actual bit runs.

As noted above, the rock abrasivity was made proportional to the rock UCS multiplied by the quartz content. The choice was arbitrary, since there is no generally agreed measure of rock abrasivity for use in drilling simulation. However, we have found this measure to work well in sedimentary rocks where the major abrasive constituent is quartz.

Once values for the rock type, UCS and abrasivity had been derived from the geophysical data, they were converted into a form that could be used by the simulator. The data were formatted into a standard LAS (Log, ASCII Standard) file. Such a file is accepted by the simulator and converted into a usable lithology. The converter has an option that allows foot-by-foot data to be “blocked” into units of similar rock type, UCS or resistivity. The blocking algorithm has the following attributes. A new block is started when:

- the rock type changes and if
- either the rock UCS or the resistivity change by a user-determined amount.

When carrying out the blocking procedure, the program automatically assigns to the block values of UCS, resistivity and all the other parameters that are the average values for each of the foot-by-foot data lines that comprise the block. We believe that this procedure is valuable not only for saving computational time and storage space, but in simplifying the view of the drilling process. This point is further discussed below.

Comparison of mwd data with results derived from the wireline data

Before embarking on the drilling simulation, we also needed to establish whether there was consistency between our expectation of the downhole geology and rock properties and the actual mwd results obtained from the drilling. Without this consistency, our premise that the drilling response was partly controlled by the geological conditions would be false.

As discussed later in the simulation for bit run 9, the influence of the geological conditions can be to affect the bit wear and hence the rate of penetration. Of more interest at this stage, however, was a study of the effect of changes in the inferred rock strength on the rate of penetration, taking into consideration the variability of the weight on bit.

Consider the mwd data and the inferred UCS and lithological data shown in Figure 1, which are from bit run 5. For convenience, on the two upper graphs, the rop, the wob and the UCS have all been arbitrarily normalised. Our inferred lithology is shown below. Of initial interest is the behaviour of the drill in the thick sandstone units at depths of 6,712-6,767 ft and 6,850-6,990 ft. Within these constant lithologies there are variations in the UCS shown in the upper plots. In the top plot

there is little correlation between the variations in the UCS and the rop. In the case of the second plot, the UCS values have been depth corrected by 0.04% up the hole and there is now a striking inverse correlation between the rop and UCS, not only in these sandstones but across the entire section. As the UCS increases, the rop decreases and vice versa. It is also possible to see how the behaviour is modified by variations in the wob made by the drillers as they tried to maintain the rop. This second plot verifies that links exist within these data between the geology and the drilling response.

We have observed similar behaviour in our analysis of the entire data set, and in all cases, depth corrections are required to bring the wireline derived data into line with the mwd results. Reasons for the need for such corrections include the increasing cable stretch experienced as the wireline tools are deployed deeper in the hole. The amount of stretch experienced will also vary depending on the mud weight and the drag of the tool and cable against the borehole wall. Given these reasons, exact *a priori* corrections would be very difficult if not impossible to determine. Instead we have corrected our wireline results on the basis of experimentation with different stretch factors.

Simulation results at large scale

Once the rock properties had been determined and the data blocked, the second stage in the tuning process began. Here the objective was to tune the drill bit aggressivity and wear resistance so that the overall properties of the bit run (total time and final wear state) were well matched. The simulator holds an inventory of drill bits, each of which is identified by bit type and size, and by a characteristic aggressivity and wear resistance that can be adjusted to tune the response of the bit.

We also recognize that bits of different types may show a greater or lesser rop in a rock of given mineralogy and strength, and be more or less worn. For example, a PDC bit may be found to have a greater rop in a shale than, say, a TCI bit operating under the same conditions in the same rock, but it may be more rapidly worn. However, we have not allowed different layers of the same rock type to have individually adjustable “hardness” or “abrasivity” beyond what is determined by the interpretation of the wireline data. Thus it may be seen that some rock layers may be drilled abnormally slowly or fast for reasons other than their strength, that are at present unexplained. A possible reason for such an effect could be, among others, if one particular layer has a higher or lower pore pressure than expected. However, we were unable to investigate this possibility since no data were provided concerning the pressure environment in the well, apart from the mud density while drilling, which remained constant over each bit run.

Experimentally, the tuning process began by loading the lithology and set of drill bits, and setting the field operating parameters. The interval to be investigated was then drilled, and the time for the bit run and its state of wear at the end of the run were noted. The two values were compared with the field values and adjustments were made to the bit aggressivity and wear resistance in the rocks being drilled. The bit run was

repeated with the same (field) operating conditions and the new bit run time and wear state were again noted. More adjustments were made and the process was repeated until the field and simulator values of run time and wear state coincided. At this point the simulator was considered to be tuned to the field conditions.

We illustrate the method by presenting results for the simulation of two bit runs from the same well. We have chosen bits of different types and diameters. Some of the parameters of the bit runs are shown in Table 1.

We shall also use these two runs to illustrate various techniques that we have found useful in running simulations.

Effect of averaging operating parameters

In carrying out our simulations, we have investigated the effects of using averaged operating conditions and rock properties. For example, the field records show weight on bit fluctuating continuously during any bit run. Figure 2 shows the record for bit run 5, with the field wob fluctuating rapidly. When running a simulation, weight on bit is set by the operator, so it would be very arduous to run a simulation in which the operator changes the weight on a foot-by-foot basis to match the field record exactly. As an alternative, we show as a stepped line in the figure the weight on bit represented as averages of the field values over nine separate intervals. These values were used in the simulation. The intention was to apply average values that corresponded closely to the actual average values over specific depth intervals. The total bit run time for the interval was then compared with the time taken to drill the same interval with a single value of wob equal to the average for the entire bit run (33,000 lb). The two run times were, respectively 45 h and 45 min and 45 h and 28 min, or a difference of 0.6 %. The coincidence is largely the result of the bit rate of penetration being almost directly proportional to weight on bit over this range.

Accordingly, it was decided in future work to run simulations under averaged values of the operating parameters for the particular bit run in most situations. This approach has the merit of making it much easier to run any simulation, since the operating conditions do not have to be changed continuously. It should also be recognized that if the intention is to obtain a reasonable estimate of the drilling behavior in a future well, it will not be possible to control the weight (or any other operating parameter) to more than an average value in any case, and so it is pointless to attempt to predict the drilling behavior with a greater degree of precision.

The same remarks can be made concerning the accuracy with which the lithology is reproduced by the blocking process (see above). Again, to the extent that the bit's rate of penetration is linearly related to rock strength, the total time to drill any interval will be the same whether it is made up of many or few layers, as long as each layer's strength is the average of the values for each of the logged elements in the layer. Again, it must be recognized that in any future well, even a close offset, there will be detailed differences in the new lithology that will

make it worthless to attempt a prediction based on more than average values for the expected lithology in any case.

Effect of normalizing output values

One consequence of running the simulation at constant averaged values of the operating parameters is that it becomes desirable to adjust the field values to match. In a simulation such as that shown in Fig. 2, it will be appreciated that, since the simulation was run at constant values of wob whereas the field values were changing on a foot-by-foot basis, the **instantaneous** values of weight on bit in the two cases usually were not the same, and therefore the field and simulated values of rop could not be expected to be the same. To allow a better comparison, therefore, values of field rate of penetration were usually normalized by the factors (simulator average wob / instantaneous field wob) and (simulator average rpm / instantaneous field rpm).

The same cautionary remarks apply to this process as were made above concerning the weight on bit in the sense that the process will give good results as long as the rop is proportional to wob and rotary speed. This is generally so, as has been stated, but there are conditions where it is not. The most common "abnormal" situation was found at the beginning of a bit run, when wob was light and the bit sharp, and particularly if the mud flow was on the low side. Under these circumstances, scaling the rop by wob alone resulted in large values of "normalized" rop. These might not easily be attained in practice because of limitations to the rop imposed by the field mud flow. This was usually adequate to clean the hole under the moderate rop achieved under the field wob but not under the high "normalized" values. Usually this effect was noticed in the early part of the bit run and became less as weight and bit wear increased towards the end of the run. Fig 3 shows an example of the effect for run 5 in which the normalized field values show rates of penetration that are often above 150 ft/hr. in the early part of the bit run when the actual field values (shown in Fig 4) seldom exceeded 100 ft/hr. In contrast, note the generally better correspondence between field and simulator values in fig 3 because of the normalization for depths below 7,000 ft when the rate of penetration was lower and less influenced by the mud flow.

Note also, however, that even in this interval, the detailed correlation of rop with rock strength is still well maintained; the data presented in Fig 1 are from the interval 6,700 – 7,000 ft.

Prediction of overall rate of penetration

Figures 3 and 4 show the predicted rate of penetration for the TCI bit (run 5) while Fig 5 shows the prediction for the PDC bit (run 9). Taking the normalized values (Figs 3 and 5) but excluding the data for the early part of bit run 5, to 7,000 ft, which we believe to be poorly modeled, as described above, we consider that we have been able to get a good correspondence between the field and simulated predictions. Note, of course, that because of the blocking of the litho data, the fine scale of the fluctuations in rop are not well represented within any rock layer, but the average rates of penetration in any layer are generally well modeled. Note the

progressive reduction in rate of penetration in both bit runs as a result of bit wear, and in the case of the PDC bit, the greater bit wear in the faster-drilling but more abrasive sands (wear is indicated by the down-sloping plots of rop for each sand interval).

In spite of the good overall match in the data, a few points for discussion remain. The first is that in some rock layers, anomalous rates of penetration were observed. In bit run 5 (Fig 4) there are two sands, lying just above and below 7,600 ft. Our interpretation of the wireline data indicates that they are of similar strength and they should therefore show similar rates of penetration, at just over 40 ft/hr. The field data show, however, that the upper layer was drilled at about 60 ft/hr, while the lower was drilled at about 30 ft/hr. This discrepancy is as yet unexplained, although a possible explanation might be that the upper sand is overpressured and the lower one underpressured with respect to the average for the well. Unfortunately, we have no information to confirm or deny this suggestion. Other apparent anomalies can be explained. For example, the apparently inverse behaviour at 7,100 ft in Fig 4 can be seen to be removed when the data are normalized for wob and rpm in Fig 3.

It should also be noted that it has not always been possible to match the field and simulated final wear states of the bit. For bit run 9 (PDC) the field wear state was T 8 and this exactly matched the result predicted by the simulator. However, for bit run 5 (TCI) it was necessary for the simulator to predict a final wear state of T 6 whereas the field reported result was T 3. The anomaly is perhaps connected in some way with the high rates of penetration measured in the early portion of the bit run. These high values required the assumption that the bit was initially very aggressive, but that it must have worn substantially to return the much lower values reported from 7,000 ft down.

In Fig 5, there seems to be a poor correlation between predicted and field values of rop between 14,325 and 14,375ft. In this case, it almost looks as if the simulator values are lagged by 20 ft or so. However, we have no evidence to support or deny this explanation.

Conclusions

In this work, we have tested whether we can derive lithological information from wireline well records in such a way that it can be used directly in the simulation of drilling performance. We have also tested whether the simulator, provided with this information, can make predictions that correspond with field drilling records. We believe that both tests have been successful.

We have also identified and discussed some circumstances where there are real or apparent discrepancies between the field and simulated results. In some cases, these can be explained by straightforward mechanical errors by, for example, not having the same depth scales for data sets that were taken by different crews using different instruments at different times. If unidentified, these errors can make it extremely difficult to see the actual correspondence between

data sets. Other sources of disagreement are at present unresolved, but may be connected with unidentified changes in formation pore pressure or other factors.

We believe the technique will be of value in predicting drilling behaviour in future wells. The predictions should be valid to the extent that the geological conditions are similar and as long as the choice of operating equipment and conditions are not changed by a large amount. We also believe that if optimization of future drilling behaviour is the objective, it is unnecessary to strive for an extremely accurate simulation of the drilling process. Therefore, averaging procedures may be usefully employed. It should be remembered that every well is different, in geology, in choice of equipment and in the selection of operating conditions. The task is to make a set of predictions that not only represent the range of available operating parameters but that are also self-consistent and reasonably accurate. From this basis, the engineer can select the one that gives the most desirable result relative to the others. This will be more productive in improving drilling performance than attempting a minutely accurate prediction of any specific scenario.

Acknowledgement

We should like to thank Dr John Thorogood and BP for allowing us to use the data set from one of their wells. Significant progress on this project was made while one of us (GAC) was on sabbatical leave as the guest of Dr Michael Hood, CEO of the Cooperative Research Centre for Mining Technology and Equipment (CMTE) in Brisbane, Australia.

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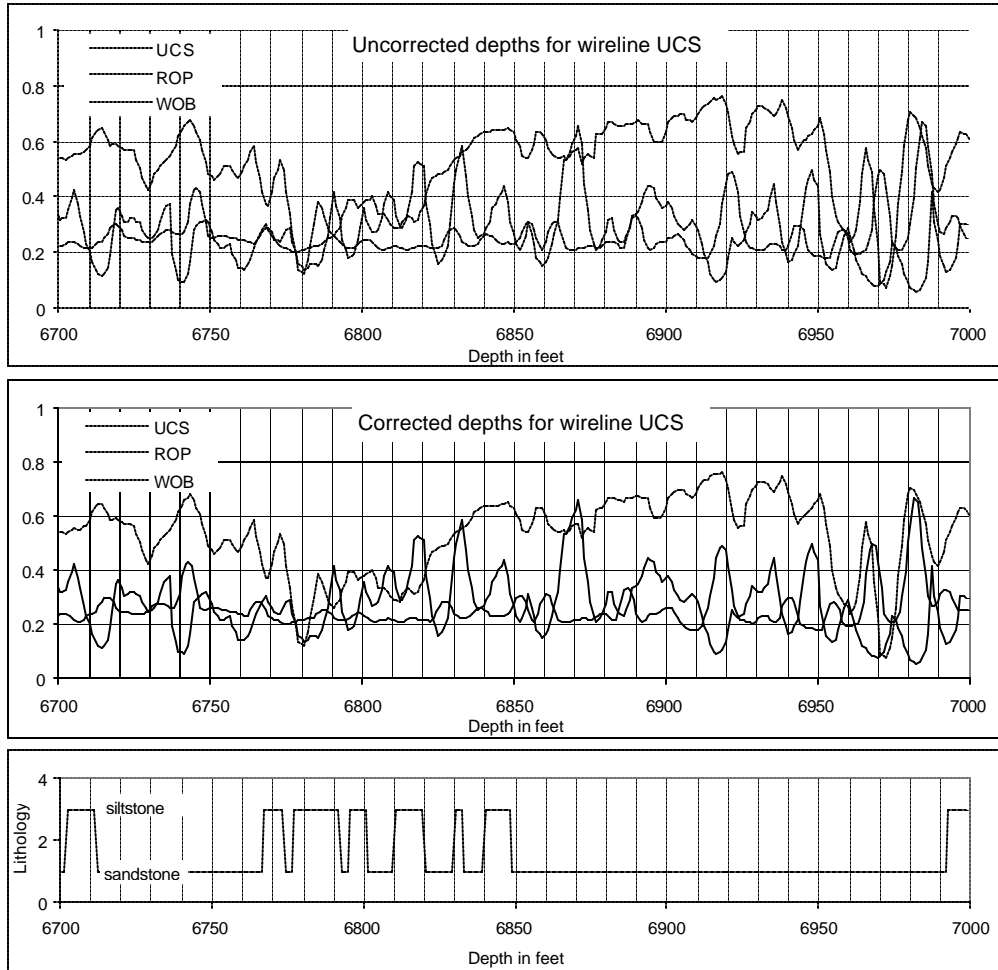


Figure 1. Comparison of arbitrarily normalised rop, wob and UCS for cases involving, top, no depth correction to the wireline data (UCS), and middle/bottom, a depth correction of 0.04% up the hole for the wireline results. Depth correction is required to establish correlations between these data.

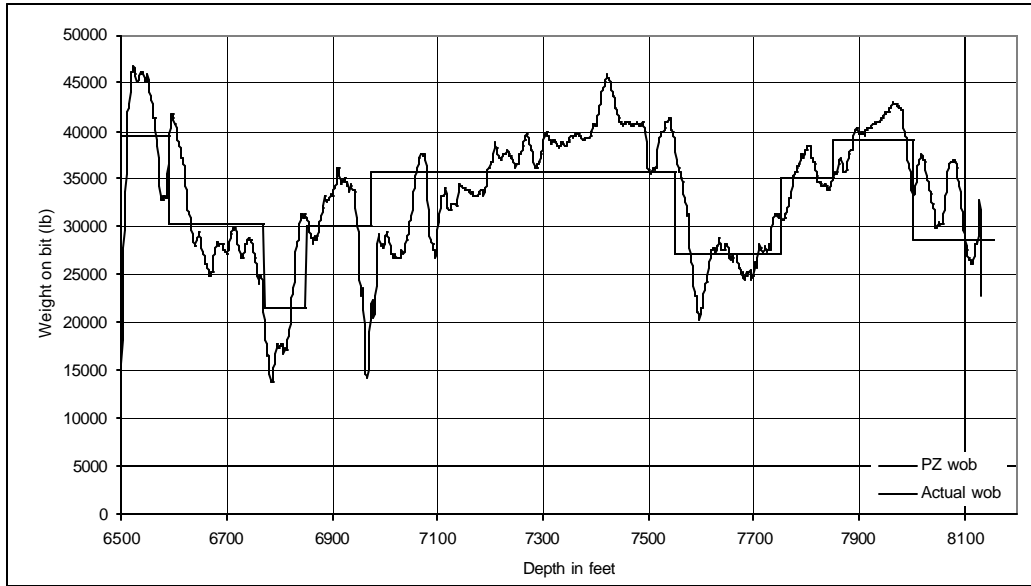


Figure 2. Comparison between actual and simulated (pz) wob for bit run 5.

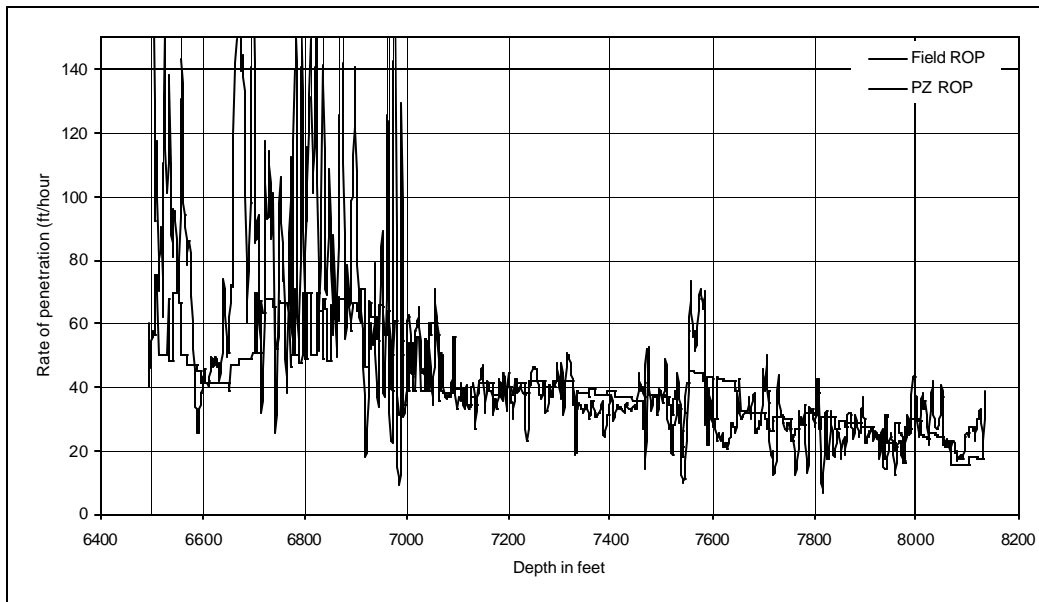


Figure 3. Field and simulator (PZ) values of rop as a function of depth for bit run 5 (TCI bit). The field rop has been normalized to the same wob and rotary speed as was used in the simulation.

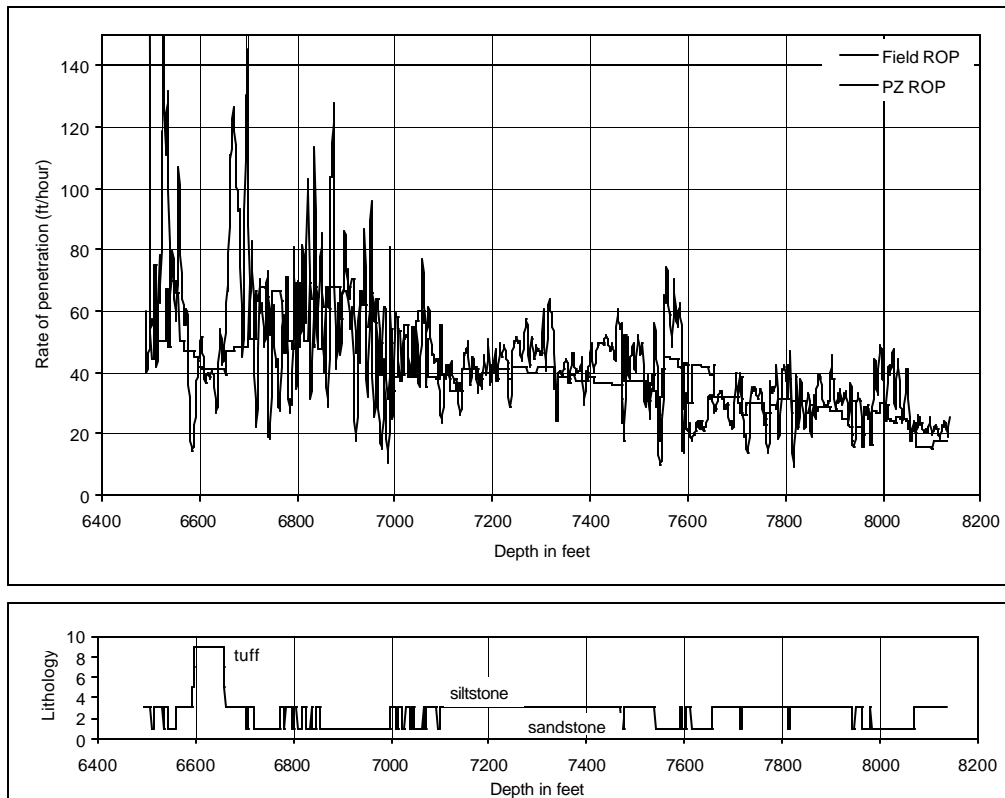


Figure 4. Field and simulator (PZ) values of rop as a function of depth for bit run 5 (TCI bit). Compare with Fig 3. In this case, the field rop has not been normalized. The “Litho” plot indicates rock type, where 1 = sand- or siltstone, 3 = shale and 9 = tuff.

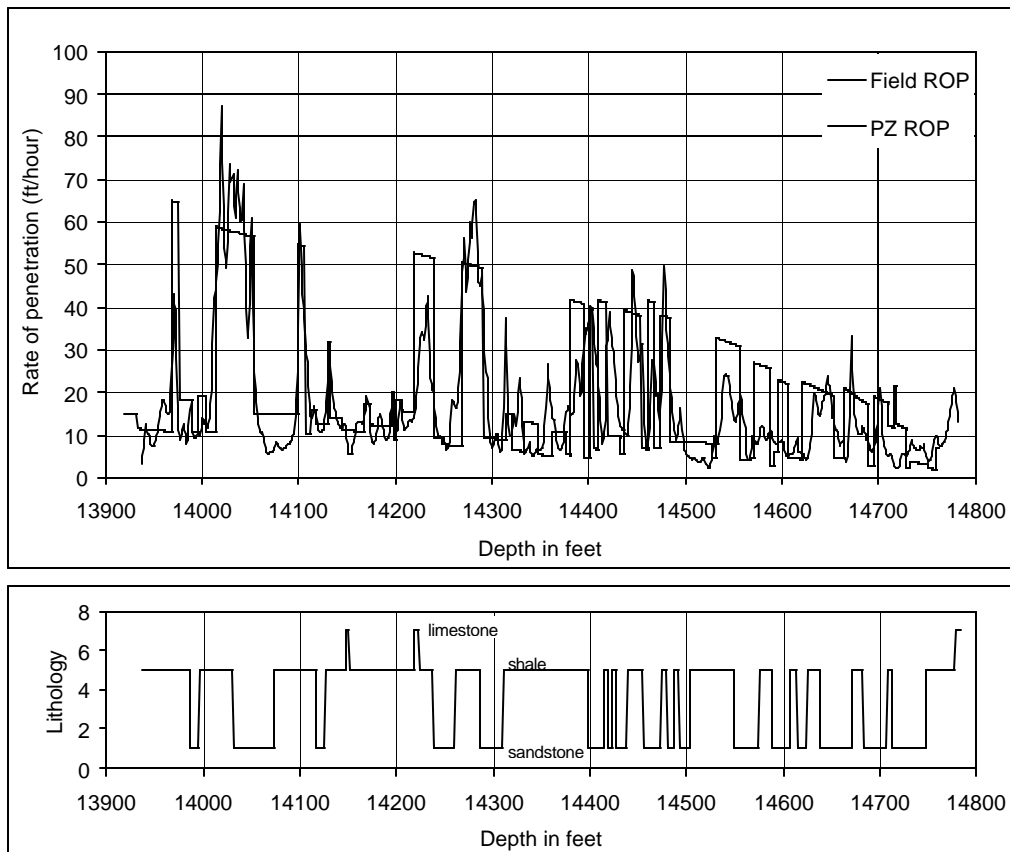


Figure 5. Field and simulator (PZ) values of rop as a function of depth for bit run 9 (PDC). The field rop has been normalized to match the simulated wob and rotary speed.

Bit run	Bit type	Depth in (ft)	Depth out (ft)	Mud wt. (ppg)
5	TCI 12.25" medium tooth	6,510	8,130	10.0
9	PDC 8.5" short tooth	13,938	14,783	14.3

Table 1. The two bit runs